Thermal comfort for multi-functional use in monumental churches

Case study Stevenskerk in Nijmegen

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P5 report
by

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Abstract

Secularization has led to a decrease in the significance of religious traditions and thereby the use of churches. Accordingly, many church buildings have been converted or are used multi functionally such as the Stevenskerk in Nijmegen (NL), the monumental case study of this project. Thereby, the lifespan of the building is extended while making use of its embodied energy.

However, the large enclosed space and the insufficient energy performance of the non-insulated building skin lead to an immense heating demand and closing of the Stevenskerk during the winter period due to unsatisfactory thermal conditions.

Excessive heating results in a high energy consumption and building related CO2 emissions which are a main contributor to the ongoing climate crisis. Furthermore, the limited usability and accessibility during the cold season reduce the visibility of the national monument. This creates a lack of understanding the relevance of conserving religious heritage among citizens.

Therefore, this project investigated different renovation strategies with the aim to improve the thermal comfort in the Stevenskerk as a case-study for monumental and multi-functional churches by answering the research question *«How can the renovation of the stained glass windows in combination with indoor space adaptations increase the thermal comfort in the multi-functional Stevenskerk in order to improve the accessibility of the monument all year around?»*

Additional ambitions and values for the identification of suitable renovation measures were defined: the usability of the space, the reduction of the heating demand, the conservation of significant monumental values, the durability of the measures with respect to their sustainability, the proportionality of the financial investment and the acoustic and lighting conditions.

Literature review, in-situ measurements in the Stevenskerk, thermal computer simulations and physical calculations in combination with research by design enabled the identification, the development and the comparison of different renovation methods. The project introduced an evaluation framework which resulted in a comparative overview of different window renovation and spatial adaptations strategies which is applicable for the Stevenskerk as well as for other multi-functional and monumental church buildings in the Netherlands.

According to the assessment of the introduced strategies, a renovation proposal for the Stevenskerk was developed. Based on the finding that one renovation measure for the whole building cannot fulfill all requirements, distinctive interventions for the different zones in the Stevenskerk are suggested. This enables a flexible and adaptive use according to the needs of different user groups and the space in a long-term perspective in accordance with its social responsibility as a building for the community.

To conclude, this project presents an approach on how to combine current user and building requirements with the preservation of heritage values by developing and selecting suitable renovation strategies in order to promote the functionality and visibility of the Stevenskerk and other multi-functional churches as «living heritage».

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Nomenclature

Abbreviations

Abbreviation	Definition
ATG	Adaptive Temperature Limits
°C	Degree Celsius
c	Center
CFD	Computer Fluid Dynamics
CO2	Carbon dioxide
EU	European Union
HVAC	Heating, Ventilation and Air Conditioning
IEQ	Indoor Environmental Quality
IR	Infrared Radiation
K	Kelvin
l	Left
LED	Light Emittind Diode
MET	The Metabolic Rate - 1 MET = 58.1 W/m^2
MRT	Mean radiant temperature [°C]
PCM	Phase Change Material
PG	Protective glazing
PPD	Predicted percentage of people in discomfort [%]
PMV	Predicted Mean Vote
r	Right
R-value	Thermal resistance of a building component
RH	Relative humidity [%]
T_a	Air temperature [°C]
T_c	Comfort temperature [°C]
T_e	Outdoor air temperature [°C]
$T_{e,ref}$	Running mean outdoor temperature [°C]
T_i	Indoor air temperature [°C]
$T_{surface\ in}$	Internal surface temperature [°C]
$T_{surface\ out}$	External surface temperature [°C]
TU Delft	Delft University of Technology
U-value	Thermal transmittance of a building component

Symbols

Symbol	Definition	Unit
C	Emmissivity material	[-]
I_{cl}	Thermal resistance of clothing	[m^2/kW]
R_{tot}	Total heat resistance	[m^{2}K/W]
r_{cav}	Heat resistance cavity	[m^{2}K/W]
r_i	Heat resistance internal surface	[m^{2}K/W]
r_{out}	Heat resistance external surface	[m^{2}K/W]
v	Velocity	[m/s]
α	Heat transfer coefficient	[W/m^{2}K]
ρ	Density	[kg/m^3]
c	specific heat	[J/kgK]
ξ	resistance factor	[-]
ΔT	Air temperature difference	[°C]

1 Context

1.1 The climate crisis and the built environment

As a result of the continuous use of coal, oil and natural gas as a heating source, the building related energy use has risen up to 35 % of the global energy consumption and to 38 % of the CO2 emissions worldwide in 2019 (Global Alliance for Buildings and Construction, 2020). Non-residential buildings account for 11 % of the global CO2 emissions (Global Alliance for Buildings and Construction, 2020) and require on average 40 % more energy than residential houses (250 kWh/m^2 in comparison to 180 kWh/m^2) (European Commission, 2013).

Due to a replacement rate of only 1 to 3 % per year new built constructions are the minority of the buildings that will exist in 2050 (Ma, Cooper, Daly, & Ledo, 2012). Thus, when targeting the European climate goals for 2050 in order to fight the ongoing climate crisis, the significance of extending the lifespan of existing non-residential buildings in order to make use of their embodied energy while decreasing their greenhouse gas emissions by energy demand reduction becomes clear.

1.2 Multi-functional, monumental churches in the Netherlands

On the one hand, secularization has clearly decreased the significance of religious traditions over the last decades. In 2018, more than half of the population in the Netherlands did not belong to any religious group and one can observe a steady decline in the attendance of church services on a regular basis from 37 % of the population in 1971 to 16 % in 2017 (CBS, 2018). This results in less use of the existing church buildings and raises the question of their future functionality.

On the other hand, in 2017 there were 4.373 listed churches and cloisters in the Netherlands (CBS, 2020) which are protected by the government because of their cultural-historical significance and therefore are to be preserved as a national monument for future generations.

This development has already led to a large number of conversions and the multi-functional use of monumental religious buildings in the Netherlands. Because the original function is adapted, the building and its interior can be preserved and is once again experienced by the users (Rijksdienst voor het Cultureel Erfgoed, n.d.).

The public significance of this building preservation becomes clear by the fact that the Dutch minister of Education, Culture and Science has made a total of 13.5 million euros available from 2018 until the end of 2021 for the «national church approach» *(de nationale kerkenaanpak)* with the aim to develop a sustainable future perspective for churches in the Netherlands. (Rijksdienst voor het Cultureel Erfgoed, n.d.) This program includes investments on creating integrated church visions within the municipalities and collecting data with a focus on the durability and the sustainability of religious heritage.

Due to the little contact of the population with religious monuments the understanding for the relevance of their conservation among citizens is lacking. Therefore, the «national church approach» furthermore aims for improving the public accessibility and to bring people in contact with the religious heritage. (Rijksdienst voor het Cultureel Erfgoed, n.d.)

Moreover, the re-use or adaptation of a monumental church relates to a type of monument with an exceptional significance for the society. Although the use of churches for the religious community has decreased, their sacred connotation is remaining. Despite not being used for religious purposes, the church can be a place of reflection and peace, a sanctuary away from the hectic everyday life. Furthermore, churches were built and nowadays still are perceived as a building for the community, often prominently located in and therefore shaping the landscape of a city.

1.3 Thermal comfort in monumental church buildings

Historically, church buildings were not equipped with a heating system. Thus, the indoor climate was determined by the outdoor weather conditions, by the large heat and moisture capacity of the massive wall constructions and the large indoor volume. In Northern Europe this results in a cooler indoor climate in the summer and warmer temperatures during the winter compared to the outside conditions (Schellen, 2002).

Due to increased comfort requirements, churches were equipped with heating systems, varying from warm air heating to floor heating, radiant heating or convector heating (Schellen, 2002). Nonetheless, for church buildings located in a heating dominated climate it is challenging to achieve a comfortable indoor environment during cold periods. During the hot season the high thermal mass of the walls leads to a rather comfortable cool indoor climate by reducing the temperature fluctuations. However, during the heating season, the large building volume in combination with immense heat losses through the non-insulated building skin result in a large heating demand. Especially in Gothic churches, the large window to wall ratio increases the heat losses and therefore the heating demand even further. Thus, heating up the church leads to a large financial investment and CO2 emissions in case the heating system is supplied by a non-renewable heating source.

Furthermore, the multi-functional use of church buildings which has increased during the past 40 years results in a thermal comfort challenge. When the occupants are dressed up suitable for an event such as a concert, an exhibition or a dinner, this might be inappropriate for the indoor climate of the church. (Schellen, 2002).

In addition, the implementation of a heating system represents a risk for the preservation of a monumental church building as well as its inventory mainly because it changes the relative humidity and the temperature level (Schellen, 2002). Potential consequences could be for example the contamination of the wall above heating elements with dark spots, the deterioration of paintings, the deposition of dust or the appearance of condensation. Furthermore, lead glass corrosion may occur due to condensation and damages to monumental church organs have been observed due to fast heating and dry air (Schellen, 2002).

1.4 Case study building

The Stevenskerk is a multi-functional church building in the center of Nijmegen in the province of Gelderland (figure 1.1). The church and its climatic challenges are case study and the starting point for this graduation project.

Figure 1.1: Aerial view (l) (Degelderlander, 2017) and outside view Gerfkamer and choir (r)

The Stevenskerk is composed of a main nave with choir, ambulatory and a transept. The smaller North and South chapels are separated from the large indoor space (figure 1.2).

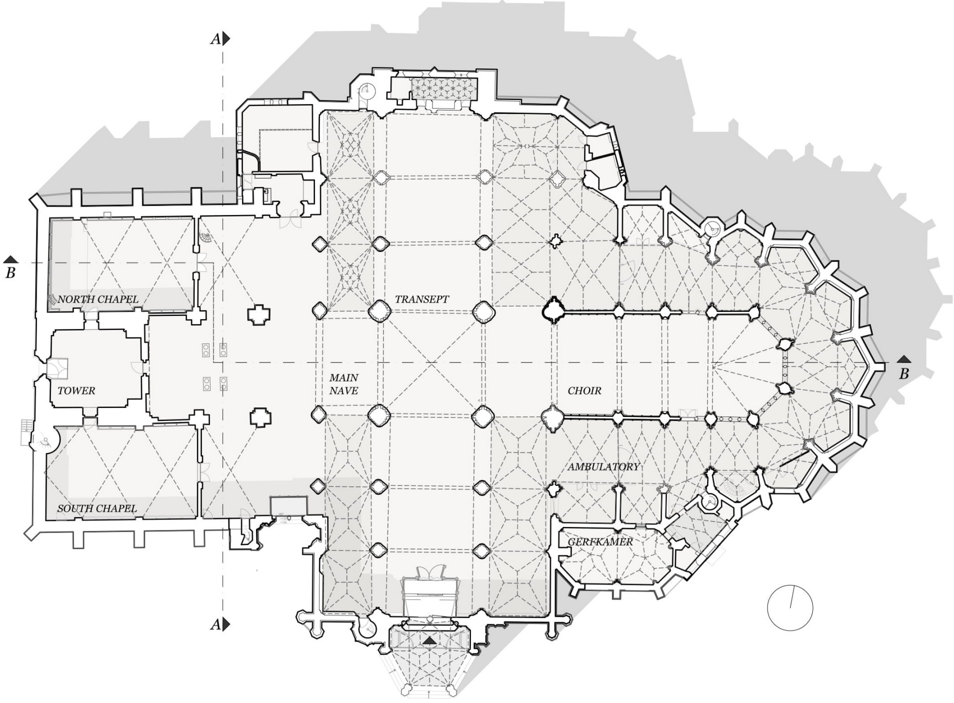


Figure 1.2: Floorplan Stevenskerk

The church is built in the medieval architectural «Gothic» style including typical elements such as high naves, pointed arches, decorative vaults and stained glass windows (Karen, 2015) (figure 1.3 and 1.4). The building is registered as a national monument and owned by a foundation *(Stichting).* The Stevenskerk and its building history are described more detailed in chapter 3.

The Stevenskerk is accessible seven days per week. However, it is only open from the 1st of April to the 1st of November and during the Christmas period. Nonetheless, the building receives on average more than 132.000 visitors per year which makes it one of the most visited churches in the province of Gelderland and a good example for «living heritage» (Rijksdienst voor het Cultureel Erfgoed, 2021).
The Stevenskerk is used for multiple functions such as church services, festivities, exhibitions or concerts. In accordance with the «national church approach» in the Netherlands, the foundation Stevenskerk is aiming at improving the building's sustainability while sustaining its social responsibility for future use and opening up the church 365 days per year (Stichting Stevenskerk, 2005).

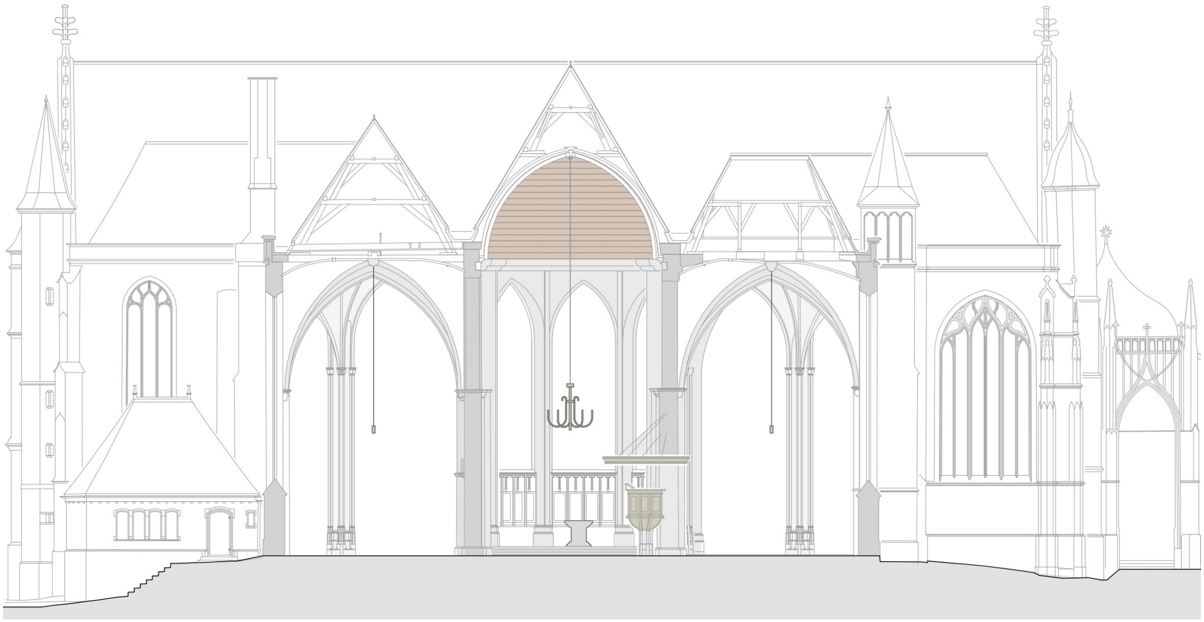


Figure 1.3: Section Stevenskerk A - A

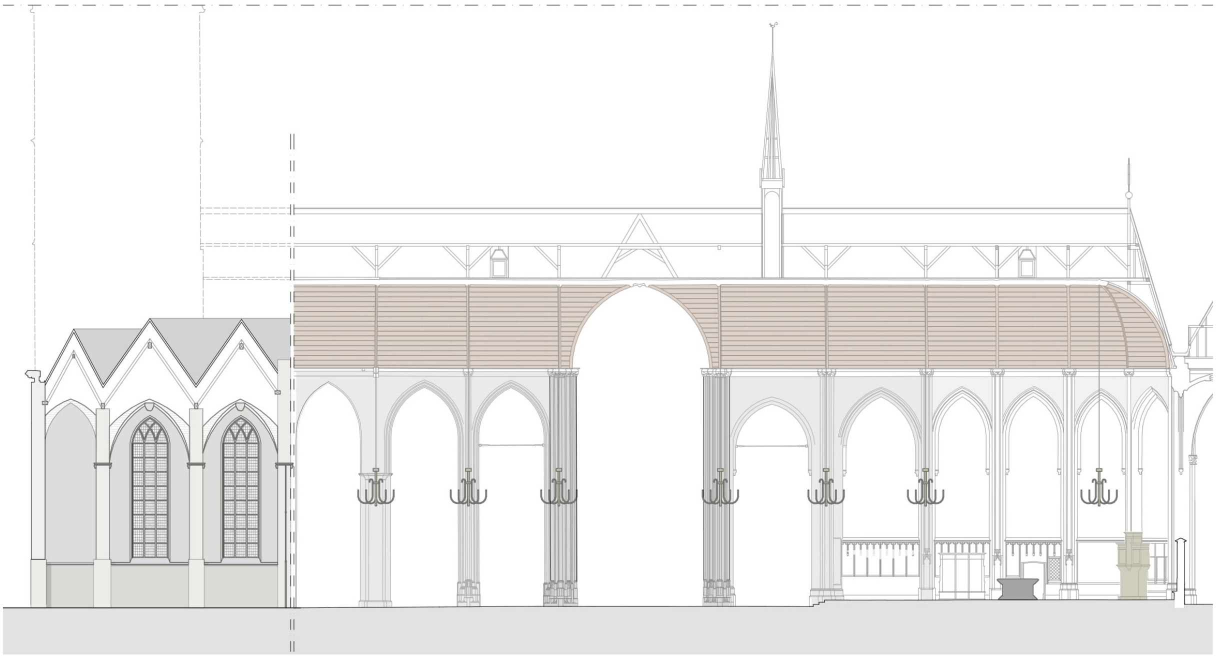


Figure 1.4: Section Stevenskerk B - B

2 Research framework

2.1 Problem statement

The 2.500 m^2 large interior of the Stevenskerk is covered with high vaults, resulting in an impressive indoor space and a volume of approximately 34.000 m^3 (Nusselder & Zandijk, 2015). During the hot season, the high thermal mass of the massive stone walls leads to a comfortable indoor environment without cooling required. During the winter period, however, the immense heating load, cold bridges and air leakages of the building skin together with an ineffective heating system resulting in a heating rate of 1 °C/4 h, make it difficult to heat the Stevenskerk to a comfortable temperature (OOM Advies, 2018). Additionally, the low internal surface temperature of the non-insulated building skin in combination with cold draft increase the thermal discomfort for the users. In order to reach an appropriate temperature level inside the Stevenskerk, a higher heating temperature is necessary which, however, results in a harmful environment for the monumental inventory.

To conclude, the large heating demand and the insufficient energy performance of the building skin lead to closing the Stevenskerk during the winter period because the thermal conditions do not correspond with the requirements for the multi-functional use of the space (figure 2.1).

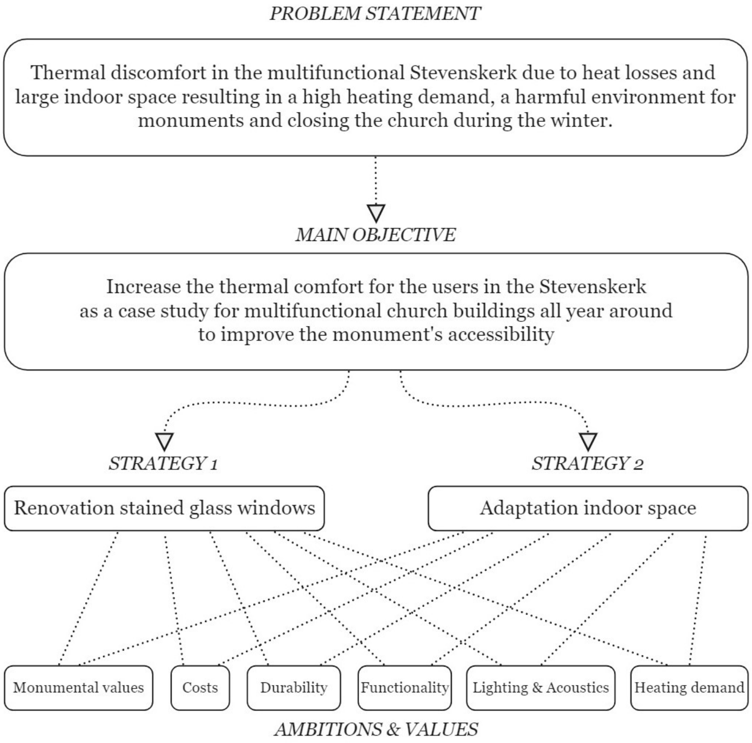


Figure 2.1: Research structure: problem statement - main objective - strategies - ambitions and values

2.2 Research objectives and restrictions

The main objective of this research is the identification of suitable measures to increase the thermal comfort for occupants in the Stevenskerk in order to improve the accessibility of the multi-functional monument (figure 2.1).

Former research has identified the renovation of the large windows as an effective measure to decrease the energy demand in the Stevenskerk (Schoch & van der Zanden, 2019). As the renovation of windows has a significant impact on the visual and architectural impression of a building it is of particular importance to consider this adaptation carefully, especially when dealing with a monumental building. In comparison, the roof insulation for example, has a large impact on the buildings thermal performance but in can be applied invisible for the visitor.

Indoor spatial adaptations have been part of numerous church transformations with the aim to extend their lifespan (Parcum, n.d.-a) and have potential for supporting multi-functionality. This directly relates to the main objective of usability and accessibility of the monumental Stevenskerk.

Therefore, the *transformation of the stained glass windows* in combination with *adaptations of the indoor space* were identified as two promising strategies to be investigated as the focus of this project. Nevertheless, other renovation strategies such as the adaptation of the heating system, the vault insulation or heat recovery are effective measures for reducing the energy demand and could be explored in further research.

This project should support the Stevenskerk foundation in determining appropriate renovation methods. As similar challenges regarding the thermal comfort appear in other multi-functional church buildings in the Netherlands, the aim is to identify measures that could also be suitable for other cases.

To ensure that the renovation proposals are appropriate not only for thermal comfort improvement in the Stevenskerk, but from a holistic building perspective, additional ambitions and values for the selection of suitable interventions were defined. Those ambitions are the functional usability of the space, the reduction of the heating demand, the conservation of significant monumental values, the durability of the measures with respect to their sustainability, the proportionality of the financial investment and the acoustic and lighting conditions (figure 2.1).

2.3 Research questions

Main research question

According to the problem statement and the research objectives this project has the aim to find suitable renovation measures to promote the accessibility of the Stevenskerk during all seasons by answering the main research question:

«How can the renovation of the stained glass windows in combination with indoor space adaptations increase the thermal comfort in the multi-functional Stevenskerk in order to improve the accessibility of the monument all year around?»

Sub questions

In order to answer the main research question the following sub-questions were identified:

Monumental values and heritage conservation

What are the monumental values in the Stevenskerk and how can their significance be assessed?

What are the conservation requirements for the monumental inventory and building components?

Thermal comfort

How can the current thermal indoor comfort in the Stevenskerk be assessed and how could it be improved?

What are the thermal comfort requirements and how can they be combined with the requirements for the heritage conservation?

Renovation strategies

Which renovation methods for stained glass are already existent and how can their performance be assessed?

What is the influence of the stained glass windows in the Stevenskerk on the thermal discomfort and how can this be improved?

Which indoor space adaptations have potential to improve the thermal comfort in a multi-functional church building?

What are the requirements for the spatial adaptations in the Stevenskerk regarding the monumental values and the functionality of the space?

How can renovation measures be combined in order to achieve a suitable renovation strategy for the Stevenskerk?

How can the assessment of renovation measures suitable for the Stevenskerk be applied to other multi-functional church buildings?

2.4 Social, scientific and professional relevance

Social relevance

Although the preservation of monumental buildings such as the Stevenskerk is protected by law as it contains significant heritage values which are valuable for future generations, the usability and the accessibility are crucial arguments for the existence of a building. According to the former minister of Education, Culture and Science Van Engelshoven : *«Investing in a monument that does not have a function is useless since the monument will deteriorate anyhow. Additionally, monuments should keep their central place and function in society.»* (Engelshoven, 2019).

Enabling the accessibility of the Stevenskerk all year around is one central aspect in developing a sustainable future perspective for the Stevenskerk in which it can take its social responsibility as a space for the community.

Scientific relevance

The literature review on stained glass renovation has identified research about the application of protective glazing as a suitable renovation strategy. Most of the literature is focused on the effect of protective glazing on the conservation of the stained glass (Godoi, Kontozova, & Van Grieken, 2005; Curteis & Seliger, 2017; Oidtmann, 1994). Furthermore, former research has assessed the physical performance of external protective glazing (Oidtmann, 1994; Wolf, Trümpler, Wakili, Binder, & Baumann, 2013).

However, there is a lack of literature assessing the impact of different protective glazing types in particular on the thermal indoor comfort. Furthermore, the introduction of alternative renovation methods for stained glass windows is lacking.

Therefore, this research aims at identifying different stained glass window renovation measures and assessing their impact on the indoor thermal comfort. Additionally, this project suggests to link the window renovation with the design of spatial adaptation strategies in order to combine their benefits for the building physical performance and the spatial functionality.

Professional relevance

Currently, there is not sufficient information available for the foundation Stevenskerk to decide on which measures to implement on this specific building with its specific requirements.

«Heritage buildings are always an intrinsic part of the built environment and apart from the influences of weather and changing tastes of occupants also subject to various usage requirements and building codes. Due to this physical reality, a heritage building cannot be treated exactly like other heritage objects.» (Kuipers & de Jonge, 2017).

This project provides an overview of promising renovation strategies, suggests assessment criteria for the selection of suitable measures and presents a combination of strategies as a renovation proposal for the Stevenskerk.

Referring to the significance of the transformation of the existing built environment for the fight against the climate crisis, this thesis provides and compares ideas how to improve the energy performance of a monumental building while enabling usability and preservation of its heritage values. The interventions for the Stevenskerk are an example for the sustainable transformation of the built environment in a challenging case. As Wubbo Ockels (1946 - 2014), astronaut and founder of *De Groene Grachten project* (an initiative for the sustainability transformation of monumental buildings) said: *«If a centuries-old building can be made sustainable, then surely it can be done anywhere?»* (Vis, 2020).

The results of this thesis may not only be relevant for the foundation Stevenskerk, but also for the owners of other multi-functional churches aiming for a sustainable improvement of the building's climate performance.

2.5 Research process and method

First literature study

A first visit to the Stevenskerk helped to gain insight in the local conditions, its monumental values and the challenges the foundation is dealing with. Afterwards, the thermal comfort was identified as the focus for this research. The first literature review provided an overview of existing research while gaining knowledge about the subject and defining the research questions and the research objectives. The literature review mainly included existing research reports about the Stevenskerk dealing with the energetic renovation and the heating system. Subsequently, the *stained glass window renovation* and *indoor space adaptations* were chosen as strategies with potential to deal with the thermal challenges in the Stevenskerk (figure 2.2).

Renovation strategies

A literature review about the renovation of stained glass windows was conducted to gain an overview about existing techniques and their advantages and disadvantages. In order to identify concepts for spatial adaptations that could be suitable for the requirements in the Stevenskerk, literature and case study projects were assessed. The gathered information was used to generate an overview of different renovation concepts and to develop other designs for the window renovation and indoor space adaptations.

Furthermore, the analysis of the stained glass windows in the Stevenskerk and their physical performance was important to identify challenges, restrictions and potentials for the thermal comfort in the church. For this, measurement data was collected by means of infrared thermography and in-situ measurements in the Stevenskerk with equipment available at the climate design department of the TU Delft.

A physical calculation model was set up for examining the physical behaviour of the present window system in the Stevenskerk. The gathered measurement data was then used to validate the model with the actual boundary conditions in the Stevenskerk. Afterwards the calculation model was used to assess different strategies for the window renovation regarding their physical performance.

Furthermore, a computer simulation model of the South chapel of the Stevenskerk was created in *DesignBuilder* and validated with the collected measurement data. Afterwards, thermal simulations with different adaptations of the model according to promising renovation measures were conducted and used to evaluate the impact of those strategies on the thermal indoor comfort (figure 2.2).

Result

Afterwards, the information gathered from the literature, the measurements, the calculations and the computer simulations was used to evaluate the different renovation strategies according to an evaluation framework based on evaluation criteria defined in line with the research objectives.

This knowledge was used to generate a comparative overview as a support for identifying suitable renovation measures for multi-functional and monumental churches. Based on this, a renovation proposal for the Stevenskerk was developed (figure 2.2).

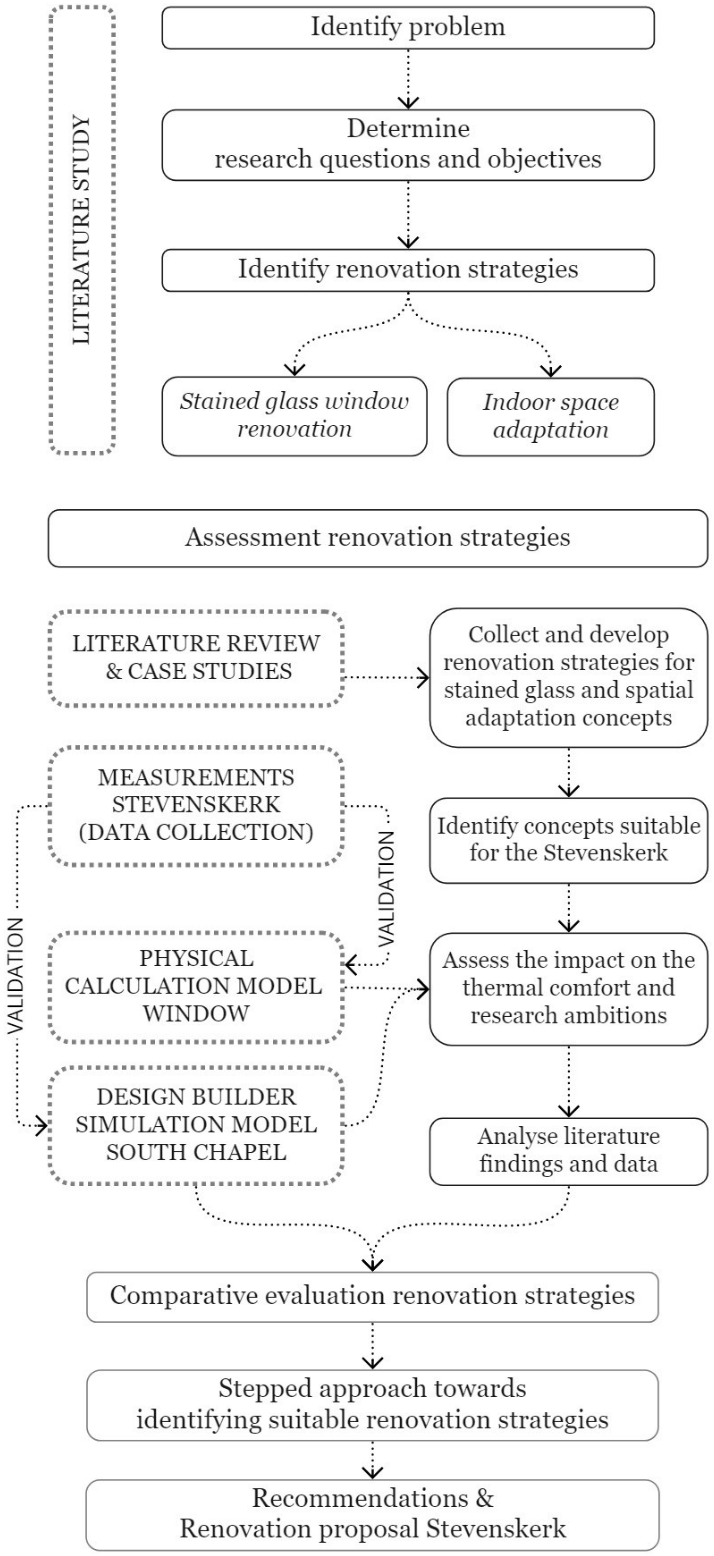


Figure 2.2: Diagram research steps and methods

3 Case study building Stevenskerk

3.1 The building

The monumental church dates back to a basilica built in the 13^{th} century. During the following centuries, several extensions, demolitions and reconstructions took place (see Appendix B figure B.1 Timeline building transformations Stevenskerk) resulting in a building with components originating from different construction periods. Today, the Stevenskerk is owned by a foundation while the tower is part of the municipality. As this project is focused on the comfort in the church, the tower is not included.

The Stevenskerk is located in the city of Nijmegen which was destroyed in 1944 by a mistaken bombardment from the Americans who actually wanted to attack the German city of Kleve. A major reconstruction of the church from 1953 to 1969 largely shaped the building's current appearance. Particular building components are described more in detail in chapter 3.3.2.

The Stevenskerk with its high tower stands on the «Hundisberg» hill, next to the market square and some shopping streets. Therefore, the Stevenskerk is very well visible or as the foundation has expressed it: *«Ask a resident of Nijmegen when he is home and he answers: 'when I see the Stevenskerk'»* (Stichting Stevenskerk, 2005).

The façade of the church built in Gothic architectural style is made of natural stone and brick with a thickness of 60 to 140 cm. The church has large lead glass windows resulting in a high window to wall ratio. The roof was recently renovated.

The Stevenskerk consists of the main nave (oriented from West to East) with two side aisles leading towards a choir with ambulatory. The transept extends from North to South. The tower is located on the Western edge of the nave and adjacent the South and North chapel. Furthermore, there are separated spaces such as the entrance, technical rooms, the entrance to the crypt and the *«Gerfkamer»* which is used as an office (figure 1.2).

Currently, the church is heated by an underfloor Hypocaust heating system combined with air heating installed during the reconstruction from 1953 to 1969. Two boilers provide the heat for two independent main pipes with heating loops located below the floor of the transept and parts of the main nave. As the air pipes, which are located in a crawl space below the light floor construction are hardly insulated, large energy losses occur. The chapels have no underfloor heating, but hot air is distributed through outlets along the walls.

Heating the church requires a lot of time. Warming up the indoor space from 10 to 18 °C takes 32 hours (OOM Advies, 2018). The foundation Stevenskerk is planning to change the heating system to a more efficient water-based floor system for keeping a standard indoor temperature. In those zones of the church where the Hypocaust heating system is present, the installation of a new underfloor heating can be integrated in the crawl space. Additional air heating will be used for support when the floor heating system cannot fulfil the heating requirements. The foundation aims at using air heat pumps, located in the roof construction of the Stevenskerk as a renewable heat source for this new heating system.

3.2 The vision for the Stevenskerk

«The foundation is working on increasing the sustainability of the Stevenskerk not as a goal in itself, but in keeping with its social responsibility for sustainable use, with the future usability and opening up of the Stevenskerk as an essential condition.» (Stichting Stevenskerk, 2005)

Previous investigations on the sustainability transformation of the Stevenskerk have identified the exchange of the current heating system, the insulation of the vaults and the windows as well as an improvement of the air tightness as the most effective measures for decreasing the heating demand of the building (Schoch & van der Zanden, 2019; Nusselder & Zandijk, 2015; Aarle, 2007). The foundation has used this research for developing a step-by-step plan for reducing energy losses and using sustainable energy sources by building renovation.

Together with *van Hoogevest Architecten*, the foundation Stevenskerk has developed a concept for the multi-functional future use of three different zones within the building (figure 3.1).

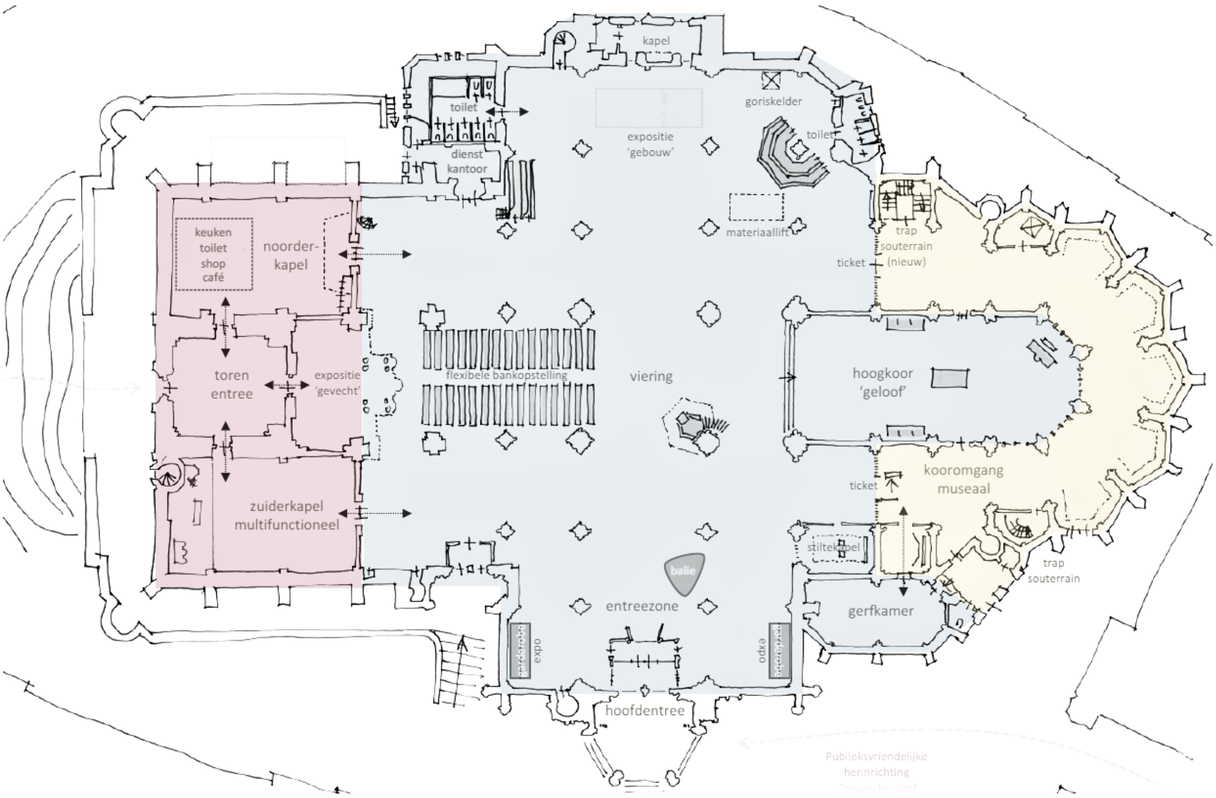


Figure 3.1: Floorplan Stevenskerk, edited from the «Visiedocument» (Stichting Stevenskerk, 2005)

Central part of the church (blue): The central part of the building will be openly accessible for visitors and tourists. This space can be used for different events such as theatre, dancing, concerts or dinners because the furniture here can be arranged flexibly (Stichting Stevenskerk, 2005).

Western part of the church (red): This area includes the side chapels which can be used as separate spaces for smaller and more intimate events such as weddings, baptisms or exhibitions. The opaque wall divisions towards the large church space are currently replaced by large glazed elements. The North chapel will be converted to a coffee place with a shop and a toilet.

Eastern part of the church (yellow): Furthermore, it is planned to divide the ambulatory of the choir from the rest of the building in order to use it as a museum with an entrance fee. This museum could also include the crypt which is currently not accessible.

3.3 The Stevenskerk as a monumental building

3.3.1 National monument

According to the hierarchic structure of the government in the Netherlands there exist three different types of monuments: The national monument, the provincial monument and the communal monument (Netsch, 2018). The Stevenskerk is a listed as a *Rijksmonument* (national monument) in the national register since the 17th of April 1973.

This status as a protected monument or as a place of worship allows member states exceptions from the energy performance requirements defined for buildings in the EU *«in so far as compliance with certain minimum energy performance requirements would unacceptably alter their character or appearance;»* (European Parliament and the Council, 2010). This European directive demonstrates that the significance of cultural-historical building values can be weighted higher than the energy performance of a building.

The motivation for this project is to investigate to what extent renovation measures increasing the thermal comfort in the Stevenskerk can be applied in accordance with its monumental significance and an improved energy performance.

The most important monumental values legitimating the national monument status, are mentioned in the *Rijksmonumentomschrijving* (national monument description). The preservation of those cultural historical values of the building and its inventory is protected by law. They are indicated and illustrated in figure 3.2 and 3.3.

However, this is the minimum of the monumental values deserving protection. Additionally, the Stevenskerk contains heritage values which are not part of the national monument description. Thus, in order to assess the suitability of any renovation strategy leading to interventions on the building fabric, those heritage values need to be identified.

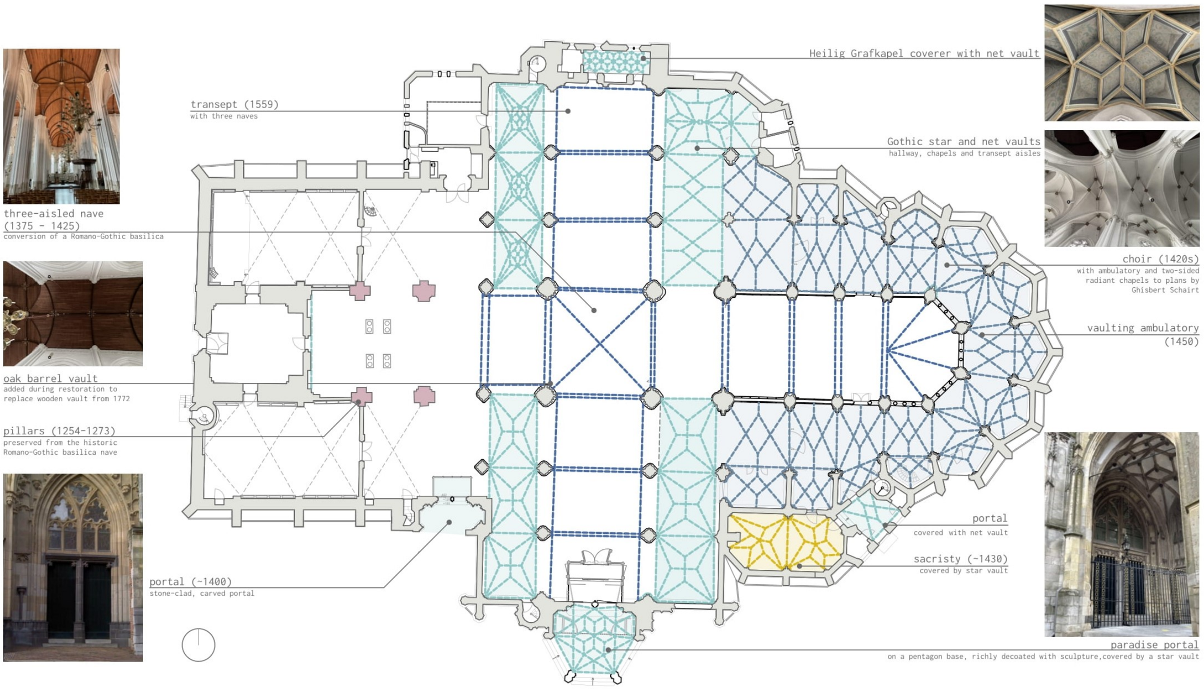


Figure 3.2: Monumental values building Stevenskerk according to the *Rijksmonumentomschrijving*

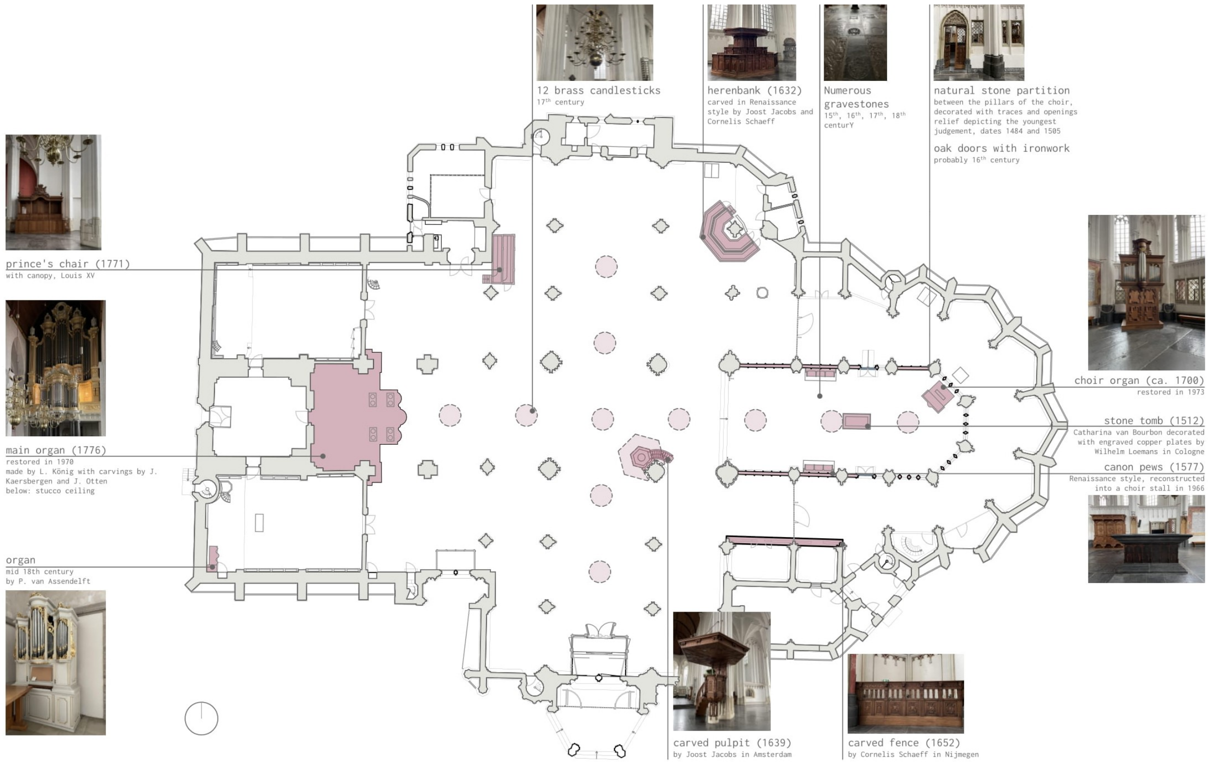


Figure 3.3: Monumental values inventory Stevenskerk according to the *Rijksmonumentomschrijving*

3.3.2 Other heritage values

The significance of heritage values legitimates their protection for future generations and can be assessed by specific criteria. Different evaluation methods for heritage criteria have been introduced:

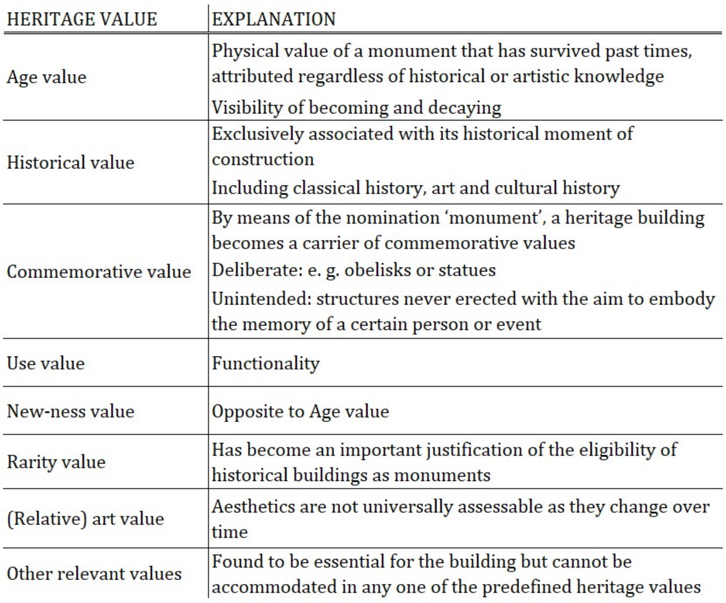
The *Burra Charter* for example defines the *«cultural significance as the aesthetic, historic, scientific, social or spiritual value for past, present and future generation.»* (Australian National Committee of ICOMOS, 2013) This cultural significance is embodied in the place itself, its fabric, setting, use, associations, meanings, records, related places and related objects (Australian National Committee of ICOMOS, 2013).

According to Ankersmit and Stappers (2009), heritage values are defined as follows: *«Heritage assets are related to important people in the past (historic value); they are of exquisite elegance (artistic value); they contain information that could be of use (information value); there is only one (uniqueness); they provide a specific sensation and emotion (experience value); they are related to a specific (ethnic) group (social value) and / or they represent a certain time, place or style (representation value)»*. Documenting heritage values according to a framework allows objectiveness in an assessment that is by its nature subjective.

The *Heritage and Architecture department* of the TU Delft developed the *«Heritage Value Matrix»* in order to support students identifying the *«aspects of importance to the cultural historical value»* of a building in its present state and to create a document clearly illustrating those heritage values giving a qualitative insight in the place (Kuipers & de Jonge, 2017).

The matrix is based on different building categories according to the shearing layers defined by Brand (Brand, 1994) and the category *«spirit of place»* for which the heritage values are filled in. Those values were mainly introduced by Alois Riegl (Bacher, 1995) and are shortly explained in figure 3.4. The identified values are evaluated using a traffic light system indicating their significance from very high (red), such as the values mentioned in the national monument description, to high (yellow), to

positive (green). This provides an overview on how renovation measures would cause changes on heritage values and helps to understand if a building element needs to be preserved in its original state or if an intervention is possible or even necessary.
This matrix was used as a method to illustrate and organize the heritage values of the Stevenskerk. Even though the perception of a building is subjective and largely influenced by observation, the identification of those heritage values was executed as objective as possible by using literature research. The elements with significance for the Stevenskerk as a whole building and the windows as a special focus of this study are listed separately. The complete heritage matrix can be found in Appendix B (figure B.2) whereas the text below mentions the most important heritage values.



HERITAGE VALUE	EXPLANATION
Age value	Physical value of a monument that has survived past times, attributed regardless of historical or artistic knowledge Visibility of becoming and decaying
Historical value	Exclusively associated with its historical moment of construction Including classical history, art and cultural history
Commemorative value	By means of the nomination 'monument', a heritage building becomes a carrier of commemorative values Deliberate: e. g. obelisks or statues Unintended: structures never erected with the aim to embody the memory of a certain person or event
Use value	Functionality
New-ness value	Opposite to Age value
Rarity value	Has become an important justification of the eligibility of historical buildings as monuments
(Relative) art value	Aesthetics are not universally assessable as they change over time
Other relevant values	Found to be essential for the building but cannot be accommodated in any one of the predefined heritage values

Figure 3.4: Explanatory overview heritage values (Kuipers & de Jonge, 2017)

01 | Sourroundings / Site

The Stevenskerk is enclosed by an organic building structure with houses dating back to the second half of the 19th and the 20th century (Mapbox, 2020), which has historically grown and therefore contains *age value*. The buildings in the neighborhood date from different construction periods (mostly from 1944 to 2009). The Stevenskerk and its past of demolition and renovation can be seen as a symbol for the history of Nijmegen and its renewal after the bombardment in the Second World War. As a reference for the history of the city, the church and its surroundings therefore contain *high historical value.*

02 | Skin

Values Stevenskerk

The old natural stone and brick facades of the Stevenskerk contain *high age* as well as *historical value* because their ageing is visible and they are a sign of the historic origin of the building. Furthermore, the old natural stone walls with ornaments in Gothic architectural style give the Stevenskerk its impression of a historical church and therefore have *relative art value.*

Values windows Stevenskerk

The large stone window openings with traceries are typical building elements in Gothic churches and were constructed as a symbol for the house of god. The traceries shaped in complex decorative geometries were originally integrated to stabilize the windows against wind loads (Goecke-Seischab & Harz, 2021). As the external walls with the openings date back to former building periods from 1390-1410 (side chapels), from 1410-1456 (choir and sacristy), from 1495-1565 (transept) (Peterse, Rooker, Camps, & Emmens, 2017), they have *very high age value.* Their Gothic appearance gives them *very high historical value.*

Historically, it was not possible to produce large glass panes and smaller elements were assembled together to create large windows. The appearance of such assembled window panes is very different from one large glazed pane due to its fragmentation and the connecting elements. Even though the stained glass windows in the Stevenskerk originate from the renovation in the 1960s, the appearance and the fragmentation of the windows has *high age* and *historical value* as it is a building element typically used in medieval churches (Lubelli, Pottgiesser, Quist, & Rexroth, 2021).

Coloured or painted stained glass was historically used after 1080 (Lubelli et al., 2021). The resulting access of natural daylight and the natural ventilation through infiltration in the windows give the windows *use value.* Furthermore, aesthetic impression, the shimmering of the clear glass in different colours, the painted glass windows and the deep window reveals giving the façade plasticity, have *very high relative art value. «Setting glass in (strong yet malleable) lead required skilled craftsmen.»* (Lubelli et al., 2021). As this technique is elaborate and expensive and does not correspond to current window requirements, stained glass windows are only produced in small scales nowadays. This explains the *high rarity value* of the stained glass windows in the Stevenskerk. Additionally, the required skilled craftsmanship for producing such large scale stained glass windows leads to *very high relative art value.*

03 | Structure

The Gothic style star and net vaults as well as the oak barrel vault over the main nave are mentioned in the national monument description (Rijksdienst voor het Cultureel Erfgoed, 1973), demonstrating their very high monumental value. As elegant, fluent building lines striving towards heaven and high vaults with key stones are typical Gothic building elements (Goecke-Seischab & Harz, 2021), those building elements have *very high age* and *historical value.* Additionally, the impressive high vaults and ornamented structural elements such as the pillars or the key stones contain *high rarity* and *relative art value* as they create a special indoor impression in the Stevenskerk.

Typical renovation ideas from the 1960s are visible in the material use of concrete for structural elements for example for the roof structure during the reconstruction (Schoch & van der Zanden, 2019). The resulting unique combination of different building ages and materials from the numerous renovations of the Stevenskerk, give the structure *historical and rarity value.*

04 | Space plan

The layout of the Stevenskerk including the three-aisled nave built from the end of the 14th century, a large-scale basilica in conception, the choirs with ambulatory and the side chapels (first half of the 15th century) as well as the sacristy and the different portals, is mentioned in the national monument description (Rijksdienst voor het Cultureel Erfgoed, 1973). As this floorplan corresponds to a Gothic church building (Goecke-Seischab & Harz, 2021), it contains *very high age, historical* and *rarity value.*

The Stevenskerk has a flexible floorplan. The large and open indoor space in the naves and the transept enables multi-functional use. Additionally, the smaller side chapels can be used for smaller events. Overall, the floorplan of the Stevenskerk has *very high use value* which is of economic significance for the foundation Stevenskerk while the functionality for religious use is important for the community of faith.

05 | Services

The Hypocaust heating system in the Stevenskerk dates back to the reconstruction from 1953 to 1969. Even though it is not sufficient for the current comfort and monumental conservation requirements (Aarle, 2007) the heating system has *historic and use value.* As an unusual heating system for churches it additionally contains *high rarity value.*

Recently, the building was equipped with a modern LED lighting system which lightens up the wooden vault. Colours and intensity of the lights can be changed according to the functionality. Additionally, the monumental chandeliers with *high historic value* are still in use.

The modern LED lighting and the chandeliers have *use* and *relative art value* as they ensure the functionality of the church if there's not sufficient daylight, create the suitable atmosphere according to the current functionality of the Stevenskerk and aesthetically illuminate the vault.

06 | Stuff

The historical inventory including the oak doors, stone relief, tombstones, the choirs stall, the pulpit, the organs, the prince chair and other elements dating back from medieval times, the 17th and 18th century, is of very high monumental significance (Rijksdienst voor het Cultureel Erfgoed, 1973). As the elements date back from historic periods and were constructed with historic materials and techniques, they contain *very high age, historical* and *rarity value.* The tomb stone for Catharina van Bourbon, erected in 1512, and engraved copper tomb stones for a canon (1570) and a mayor (1665), additionally have deliberate *commemorative value* as they were built for memorizing those personalities. As the pulpits (1693 and 18th century) and the organs (1774, 1700, mid-18th century) are used during religious practices, they contain *use value.* The inventory created with elaborate techniques requiring craftsmanship such as the carved pulpit (1693), the prince's chair (1771) or the 18th century organ case have *relative art value.*

07 | Spirit of place

Values Stevenskerk

The high indoor space with slender pillars, covered with ornamented vaults and the large windows in the Stevenskerk create a sacral and spiritual atmosphere while shaping a light and open space. As those elements represent Gothic architecture and its impression of striving towards heaven, this specific atmosphere and interior impression of the space has *very high historical value* and *very high relative art value.*

The Stevenskerk is a tourist attraction, receiving about 132.000 visitors per year (Rijksdienst voor het Cultureel Erfgoed, 2021). Additionally, the building is used for cultural, communal and religious events. As an iconic church in the city of Nijmegen, the Stevenskerk is a building for the community and a space of reflection. Therefore it contains *very high use value.*

Values windows Stevenskerk

A large amount of natural daylight is filtered through the lightly coloured stained glass windows and creates an impressive and beautiful indoor lighting experience for the visitor. This special lighting impression inside the Stevenskerk has *very high relative art value.*

3.4 Inventory and thermography stained glass windows

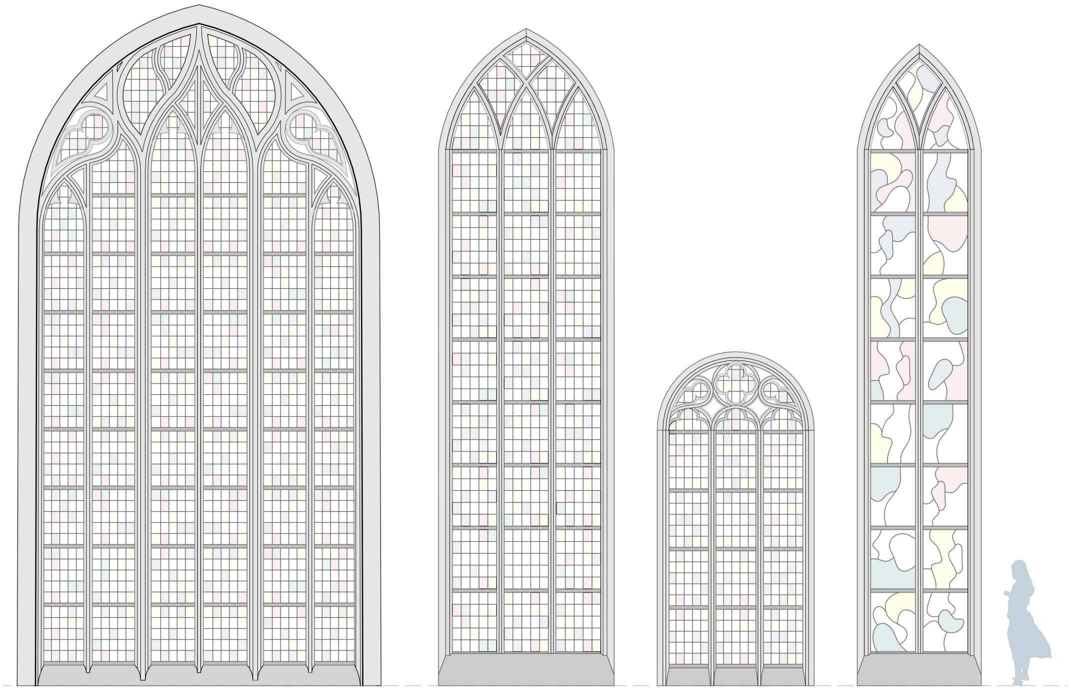


Figure 3.5: Illustration different window types in the Stevenskerk

Figure 3.6: Detailed photographs windows outside (l) , window reveal inside (c) and glass inside (r)

Introduction:

In order to assess the suitability of renovation methods for the stained glass windows of the Stevenskerk an inventory of the different window types was compiled. Different window sizes, reveals or glazing types may result in different preferences for the renovation. Furthermore, *«specific monumental values must be taken into account - not every historic window can be fitted with insulating glazing just like that»* (Vis, 2020). This inventory is limited to the large lead glass windows in the church and does not take into account other windows types which are present in the building. The stained glass windows in the Stevenskerk have vertical natural stone mullions forming a tracery in the top part of the window as well as a natural stone window frame (figure 3.5). The window reveal inclines diagonally towards the window (figure 3.6).

Infrared images:

Thermal imaging was used to show the surface temperatures of the windows. The pictures analyzed and shown below were taken in the afternoon of the 7th of December 2021 with an infrared camera type *FLIR T420*. The outdoor temperature was around 5 °C while inside the Stevenskerk it was about 10-12 °C. Only the Gerfkamer was heated up to around 20 °C.

Afterwards, the photographs were edited with the computer program *FLIR tools*. To enable comparability between the pictures, the temperature range of the infrared scale was unitized to 0-10 °C. Furthermore, the reflective temperatures were adapted to the correspondent surrounding temperature. The clear sky resulted in reflection on the external glazing surface in the outside photographs. Therefore, some outside pictures show the sky temperature instead of the glazing surface temperature.

3.4.1 Single glass windows with complex traceries

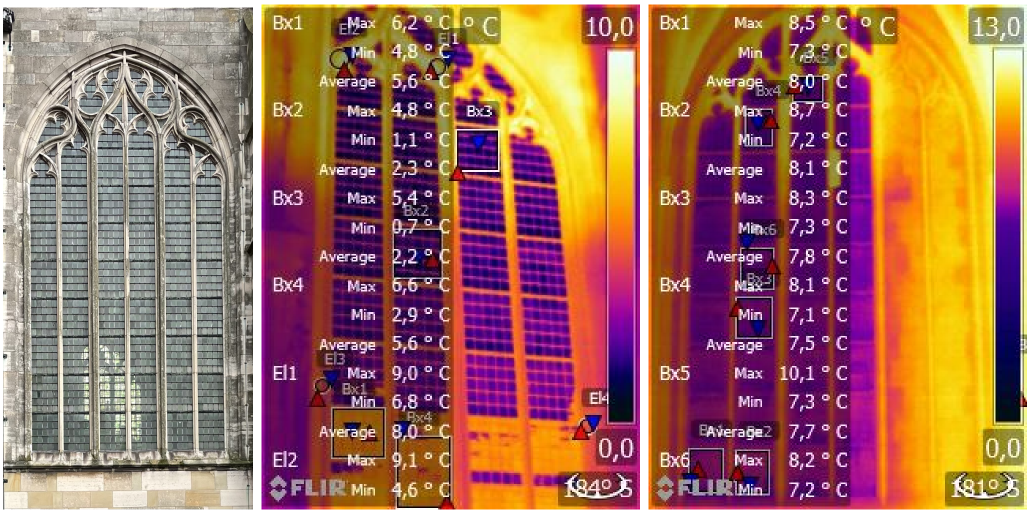


Figure 3.7: Single glass, complex traceries - Photograph (l), thermal image outside (c) and inside (r)

Description:

The transparent stained glass windows in the Stevenskerk are composed of small rectangular glass elements (ca. 12 x 15 cm), shimmering in light blue, yellow and pink colours (figure 3.6). The large window openings have a pointed arch shape which is characteristic for Gothic architecture. The openings are divided by vertical mullions made of natural stone while the slender horizontal divisions are made of dark metal material which visually merges with the lead connections of the glass elements. Thus, the vertical accent of the window shape, typical for the Gothic building style is underlined. The windows are ornamented with complex traceries on the in- and on the outside (figure 3.7 - l).

Analysis infrared images:

The surface temperature difference between in- and outside for the single stained glass windows is only 2-2.5 °C (figure 3.7 - c and - r). This low value can be explained with the very bad insulation performance of the single glazing.

3.4.2 Windows with internal protective glazing Side chapels

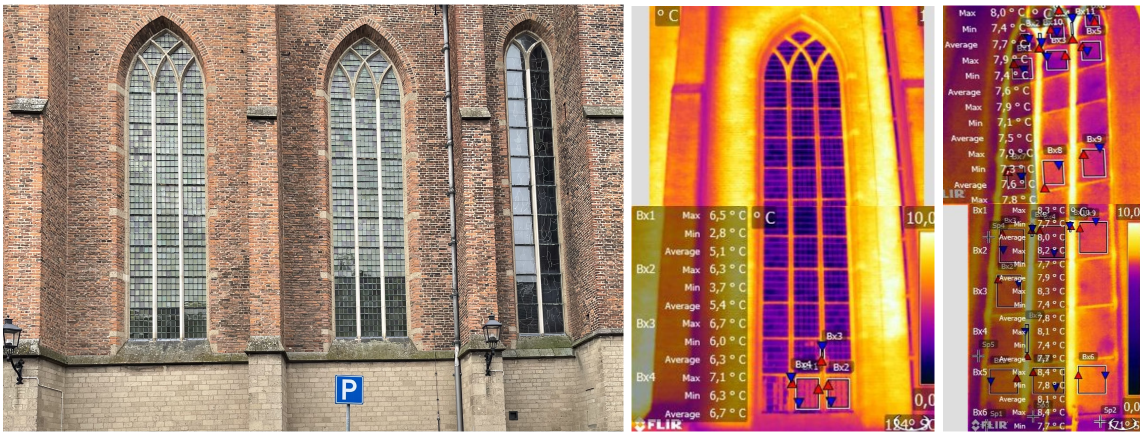


Figure 3.8: Windows with internal PG South chapel - Photograph (l), thermal image outside (c) and inside (r)

Description:

The stained glass windows of the side chapels have intersecting traceries. There are only two or three vertical window columns and the shape of the traceries of these windows is less complex. Furthermore, it is noticeable that the window shape is more slender and the window to wall ratio is lower than in the large space of the Stevenskerk (figure 3.8 - l).

In 2013, frame-less interior single protective glazing (PG) with very low impact on the aesthetic appearance of the windows was added in the Side chapels. The protective glazing is connected to the transoms of the stained glass with a small cavity while the air in the cavity can flow vertically through the connectors. The cavity is ventilated with indoor air. The protective glazing was fitted into the shape of the window tracery. The aim of this construction was the improvement of the indoor thermal comfort, however the result of this window adaptation is not as desired and cold draft is experienced by the occupants.

Analysis infrared images:

The internal thermal photographs for the windows of the South chapel show a small thermal gradient increasing from the top of the windows to the bottom, from 7.6-8.1 °C (figure 3.8 - r).

Furthermore, there are cold spots at the bottom seam of the protective glazing with a temperature around 7 °C (figure 3.8 - r) which might illustrate a cold draft of cooled cavity air entering the chapel. This assumption could be proved by performing measurements which will be described in chapter 5.2. Additionally, those cold spots also result from the lower thickness of the stone wall in this area due to the shape of the window reveal.

The surface temperature difference between in- and outside is about 2.9 °C which is larger than for the single glazing. This shows that the insulation value of the construction was improved to a certain extent by adding secondary glazing.

3.4.3 Windows with internal protective glazing in the Gerfkamer

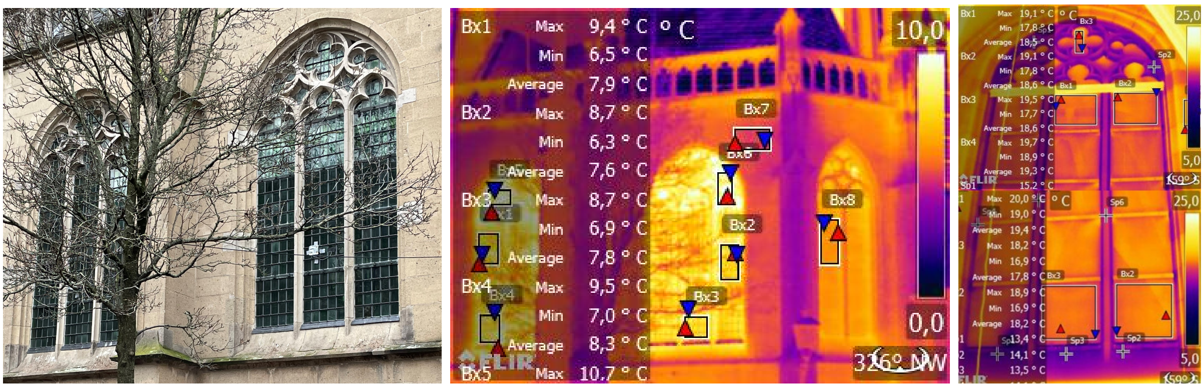


Figure 3.9: Windows with internal PG Gerfkamer - Photograph (l) and thermal image outside (c) and inside (r)

Description:

Only the window openings of the Gerfkamer have a round arch shape and due to the height of the Gerfkamer they are smaller and lower than the other windows (figure 3.9 - l).

The Gerfkamer is located on the right of the main entrance and on the South façade of the ambulatory. It is used as an office and a conference room and therefore heated regularly. Interior protective glazing was added to the two windows as described for the Side chapel (see 3.4.2) in order to improve their thermal insulation performance. The protective glazing was fitted into the geometric tracery of the windows.

Analysis infrared images:

According to the thermal images, the temperature difference between in- and outside of the glass is 11.8 °C: $T_{surface\ in}$=19 °C and $T_{surface\ out}$=8 °C (figure 3.9 - c and - r). This can be explained by the high indoor temperature of about 20 °C in the Gerfkamer and the improved insulation value due to additional glazing.

There is a temperature gradient increasing from the bottom to the top. It was not clear why the temperature gradient proceeds the other way around than for the windows in the South chapel as the construction is the same. A possible explanation will be described together with further measurements in chapter 5.2.

As already noticed at other windows, the thermal images show cold spots, especially at the bottom seams of the protective glazing with a temperature around 13 °C (figure 3.9 - r).

3.4.4 Painted glass windows with external protective glazing

Figure 3.10: Painted glass windows with external PG - Photographs (l) and thermal images (r)

Description:

In 2001, two windows, painted by the Dutch artist Marc Mulders were installed (figure 3.10 - l). They were donated by the Radboud University to the city of Nijmegen on the occasion of the fifty years' anniversary of the faculty of medicine. These are the only figurative windows in the Stevenskerk and refer to the Christian tradition depicting elements of the creed and to concepts of medical care. The colours of the windows are reflected in the Stevenskerk's logo. Both windows are located side by side in the Southern aisle of the main nave.

Specifically, these two windows have a protective single glazing placed on the outside of the painted glass. The protective glazing is clearly visible from the outside due to reflections of the surroundings (figure 3.10 - l). Additionally, the partition of those windows varies in its organic shape from the other rectangular divided stained glass windows.

Analysis infrared images:

On the inside and on the outside of the glass one can observe a small temperature rise from the bottom to the top. Possibly this comes from the fact that warmer air within the cavity rises up. For both windows the temperature difference between in- and outside are about 4-4.5 °C (figure 3.10 - r). This is larger than for the single stained glass windows and can be explained by a better insulation value of the construction with additional glazing.

According to this first analysis the thermal performance of these windows seems to be comparably good. As this is a unique window type in the Stevenskerk and the protective glazing has already been applied on the outside, these windows were not analysed more into detail during this project.

3.4.5 Challenges stained glass windows

By the first on-site analysis and literature review the following challenges for the stained glass windows in the Stevenskerk were identified. During the project those were investigated and assessed more into detail (see chapter 5).

- Low R-value (thermal resistance) of the large single glazed windows leads to heat losses and reduces the MRT in the Stevenskerk
- Cold spots in the bottom area of the internal secondary glazing resulting from low heat resistance of the slender window frame and/or from cold draft flowing out of the ventilated cavity
- Risk of external weathering for stained glass for example due to vandalism, dirt or rain

4 Thermal comfort and heritage conservation

4.1 Fundamentals thermal comfort

Thermal comfort is defined as *«That condition of mind which expresses satisfaction with the thermal environment (ISO, 2005).»* However, it is challenging to achieve this condition for a group of occupants as thermal comfort is subjective and perceived differently by everyone. Generally, the human body's core temperature is kept at 37 °C. When the skin temperature lies above or below 34 °C, heat or cold sensors are activated and trigger body reactions such as increasing the blood flow and sweating or decreasing the blood flow and shivering respectively (Itard & Bluyssen, 2004).

4.1.1 Thermal comfort parameters and their relation to the Stevenskerk

The activity level or metabolism - MET = [W/m ^{2}]:
When occupants are performing more active activities they have a higher metabolic rate and therefore require a lower room temperature for feeling thermal comfort. (Itard & Bluyssen, 2004) Therefore, the thermal comfort requirements for the Stevenskerk change according to the current use of the multi-functional building.

Thermal resistance of clothing - I_{cl} = [m ^{2}/kW]:
Light summer clothing has a much lower thermal resistance than heavy, layered winter clothing. (Itard & Bluyssen, 2004) Therefore, occupants entering a cold church building during warmer months are more likely to sense cold than in the winter when they wear a warm winter jacket. Therefore, the dress code for the performed activity as well as the outdoor climate should be considered when assessing the thermal comfort in the Stevenskerk.

Air temperature - T_a = [°C]:
Generally, an indoor air temperature of 18 to 28 °C is perceived as comfortable. However, other comfort parameters as well as regional or seasonal preferences must be taken into account. Generally, for Northern European countries, such as the Netherlands, the comfortable indoor air temperatures are 20 °C during winter and 24 °C during summer (Itard & Bluyssen, 2004).

Relative humidity - RH = [%]:

The maximum quantity of water vapour that can be absorbed in the air depends on its temperature and pressure. The sensation of humidity relates to how far the air is from water pressure at saturation which is defined as relative humidity. The relative humidity influences the range of air temperature one perceives as comfortable and the other way around. At T_a = 18 °C for example, a RH from ca. 62 to 74 % is perceived as comfortable, while RH levels from 62 to 85 % and from 32 to 62 % are still comfortable. Higher or lower RH levels lead to discomfort for the occupant. Overall, a RH level from 30 to 70 % corresponds to a comfortable and healthy environment (Itard & Bluyssen, 2004).

Air speed and turbulence - v = [m/s]:

At cold air temperatures the air speed resulting from draft or ventilation increases the heat transfer from body to air and can be experienced as very unpleasant (Itard & Bluyssen, 2004). Therefore, during winter, cold drafts represent a comfort problem in the Stevenskerk.

Mean radiant temperature - MRT = [°C]:

Every surface which has a temperature above the absolute zero (0 K or -273 °C) emits radiation, proportionate to the temperature in Kelvin to the power of four. Therefore, there is radiative heat transfer between the surface of the body of the building user and the enclosing building elements (Itard & Bluyssen, 2004).

This radiation is expressed in terms of the Mean radiant temperature which can be described as: *«The temperature of a uniform environment at which a person would exchange the same amount of heat by radiation as in the actual environment»* (Kurvers & Leyten, 2022).

Thus, the cold internal surfaces of the non insulated building skin of the Stevenskerk reduce the MRT which can cause discomfort to the occupant. The impact of the emitted radiation of enclosing surfaces depends on the location of the user and the equivalent «Viewfactor», the temperature difference between the heat exchanging surfaces and the emission coefficient of the radiating surface (Kurvers & Leyten, 2022).

4.1.2 Thermal comfort models

The *static model* defines thermal comfort as the equilibrium of the heat balance of the human body. The *adaptive model* takes into account that occupants will take *«physiological, psychological, social, technological, cultural or behavioural actions in order to re-establish their thermal comfort (for example change their clothing or open the window)»* (Bluyssen, Bayon, & Hamilton, 2009).
The *adaptive comfort standard* combines both theories. It recommends comfort ranges for the indoor operative temperature in relation to the ATG (*Adaptieve Temperatuur Grenswaarden*) neutral temperature which is calculated from the daily maximum and minimum outside temperatures over four days (Raue et al., 2006). The ATG guideline is applicable for naturally ventilated buildings (Bluyssen et al., 2009). Overall, the adaptive comfort standard allows for a wider range of acceptable temperatures. Figure 4.1 illustrates the comfort limits according to the ATG guideline for type Beta spaces depending on the running mean outdoor temperature (Raue et al., 2006). The Stevenskerk can be classified as a Beta building with a limited degree of occupant control with regards to thermal comfort for example due to non-operable windows.

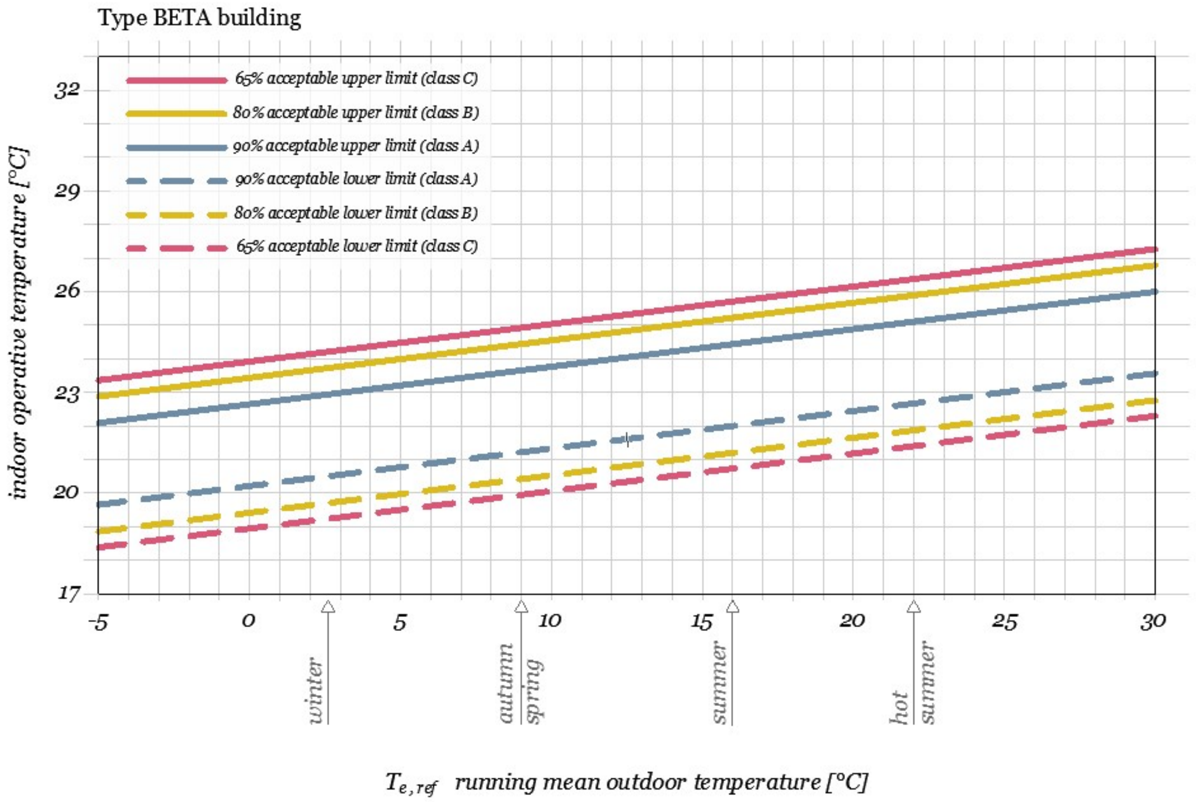
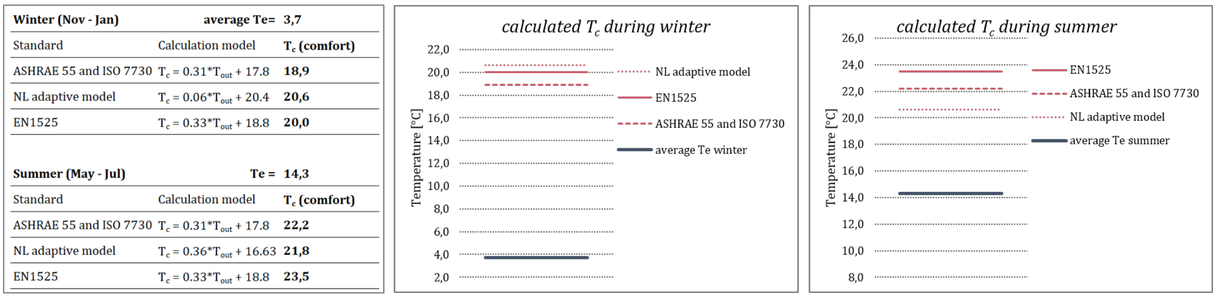


Figure 4.1: ATG comfort limits for Beta buildings in relation to $T_{e,ref}$ from (Raue et al., 2006)

4.1.3 Thermal comfort standards

«There are three well-known and widely used international standards that relate specifically to thermal comfort: ISO Standard 7730 (2005), ASHRAE Standard 55 (2004) and CEN Standard EN15251 (2007)» (Nicol & Humphreys, 2002). Those standards give boundary conditions for a comfortable indoor environment and were therefore used to identify the comfort range of the indoor air temperature in the Stevenskerk. Figure 4.2 illustrates the calculated result using the average outdoor temperature for the Netherlands. The outcome shows a comfort range of about 19 to 20 °C during winter and 22 to 24 °C during summer.



Winter (Nov - Jan)	**average Te=**	**3,7**
Standard	Calculation model	**T_c (comfort)**
ASHRAE 55 and ISO 7730	$T_c = 0.31*T_{out} + 17.8$	**18,9**
NL adaptive model	$T_c = 0.06*T_{out} + 20.4$	**20,6**
EN1525	$T_c = 0.33*T_{out} + 18.8$	**20,0**

Summer (May - Jul)	**Te =**	**14,3**
Standard	Calculation model	**T_c (comfort)**
ASHRAE 55 and ISO 7730	$T_c = 0.31*T_{out} + 17.8$	**22,2**
NL adaptive model	$T_c = 0.36*T_{out} + 16.63$	**21,8**
EN1525	$T_c = 0.33*T_{out} + 18.8$	**23,5**

Figure 4.2: Overview and illustration calculated comfort temperatures

4.2 Thermal discomfort in the Stevenskerk

Introduction:

The introduced parameters apply for the human body as a whole. However, it is possible that the body is partially heated or cooled resulting in local discomfort. Raising or lowering the average temperature of the space cannot generally remove discomfort when local discomfort remains (Itard & Bluyssen, 2004).

Draught and turbulence:

People at static activities like sitting are sensitive for locally too high air speed especially at the sensitive spots such as their neck and ankles. Draught discomfort depends on the mean air velocity, its frequency and amplitude and on the air temperature (Itard & Bluyssen, 2004).

Cold air-draft is experienced by occupants in the Gerfkamer and the side chapels, where internal protective glazing was applied to the windows. The aim of this research is to investigate this airflow by means of measurements and calculations (see chapter 5). Previous measurements documented an average air speed of 0.16 m/s near the benches in the Stevenskerk. This is slightly higher than defined as comfortable and can therefore cause draught problems (Aarle, 2007).

During the visits in the Stevenskerk it became clear that the building skin has high permeability due to air leakages in the natural stone walls, the windows and the vaults. On the one hand this leads to an infiltration with fresh outside air which is necessary in order to provide sufficient natural ventilation. On the other hand, this result in heat losses and cold draft (figure 4.3). Additionally, in the large church space air gaps at the doors towards the unheated stairwell towers and the outside have been identified as the source for draught (Schoch & van der Zanden, 2019). Cold air passes to the inside because of pressure differences caused by temperature variations or wind. The installation of door closers and the sealing of gaps could solve this problem.

To conclude, the infiltration with cold outside air leads to discomfort in the Stevenskerk and should therefore be reduced. However, sufficient ventilation for the indoor space has to preserved (see chapter 9).

Large radiation asymmetry:
Even if the overall MRT lies within the comfort range, too large differences between the enclosing surface temperatures result in local discomfort. The radiant asymmetry is defined by the temperature difference of two surfaces in opposite direction (e. g. floor and ceiling).
In the Stevenskerk, radiation asymmetry is caused by the surface temperature of non insulated external walls and large windows which are much colder than internal walls when the space is heated up (figure 4.3). Furthermore, the difference in temperature level between the warm indoor air and the air-layer adjacent to the facade leads to downdraft along the cold surface because of the different density of the air-layers. This results in local discomfort due to draft (figure 4.3).

Large vertical temperature gradients
The vertical temperature gradient is defined by the temperature difference between 1.1 and 0.1 m above the floor, which corresponds to the height of the neck and the feet of the occupants. It is perceived as unpleasant to have a warm head while the feet are cold. This form of discomfort is unlikely to occur in the Stevenskerk as the building is equipped with a floor heating and the warm air rises. Due to the immense indoor height, however, one could expect the risk of stratification and vertical temperature gradients towards higher locations. Previous measurements, however, have shown that during heating the temperature gradient over the height of the Stevenskerk is only 0.8 °C over 12.1 m which corresponds to 0.07 °C/m (Aarle, 2007) and does not cause thermal discomfort.

Warm or cold floor
Due to the direct contact between feet and floor, conductive heat transfer because of too extreme floor temperatures can cause local discomfort. The heat transfer depends on the conductivity of the floor material. Therefore, the heating temperature of the floor heating in the Stevenskerk should not be too high. However, the required supply temperature for achieving a comfortable indoor temperature depends on the efficiency of the heating system and the heating load of the building. Thus, by an improvement of the thermal insulation performance of the building skin, the risk for discomfort due to a too high floor temperature will be reduced.

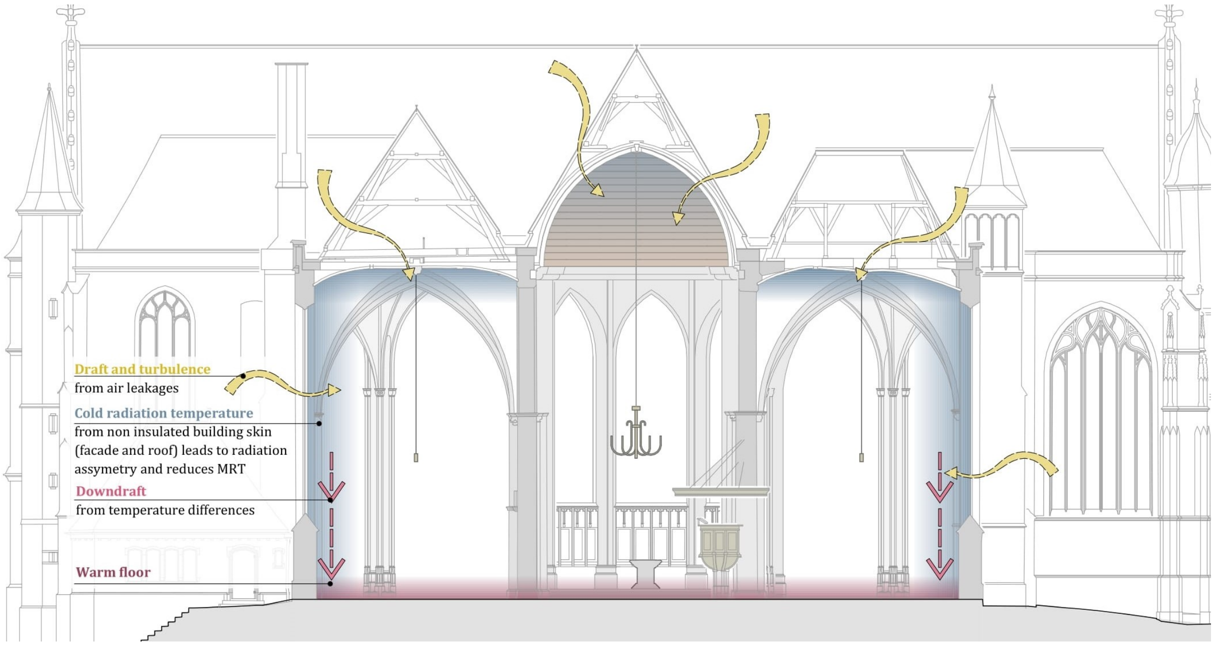


Figure 4.3: Illustration risks for thermal discomfort in the Stevenskerk

4.3 Conservation risks for the monumental Stevenskerk

Introduction:

The building materials and the monumental inventory of the Stevenskerk have specific conservation requirements. If those requirements are not met, this can cause their degradation. From the point of view of artwork conservation, each heating operation which forces the indoor climate to strongly depart from the historical climate, causes a potential harmful situation (Camuffo, 2010).

Relative humidity:

For the preservation of organic, hygroscopic materials RH levels (max. 25 - 75 %) in the mid range are required (Ankersmit & Stappers, 2009). Hygroscopic materials absorb moisture when the environmental relative humidity rises, and loose moisture when relative humidity drops. Therefore, extremely high or low RH or temperature levels result in hygrothermal load on those materials and can result in structural damage, deformation and cracking (Normcommissie 342346, 2010). In the Stevenskerk, monumental inventory such as the wooden organs and the carved pulpit and furniture are sensitive to hygrothermal damage.

Currently, the historic inventory (panels and paintings on the wall) in the Stevenskerk is facing preservation risks due to the air heating. The high supply temperature leads to localised extreme heating up and therefore drastically reduces the RH level (Nusselder & Zandijk, 2015).

Moreover, the degradation due to condensation is a risk for monument conservation. It can for example lead to salt crystallization of masonry walls and corrosion of the stained glass windows.

In a room with an average air temperature and a high RH level, air which passes along surfaces with a colder surface temperature will condensate because the dew point of the air is reduced by cooling down. In the Stevenskerk those surfaces may be the non-insulated wall or window surfaces.

Next to the risk for condensation, too high RH can lead to fungal growth. However, oak wood from which the barrel vault in the Stevenskerk are constructed, has a natural resistance against it (Ankersmit & Stappers, 2009).

Air quality:

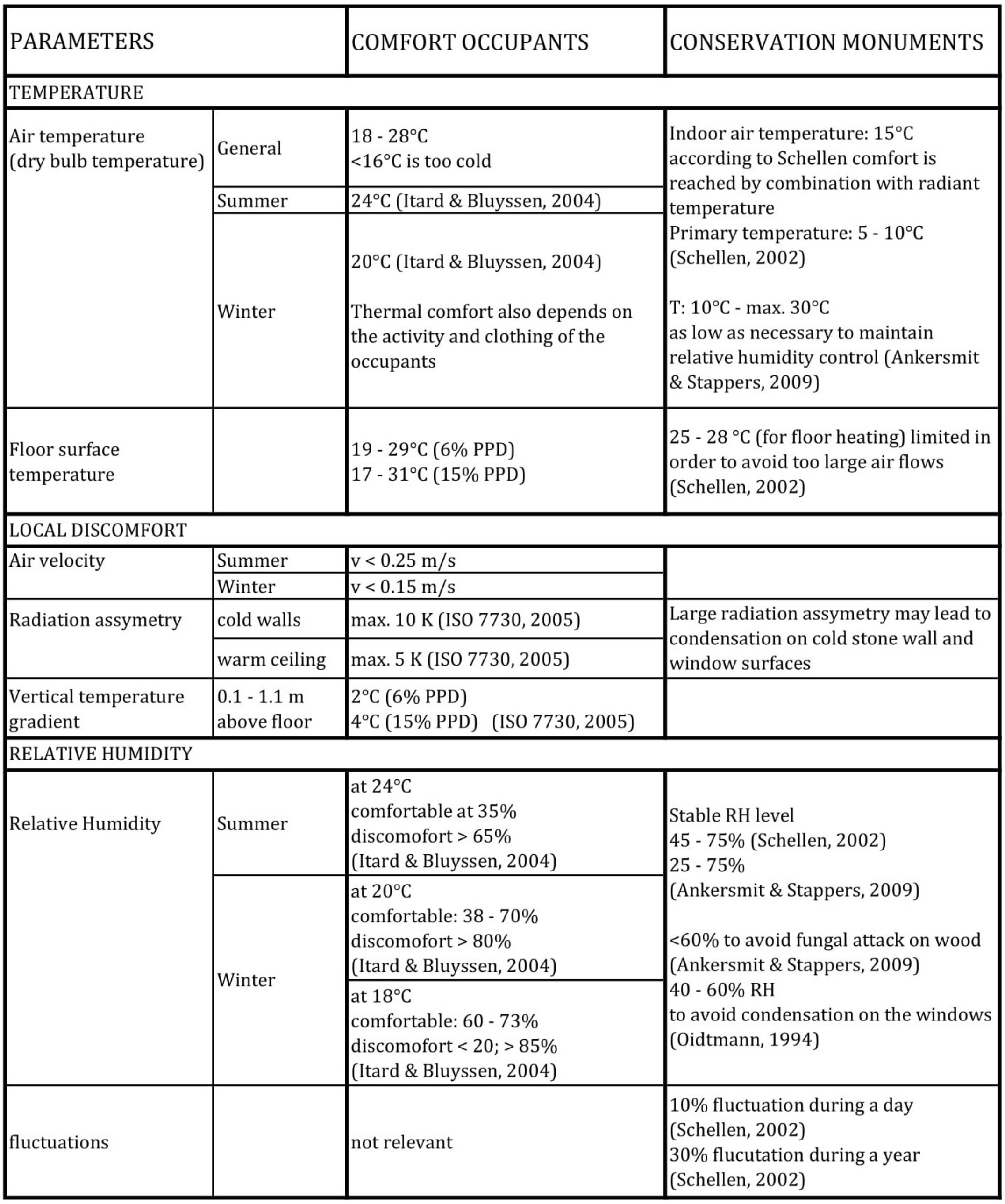
The air duct system built around 1966 may contain fine dust or asbestos load resulting in a low air quality blown into the church and a harmful environment for the monumental inventory as well as the occupants (Nusselder & Zandijk, 2015).

Additionally, the monumental chandeliers may represent a conservation risk. Pollution sources like soot from candles in relation to relatively large air flows which may be generated by floor heating can lead to contamination of monuments (Schellen, 2002).

4.4 Balancing thermal comfort and conservation

4.4.1 Thermal comfort and conservation requirements

In figure 4.4 the main requirements for the thermal comfort of the occupants and conservation of the monumental elements according to the literature and standards reviewed are summarized (Itard & Bluyssen, 2004; ISO, 2005; Oidtmann, 1994; Schellen, 2002; Ankersmit & Stappers, 2009). Most of the requirements can be combined, whereas, the air temperature level is a critical point where a compromise needs to be found.



PARAMETERS		COMFORT OCCUPANTS	CONSERVATION MONUMENTS
TEMPERATURE			
Air temperature (dry bulb temperature)	General	18 - 28°C <16°C is too cold	Indoor air temperature: 15°C according to Schellen comfort is reached by combination with radiant temperature Primary temperature: 5 - 10°C (Schellen, 2002) T: 10°C - max. 30°C as low as necessary to maintain relative humidity control (Ankersmit & Stappers, 2009)
	Summer	24°C (Itard & Bluyssen, 2004)	
	Winter	20°C (Itard & Bluyssen, 2004) Thermal comfort also depends on the activity and clothing of the occupants	
Floor surface temperature		19 - 29°C (6% PPD) 17 - 31°C (15% PPD)	25 - 28 °C (for floor heating) limited in order to avoid too large air flows (Schellen, 2002)
LOCAL DISCOMFORT			
Air velocity	Summer	v < 0.25 m/s	
	Winter	v < 0.15 m/s	
Radiation assymetry	cold walls	max. 10 K (ISO 7730, 2005)	Large radiation assymetry may lead to condensation on cold stone wall and window surfaces
	warm ceiling	max. 5 K (ISO 7730, 2005)	
Vertical temperature gradient	0.1 - 1.1 m above floor	2°C (6% PPD) 4°C (15% PPD) (ISO 7730, 2005)	
RELATIVE HUMIDITY			
Relative Humidity	Summer	at 24°C comfortable at 35% discomofort > 65% (Itard & Bluyssen, 2004)	Stable RH level 45 - 75% (Schellen, 2002) 25 - 75% (Ankersmit & Stappers, 2009) <60% to avoid fungal attack on wood (Ankersmit & Stappers, 2009) 40 - 60% RH to avoid condensation on the windows (Oidtmann, 1994)
	Winter	at 20°C comfortable: 38 - 70% discomofort > 80% (Itard & Bluyssen, 2004)	
		at 18°C comfortable: 60 - 73% discomofort < 20; > 85% (Itard & Bluyssen, 2004)	
fluctuations		not relevant	10% fluctuation during a day (Schellen, 2002) 30% flucutation during a year (Schellen, 2002)

Figure 4.4: Overview thermal comfort and conservation requirements

4.4.2 NEN-EN 15759

For compatibility of thermal comfort standards and the preservation conditions for religious monuments in Europe, a standard for the *Conservation of cultural property* has been developed. It states: *«Since the comfort criteria may be in conflict with the criteria for conservation, the general standards on thermal comfort are not automatically applicable in places of worship. The specification for thermal comfort [...] has to be determined on a case-by-case basis.»* (Normcommissie 342346, 2011b).

The NEN-EN 15759 indicates a stepped approach in order to determine an appropriate indoor climate with respect to conservation and thermal comfort, starting with the establishment of the historic indoor climate, the determination of climate specifications for conversation and for thermal comfort, and finally finding a compromise between both of them.

According to the NEN-EN 15759-1, *«The temperature required for services is the key parameter in finding a compromise. A lower temperature will generally improve conservation conditions. With appropriate clothing and limited length of stay, there is no definite lower limit for temperature with respect to thermal comfort. If it can be assumed that users will wear clothing suitable for the current outdoor conditions, the heating can be reduced and conservation conditions improved. This standard proposes a limitation of the thermal comfort range from a "neutral" sensation to "slightly cool".»* (Normcommissie 342346, 2011a).

5 Window renovation

5.1 Protective glazing for stained glass

5.1.1 Introduction protective glazing

The application of protective glazing as a secondary layer on stained glass windows is a common practice for improving their thermal insulation and to protect them from degradation (Oidtmann, 1994).
However, the risk of condensation on the stained glass may be increased by the application of protective glazing. As condensation leads to damages such as lead corrosion or the damage of colour on painted stained glass windows, guidelines for the application of stained glass windows haven been composed (van Deskundigen Restauratiekwaliteit, 2015) and (voor de Monumentenzorg, 2002).
The protective glazing systems which have been applied on stained glass in practice differ in the following parameters:

- The type of glazing applied
- The location of the stained glass
- The location of the protective glass
- The cavity thickness
- The ventilation type

Depending on the motivation for the application as well as the specific circumstances such as the windows condition, monumental value, the building use, the requirements for the renovated window etc., different configurations of the protective glazing system can be applied.
By literature review some of the most important advantages and disadvantages for the application of the following systems were summarized in a comparative table (Appendix B figure B.3).

5.1.2 Protective glazing types

Internal protective glazing:
The application of the secondary glazing on the inside results in the conservation of the historic outside impression of the building. Furthermore, the stained glass remains in its original position which is beneficial for its conservation. In order to avoid condensation in the cavity, the literature recommends sufficient ventilation in the cavity between the stained glass and the protective glazing (Oidtmann, 1994).
Internal ventilation: The ventilation of the cavity with indoor air creates a condensation risk on the internal surface of the stained glass as the warm, humid indoor air cools down along the cold external window pane.

External ventilation: When the cavity is ventilated with outdoor air, there is a low condensation risk as the cold external air warms up in the cavity which reduces its RH level.

According to the literature review, for the application of internal protective glazing, the use of insulated or coated glass with external ventilation is the most suitable solution for the thermal improvement and the conservation of the stained glass windows (OOM advies, n.d.). On the one hand, the treatment of the new glazing improves the thermal insulation value of the window. On the other hand, the external ventilation reduces the risk of condensation in the cavity in comparison to internal ventilation as outdoor air contains less absolute humidity than indoor air.

However, when detailing the ventilation openings to the outside, the prevention of rain, dirt or insects entering the cavity should be considered.

External protective glazing for internal and external ventilation:

The advantage of external protective glazing is the protection of the stained glass from outside degradation due to weathering or vandalism. Furthermore, the stained glass window remains in its original position. However, the outside impression of the windows and the building is changed drastically. Firstly, modern glazing reflects the surrounding (see figure 3.10 left). Moreover, the fragmentation of the windows due to the lead connections between the small window panes is covered. Additionally, the plasticity of the facade due to the deep window reveals would be reduced by increasing the thickness of the window construction.

Internal ventilation: When the cavity is ventilated with indoor air there is a condensation risk on the internal surface of the protective glazing in the cavity as the warm, humid indoor air enters the cavity and cools down along the secondary glazing (Oidtmann, 1994). By the application of better insulating external glazing the temperature in the cavity remains closer to the indoor temperature which reduces this condensation risk.

External ventilation: The external ventilation creates a condensation risk on the internal surface of the stained glass because the cold air entering the cavity cools down the internal stained glass (Oidtmann, 1994). As a result, warm and humid indoor air which flows along the stained glass may condensate. However, this surface is open and therefore humidity could evaporate and not remain for a long period. The insulating effect of external protective glazing with external ventilation is limited (OOM advies, n.d.).

The application of double glazing as secondary glazing would further improve the overall insulation performance of external protective glazing. However, double glazing is more expensive to install and to maintain.

Museum arrangement:

New insulating glazing is placed at the location of the stained glass whereas the original stained glass is removed and placed in a special frame and placed on the inside of the new glazing which makes this a comparatively expensive system. The cavity is ventilated with indoor air (OOM advies, n.d.).

Accordingly, the museum arrangement changes the appearance from the inside and the outside. However, a very high art-historical value of the stained glass could justify this change in appearance in return for the conservation of the stained glass. However, the removal of the stained could lead to a risk of damage.

Bonded glazing:

The stained glass is removed and placed between two glass panes of a double glazing which is more expensive than the placement of protective glazing. This system changes the visibility of the stained glass from the in- and outside. Furthermore, structural changes on the stained glass would be required to fit them into the new glass. Additionally, the bonded glazing creates a risk of condensation and thermal breakage, especially for large windows.

5.1.3 Protective glazing for the Stevenskerk

Based on the literature review and the heritage assessment of the Stevenskerk it can be concluded that the application of external secondary glazing would largely alter its external impression. Thus, the value of craftsmanship, the historic value of the building skin and the relative art value of the Stevenskerk would be changed.

Furthermore, the *museum arrangement* and the *bonded glazing* are not suitable for the clear glass windows in the Stevenskerk due to the high complexity and costs of the systems, the change of aesthetics from the in- and outside and the damaging risks for the lead glass.

Based only on the literature review, it is not possible to identify one most suitable protective glazing type for the Stevenskerk because the specific local circumstances and the different requirements of the spaces in the church should be taken into account. Further investigation in particular on the indoor thermal comfort improvement, the physical correlations of the protective glazing and ventilation systems and as well as the analysis of protective glazing present in the Stevenskerk is required.

5.2 Assessment of the protective glazing in the Stevenskerk

5.2.1 Objectives

In the Side Chapels and in the Gerfkamer internal protective single glazing with 6 mm safety glass and internal ventilation had been applied. According to the users' experience, the thermal discomfort during winter has increased since the application. Therefore, different measurements were taken to understand the physical behaviour and issues of the present secondary glazing system.

Furthermore, the measurements supported the evaluation of different potential window renovation strategies. For this assessment a physical calculation model of the protective glazing in *Excel* was used which could be validated with the measurement data. As one potential adaptation method of the current system the closing of the ventilation cavity was tested in order to assess its potential benefit for the thermal comfort and its risks for condensation.

In comparison to existing research and data collected on the performance of protective glazing on stained glass windows (Oidtmann, 1994; Curteis & Seliger, 2017), the data gathered in the Stevenskerk includes the local circumstances and boundary conditions such as the irregular use and structural characteristics. In addition, the measurement data was used to validate thermal comfort computer simulations of spatial adaptation strategies in the South chapel with *Design Builder* (chapter 7).

5.2.2 Measurement set-up

The measurements were performed during the winter (January and February 2022) when problems regarding thermal comfort occur in the Stevenskerk. The availability of the measurement equipment as well as the time frame of the graduation project set constrictions to the assessment period and the amount of measurement points.

Different momentary and continuous measurements were taken in the Gerfkamer and in the South chapel (Appendix B figure B.4). In both rooms there are two identical windows regarding their size and orientation. For one of those windows in the South chapel and the Gerfkamer the lateral cavity ventilation openings were closed with silicone and the bottom ventilation opening was covered with a brass profile, sealed with silicone. This condition enabled the direct comparison of the internal single protective glazing system with a ventilated and with a closed cavity.

Figure 5.1: HOBO logger (*HOBO-U12*, 2020)

Figure 5.2: Anemometer (*SDL350*, 2019)

Figure 5.3: Infrared camera (Flir commercial systems, 2012)

Measurement equipment

Data loggers: ONSET HOBO U12 Data loggers (figure 5.1) were used for measuring temperature and relative humidity levels. By the addition of external sensors, additional temperatures were recorded. The logger measures temperature levels from - 20 °C to + 70 °C and has an inaccuracy of 0.35 °C. Relative humidity levels from 5 to 95 % are recorded with an inaccuracy of +/- 2.5 %.
Anemometer: For measuring air velocity streams the hot wire Anemometer Extech SDL350 was used (figure 5.2). This tool can measure small air velocities from 0.2 to 25 m/s with a resolution of 0.01 m/s and a basic accuracy of +/- 5 %rdg. The measured temperature ranges from 0 to 50 °C (see product data sheet). Therefore, this anemometer is suitable for the internal winter conditions above 0 °C in the Stevenskerk and the measurements of small air velocities.
Infrared camera: After placing the data loggers the setup was documented with the infrared thermal camera type FLIR T420 (figure 5.3).
Smoke test: A smoke test was performed at the open cavity window in the South chapel. A piece of paper was blown out close to the ventilation opening. The smoke visualized the air-stream of the air coming out of the cavity in streaming into the space. This test confirmed the expectation that the air-stream in the cavity is directed from the top to the bottom of the cavity and then into the space.

Boundary conditions Gerfkamer

The Gerfkamer has a floor area of about 50 m^2 and a maximum height of about 8 m. The office has a regular heating schedule from 9 am to 6 pm and is equipped with a thermostat set to 18.5 °C. The Gerfkamer is not supplied by the Hypocaust air heating but on the South facade there are two radiators located below the windows. As the stained glass windows are non operable, the Gerfkamer is equipped with an electric extract fan as a ventilation system to ensure sufficient fresh air income by infiltration.
On each of the south-oriented windows two loggers (Loggers B-E) with external sensors were placed in order to measure the external surface temperature of the stained glass, the air temperature in the cavity and the internal surface temperature of the protective glazing (figure 5.4). Because the internal protective glazing could not be removed, it was not possible to place loggers, but only external sensors into the windows' cavities. Thus, the RH humidity level in the cavity was not measured.
One data logger (Logger A) was placed in the centre of the room at the table where an occupant could sit. An external sensor was connected and covered with a black surface in order to absorb all radiation (emmissivity = 1) for measuring the mean radiant temperature (figure 5.4).
The momentary air velocity measurements were taken at different locations to find the horizontal flow velocity of the air stream out of the open cavity and the vertical airflow velocity along the window and wall surface.

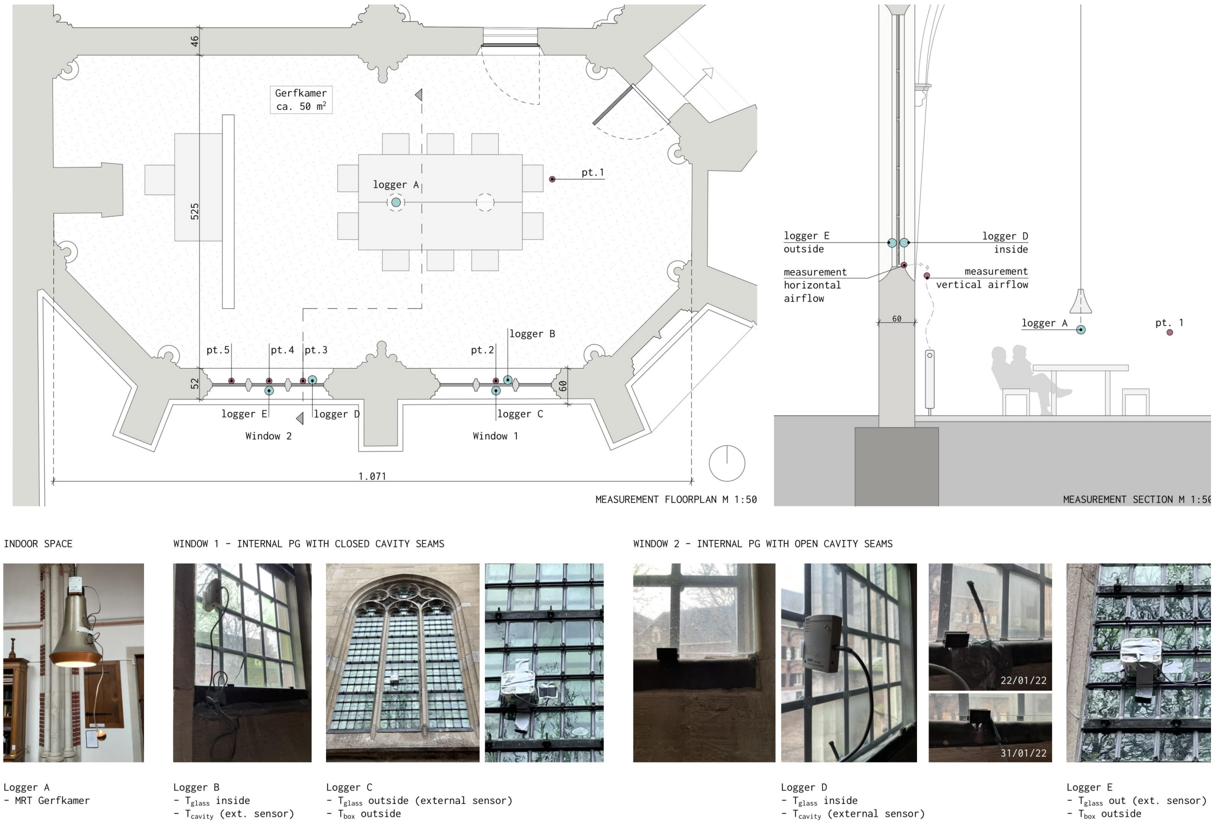


Figure 5.4: Measurement set-up in the Gerfkamer

Boundary conditions South chapel

The South chapel has about 120 m^2 floor area and a maximum height of about 13 m. It is used irregularly for different types of events. Therefore, this space does not have a regular heating schedule. The South chapel is supplied by the air heating system. Hot air is blown into the space through openings in the ground along the south façade while openings in the ground along the internal North wall of the chapel suck air in.

The South oriented windows were equipped with loggers (figure 5.5). One logger (Logger B) was placed inside of the cavity of the ventilated system to measure the air temperature and the relative humidity in the cavity. An external sensor was attached to it and placed on the protective glazing to measure the internal surface temperature. On the window with the closed cavity three loggers (Loggers C-E) were placed in order to measure the external surface temperature of the stained glass, the air temperature and the relative humidity in the cavity as well as the internal surface temperature of the protective glazing. Additionally, one logger (Logger A) was mounted to one of the chandeliers in order to measure the air and mean radiant temperature in the South chapel.

Processing measurement data from the HOBO loggers

On the 18th of February all data loggers were removed. With the *HOBOware* computer program the collected data-sets were exported into an Excel file for further processing and comparison. The collected data was firstly mapped in graphs over the complete measurement period and afterwards more specific time intervals were analysed. For the assessment of the collected data it had to be considered that the temperature measurements, especially during the day were also influenced by other parameters such as the sunlight, occupants or equipment such as computers et cetera which are often unknown and where therefore not included in the analysis.

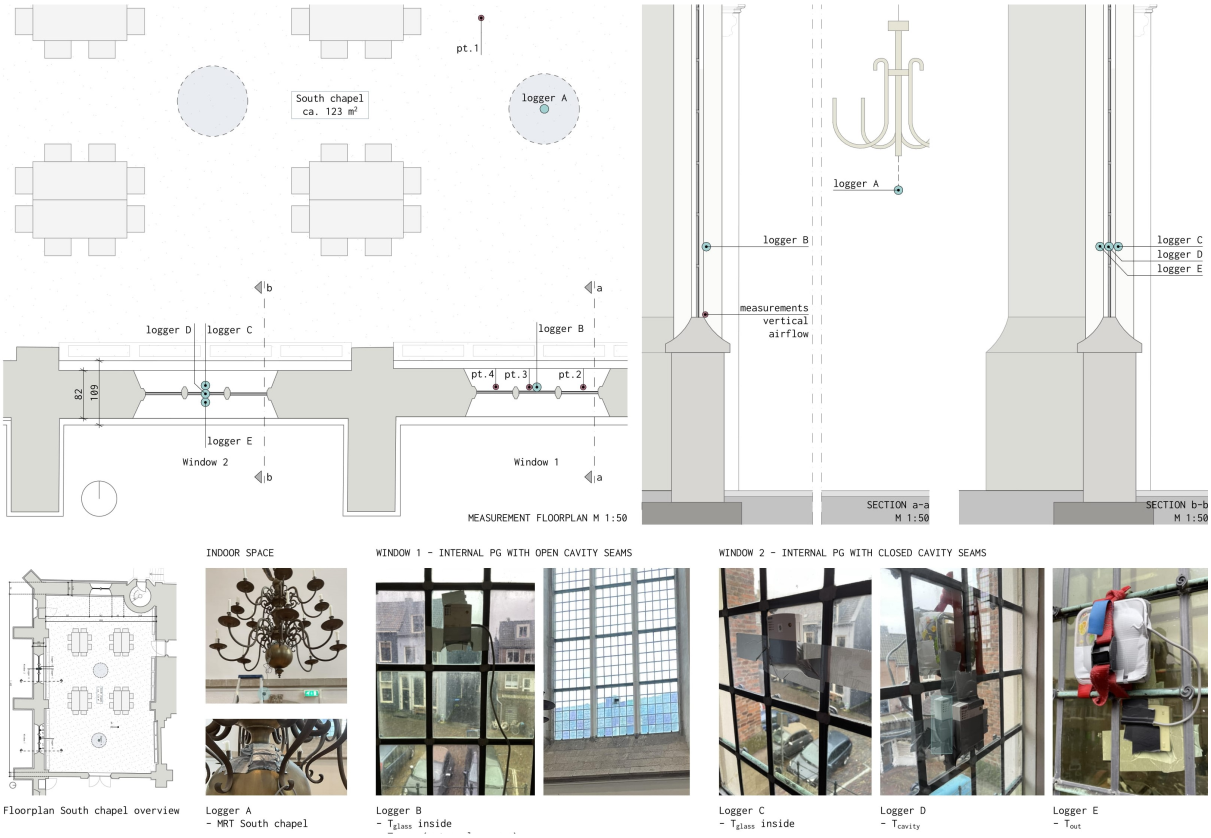


Figure 5.5: Measurement set-up in the South chapel

5.2.3 Comparative analysis temperature levels

Full measurement period

Regarding the thermal comfort, the surface temperature of the interior protective glazing is a critical parameter. Firstly, it influences the MRT and the radiation asymmetry perceived by the occupant. Secondly, the temperature difference between the surface and the internal air temperature results in pressure difference between the internal air and the air cooling down along the surface which leads to a downdraft along the window.

Therefore, the surface temperatures of the internal protective glazing for the closed and the ventilated cavity were mapped together with the internal air temperature and the MRT over the entire measurement period for the Gerfkamer (figure 5.6) and the South chapel (figure 5.7).

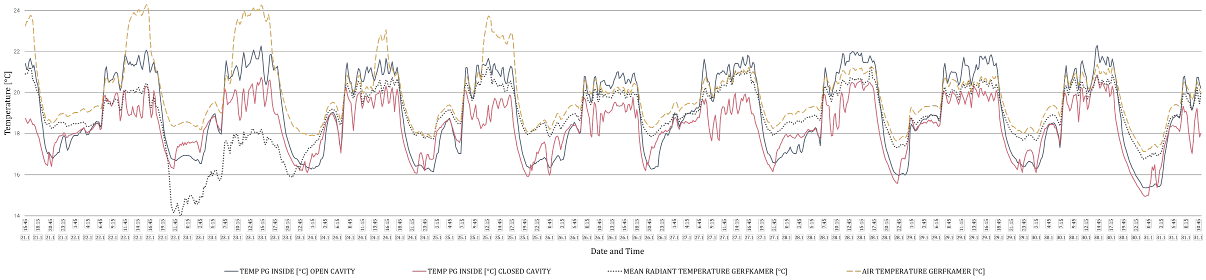


Figure 5.6: Graph full measurement period Gerfkamer: Internal surface temperature window open and closed cavity, air temperature and MRT

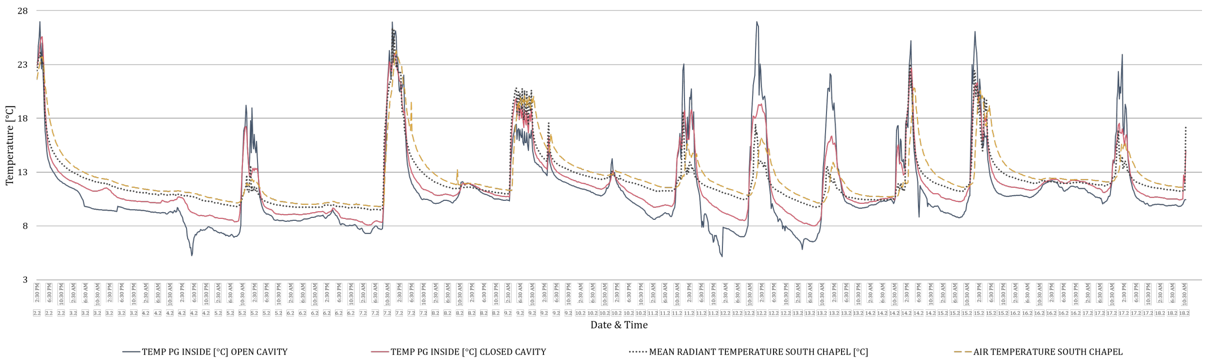


Figure 5.7: Graph full measurement period South Chapel: Internal surface temperature window open and closed cavity, air temperature and MRT

As expected, the air temperature level at the measurement points is constantly higher than the measured MRT. This temperature difference results from the colder enclosing surfaces of the non-insulated building skin. Furthermore, the graphs illustrate the daily heating cycle from 9am until 6pm in the Gerfkamer while the temperature measurements in the South chapel illustrate an irregular heating schedule resulting from its irregular use.

The graphs depict different resulting surface temperatures during the heating period than during times when there is less heating. Therefore, these periods were assessed separately.

During the heating cycle

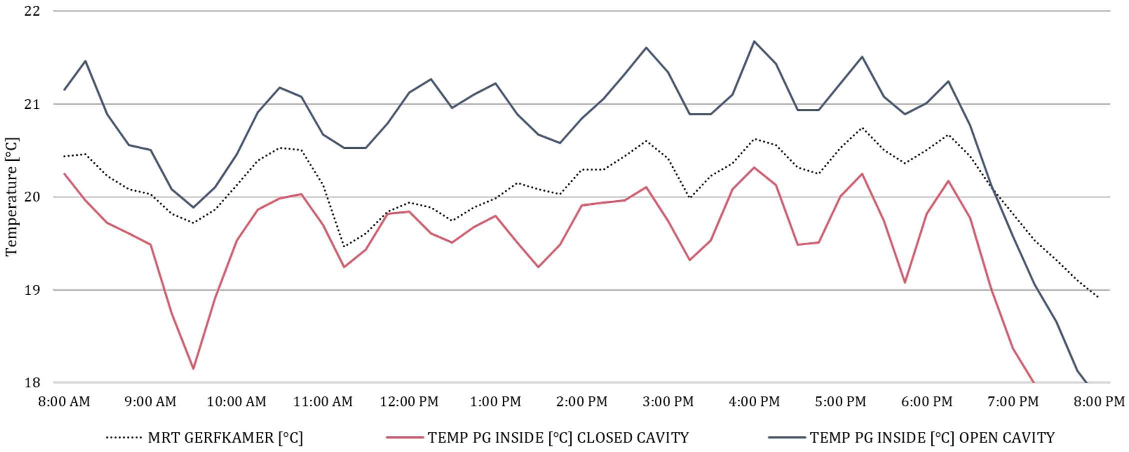


Figure 5.8: Graph Gerfkamer 24/01/2022 with heating:
Surface temperatures protective glazing inside for open and closed cavity and MRT

During heating, the surface temperature of the ventilated cavity construction is higher than the surface temperature of the window with the closed cavity (figure 5.8). During the 24th of January for example, the surface temperature of the ventilated cavity system in the Gerfkamer was on average 1.2 °C warmer than the surface of the closed system.

This observation coincides with the expectations because the hot air rising from the radiators can enter the cavity and consequently the protective glazing layer as well as the cavity space are heated up. In contrast, when the cavity is closed, the air in the cavity is enclosed functioning as an insulating layer.

Without heading

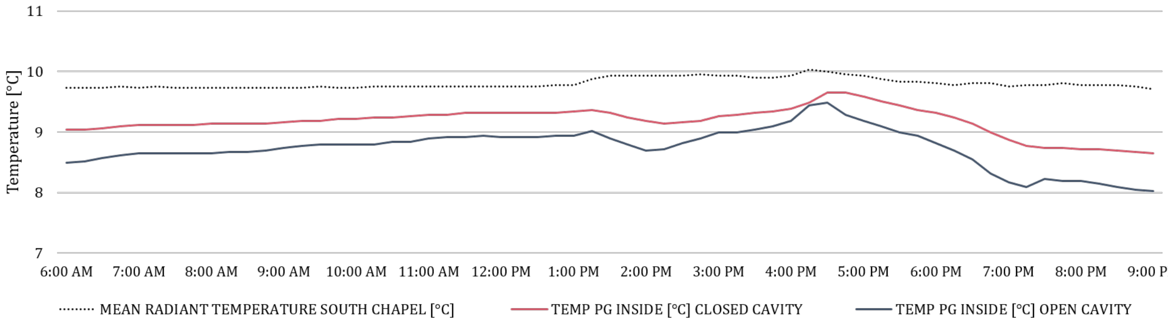


Figure 5.9: Graph South chapel 06/02/2022, no heating:
Surface temperatures protective glazing inside for open and closed cavity and MRT

Without heating, the surface temperature of the protective glazing with the closed cavity is higher than the surface temperature of the open cavity construction (figure 5.9). During the 6^{th} of February for example, when there was no heating in the South chapel, the surface temperature of the closed cavity system was on average 0.6 °C warmer than the surface of the ventilated system. This result coincides with the expectations because the layer of enclosed air has a higher heating resistance than the ventilated air layer (ISO, 2017).

Interpretation of the results

One could interpret that the higher surface temperature of the ventilated window during the heating period leads to a more comfortable indoor environment because it reduces the radiation asymmetry and the downdraft along the window surface. However, the lower surface temperature during the periods with less or no heating shows that the insulation performance of the ventilated construction is worse. This means that while the surface temperature of the open cavity construction might be higher during heating, the heating losses are larger with this construction as the heat dissipates through the cavity and the permeable lead glass layer. This theory is affirmed by the fact that the heating demand in the Gerfkamer has increased since the installation of the protective glazing. Additionally, the temperature gradient increasing from bottom to top which had been identified in the thermal imaging (see chapter 3.4.3) can be explained by the hot air entering the cavity.

Therefore, closing the ventilation opening of the cavity has potential to improve the insulation performance of the window and thereby increasing the overall air temperature and therefore the thermal comfort at the same heating level. However, this improvement is limited as the measurements show only small temperature differences of about 0.6 °C during the periods without heating.

This interpretation result could be tested by closing the cavity of both windows in the Gerfkamer and recording the heatin demand in comparison to the previous situation.

5.2.4 Comparative analysis relative humidity levels

Condensation risk

A condensation risk along the stained glass windows with internal protective glazing arises when the absolute humidity of the air entering the cavity lies above the saturation of the cavity temperature. This would mean that the air in the cavity cannot absorb any more moisture leading to condensation on the stained glass because its surface is colder than the internal secondary glass and therefore has a lower dew point temperature.

When the cavity between the stained glass and the secondary glazing would be perfectly closed and airtight there would be no condensation risk because no humidity could enter the inter-space. However, in reality such a system is nearly impossible to build, especially within the scope of historical buildings. There will always be infiltration from the outside because the stained glass is not airtight and cracks are present in the natural stone.

Therefore, when closing the ventilation openings, the condensation risk may increase due to the absence of air movement in the cavity when the relative humidity ratio reaches the dew point of the air temperature in the cavity.

Comparison condensation risk assessment during a heated day

In order to assess if the condensation risk in the cavity has increased due the absence of ventilation, the measured RH levels in the cavities were compared. This comparison was only possible for the South chapel because in the Gerfkamer the logger could not be placed in the cavity.

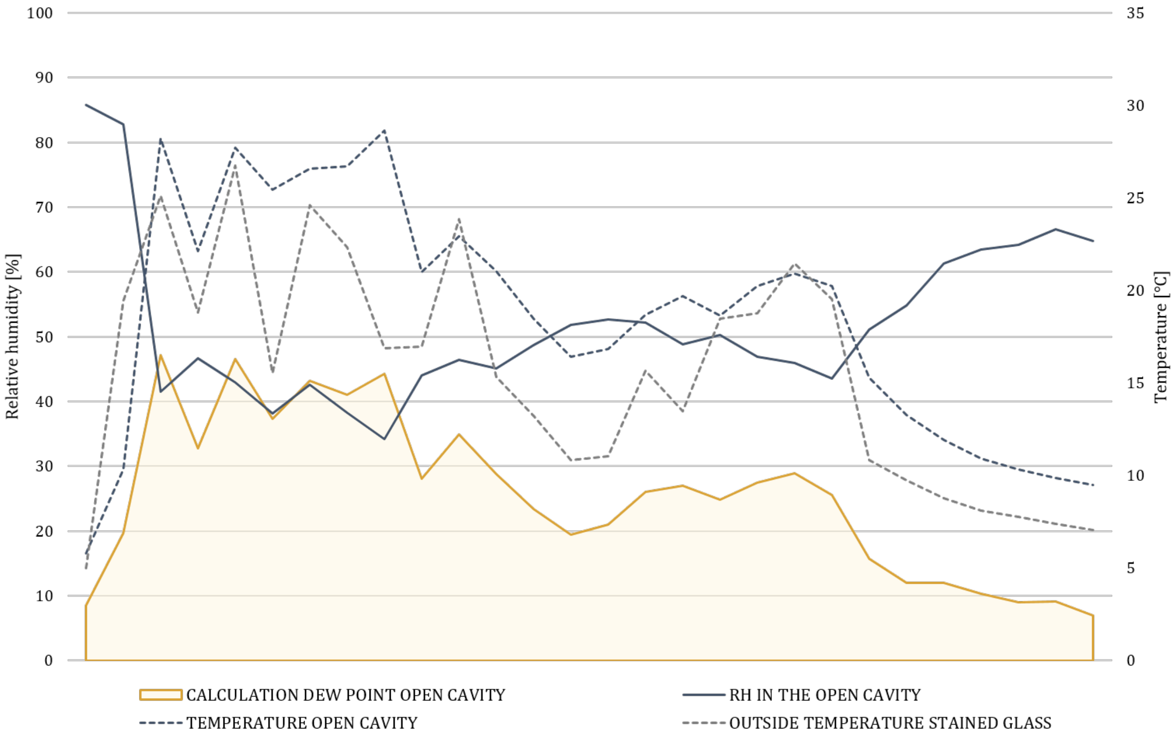


Figure 5.10: Graph South chapel 07/02/2022: Open cavity window during heating period

For a comparative assessment of the condensation risk, the dew point temperature in the cavity was calculated and plotted as a graph (yellow area) together with the RH and the temperature level in the cavity (figure 5.10 and 5.11). Additionally, the outside temperature of the stained glass is illustrated in the graphs because the air in the cavity might cool down to this level. If this temperature level lies

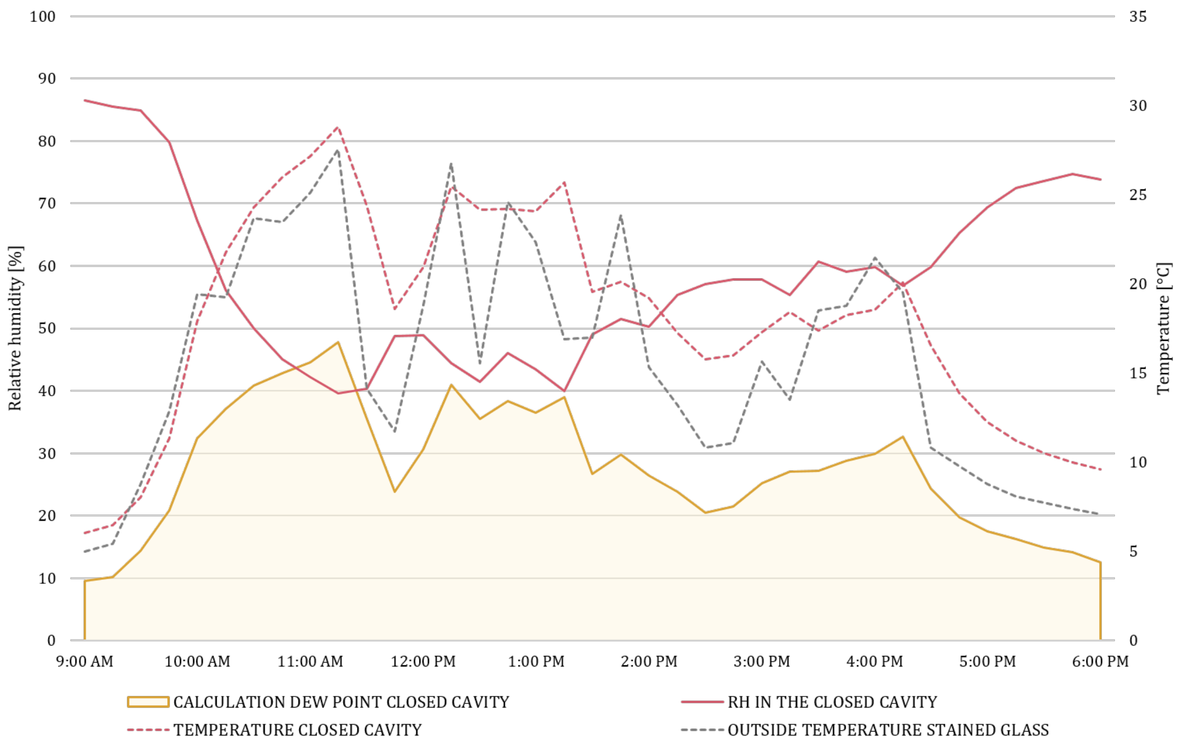


Figure 5.11: Graph South chapel 07/02/2022: Closed cavity window during heating period

below the dew point, condensation would occur on the stained glass. This can be assessed by checking if the graph of the outside temperature of the stained glass meets the graph of the calculated dew point, condensation would occur.

On the 7th of February in the closed cavity the difference between the dew point and the stained glass is on average 6.0 °C (figure 5.11). For the window with the ventilated cavity the difference between the dew point and the stained glass is on average 6.3 °C (figure 5.10). Thus, on average, the risk of condensation for both windows during this day is similar for both window constructions and no condensation occurred.

Comparison relative humidity level during full measurement period

According to the data collected in the South chapel, the RH in the ventilated cavity is on average 71 %. By closing the cavity, this ratio is slightly increased to 74 % on average which represents an increased risk for condensation. The maximum measured value for both constructions lies at 92 %. For both windows, the average RH levels lie above the range of 40 to 60 % which was recommended for the conservation of coloured stained glass (Oidtmann, 1994). Therefore, it should be assessed if the relatively high RH ratio in the cavity represents a conservation risk for the windows. As the glass in the Stevenskerk is coloured and not painted this risk is probably limited as long as condensation does not occur.

As one would expect that the airflow in the ventilated cavity would reduce the humidity level in the cavity by moisture transport is was surprising that such similar comparatively high RH levels in both windows were measured. This could indicate that the ventilation of the cavity in the South chapel is not working as desired.

Guidelines for the application of protective glazing recommend the use of ventilated cavities with a thickness of 40 to 60 mm for continuous airflow to avoid condensation (Curteis & Seliger, 2017).

In the Stevenskerk, however, the cavity thickness at the bridging rods narrows down from about 40 mm along the glazing to 10 mm at the level of the horizontal window partitions (figure 5.12). The cavity thickness was chosen due to aesthetics of the internal elevation of the windows. The location of the internal glazing closer to the stained glass windows, resulting in a smaller cavity width, preserved the visibility of the natural stone mullions and their plasticity. However, this contraction is probably blocking the vertical air-stream in the cavity which is disadvantageous for the moisture regulation.

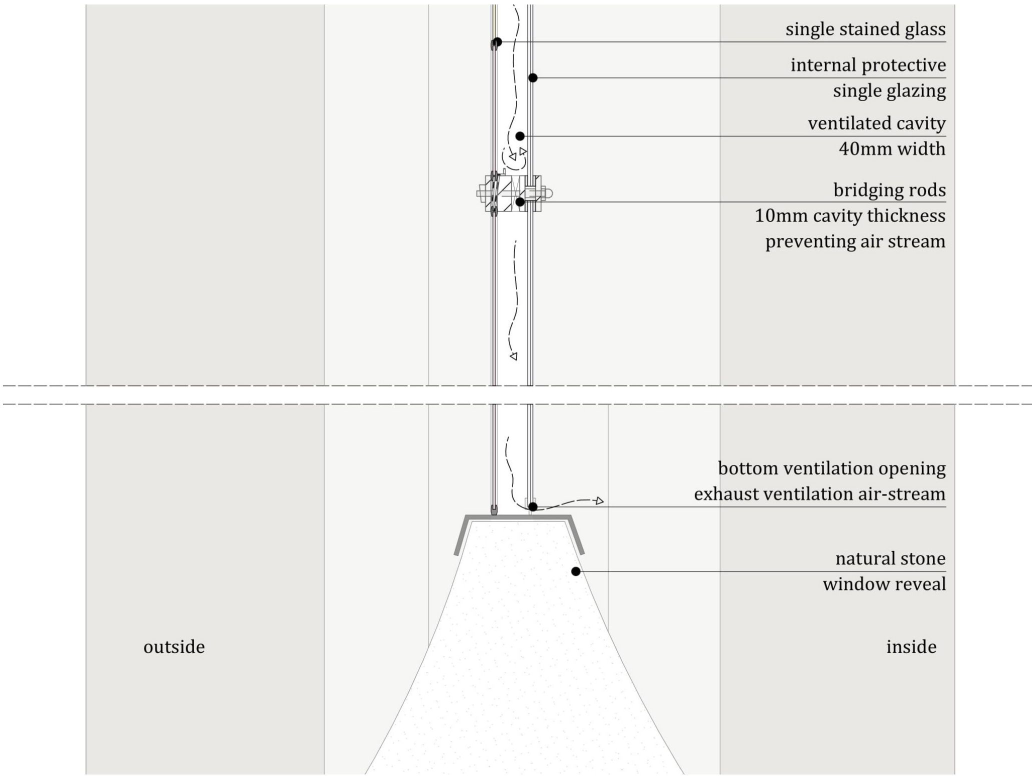


Figure 5.12: Drawing internal protective single glazing - Bridging rods blocking ventilation flow

Comparison condensation risk during the full measurement period

During the measurement period, the dew point temperature lies predominantly below the temperature of the external stained glass surface temperature in both windows which means that no condensation would occur (as shown above).

However, during the full measurement period, the data includes three short periods (max. 45 min) when the risk for condensation was very high because the external surface temperature of the stained glass was below the dew point of the cavity air. This occurred during a non-heating period (MRT South chapel = ca. 10 °C) which could be expected as this leads to a lower temperature and dew point in the cavity.

It is important to note that this is the case for both window constructions, the ventilated and the closed system. However, the appearance of condensation on the stained glass could not be verified visually. Therefore, further observation of the windows it is recommended.

5.2.5 Conclusion

The temperature measurements in the Stevenskerk have shown that closing the cavity of the protective glazing from internal ventilation is beneficial for the heat resistance of the window to a limited extent. The temperature difference between the compared window surfaces during a non-heated period is about 0.5 °C which shows the small but noticeable improvement of this adaptation for thermal comfort improvement. However, the measurements have shown that there is a risk for condensation in the cavity for the internal protective glazing with a ventilated as well as a closed closed cavity. Therefore, further observation of the test windows is recommended.

5.3 Physical calculation models

Introduction

Physical calculations enabled a better understanding and a comparison of the consequences of renovation methods applied to the windows in the Stevenskerk. Those calculations are used to represent the temperature gradient over the cross-section of the window to predict their influence on the thermal comfort. For this, especially, the internal surface temperature of the window is of interest.

The aim was to set up two simple calculation tools which are in accordance with the boundary conditions at the Stevenskerk and can thereby give an impression of the performance of the ventilated and the closed cavity window. The calculation models are based on existing calculation models and principles. The detailed description of those can be found in Appendix C.

The models were validated with measurement data from the South chapel as those windows best represent the large window size in the Stevenskerk (see Appendix C). Afterwards the models were used to test adaptations of the window system and how those influence the indoor thermal comfort.

The models should represent the average winter situation in the Stevenskerk as this is the critical season when the thermal comfort is currently not satisfactory. Exceptions such as extreme weather conditions are not considered in the model as well as the influence of the sunlight on the system as this is not the focus of this study.

Conclusion

Overall, the comparison between the measured and the calculated temperature gradients for the windows in the Stevenskerk have shown that the models represent an approximation but not accurate copy of the reality. When influential parameters such as the heating or the sunlight income change, the models need adaptation in order to coincide with the real situation. Further refinement of the calculation models by validation with more measurement data as well as the integration of the sun or the RH level could help to further improve the accordance between the model and reality.

Nonetheless, the comparison of the calculated temperature gradients over the window construction with the measured temperatures especially during non-heated periods, when there is no sun and heating impact, show very similar results. Therefore, the introduced calculation models can serve as a tool for comparing the thermal performance of different renovation measures by the adaptation of the model under uniform boundary conditions (chapter 8).

5.4 Alternative window renovation strategies

When analyzing the windows in the Stevenskerk by means of thermography it was noticeable that the natural stone mullions and window reveals are thermal bridges because of their smaller cross-section in comparison to the thick walls (figure 5.13).
Additionally, cracks in the window reveals were noticed (figure 5.13 - l) through which cold outdoor air enters the building resulting in draft and heating losses.
Those sources of discomfort cannot be eliminated by the application of a protective glazing system focusing in particular on improving the thermal resistance of the stained glass.
Therefore, alternative renovation strategies for the stained glass windows with the potential for thermal indoor comfort improvement are introduced. The measures are based on case study projects and research by design.

Figure 5.13: Images infiltration cracks natural stone (l) and thermal bridges (c, r)

5.4.1 Internal secondary window

Introduction
This strategy was developed to improve the effect of the application of secondary glazing on the windows with regards to the thermal bridges in the window frame.
Instead of placing the secondary glazing within the window frame, the application of a double glazed window on the inside of the existing stone window frame can be an alternative (figure 5.14).

Aesthetics
The outside impression is not influenced by this measure. The internal elevation of the window, however is changed as the natural stone window frame with its ornaments will be covered by double glazing. In contrary to outside glazing application, however, the glass will largely remain transparent and not lead to reflection.
Due to practicality, depending on the window size, the secondary window cannot be applied as one element. Therefore, it could be divided into smaller elements.

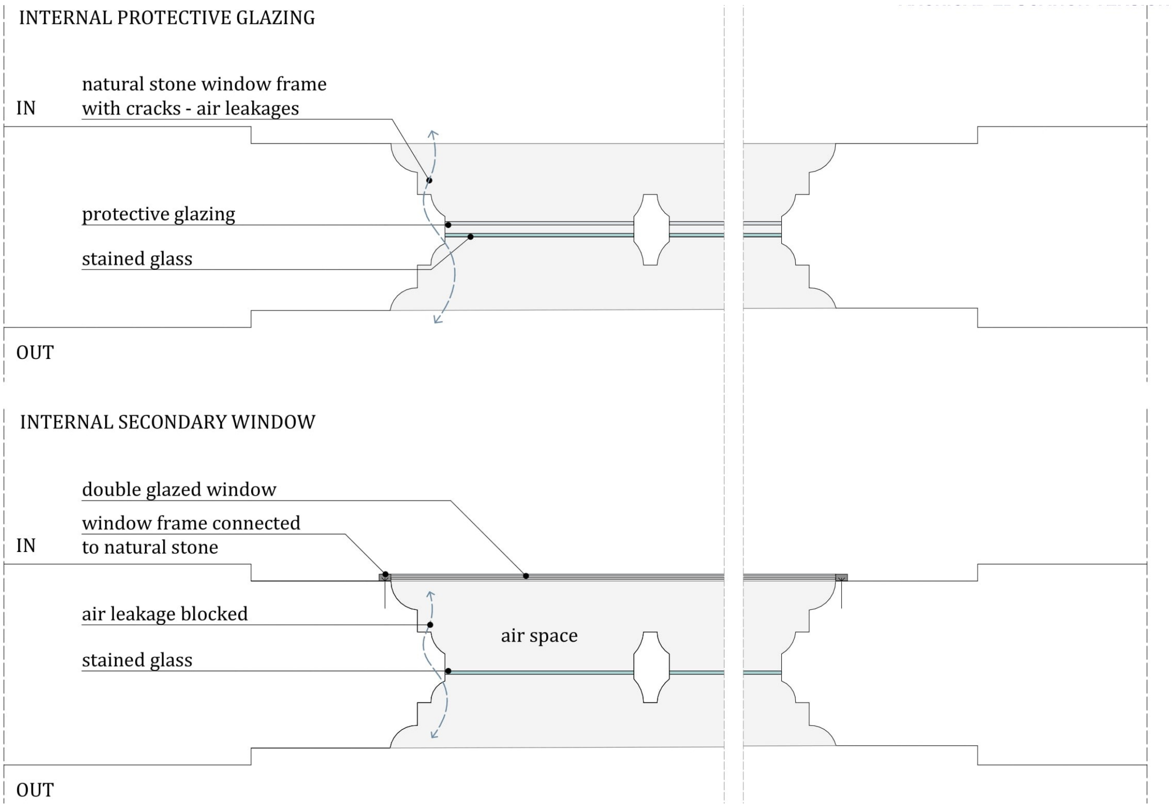


Figure 5.14: Internal secondary window plan

Building physics

The leakages in the window reveal and frame are covered with the new window reducing cold draft. Additionally, well-insulating double glazing can be used for the secondary window which leads to a good insulation performance of the window construction. When adapting the calculation model accordingly, this system would have a U-value of about 1 W/m^{2}K which represents a very significant improvement of about 4.75 W/m^{2}K in comparison to single stained glass.

This calculation is based on an non ventilated system and airtight connections between the internal window and the walls. Accordingly, there is only air infiltration from the outside due to leakage in the stained glass. Thus, there is no condensation risk on the historic windows expected because of the good insulation performance of the secondary window which keeps the air temperature in the cavity close to the outside temperature. However, when there is infiltration from the inside, due to structural defects, the warm indoor air entering the cavity might lead to a condensation risk on the stained glass.

5.4.2 Curtains

Case study projects:

Figure 5.15 left shows the chapel curtain which was suggested as a concept for compartmentalization of the indoor space in the Stevenskerk enabling separate climate conditions. (Rijksdienst voor het Cultureel Erfgoed, 2021). The curtain on the right (figure 5.15 - r) is made of fabric on which a phase change material (PCM) was printed. Therefore, it stores or releases heat depending on the external temperature conditions and thereby supports the regulation of the indoor temperature (Haan, 2020).

Figure 5.15: Chapel curtain Stevenskerk (l) (Rijksdienst voor het Cultureel Erfgoed, 2021) and curtain containing PCM (r) (Haan, 2020)

Introduction:

Curtains can serve as an additional insulation layer for building elements such as tapestry has been in use as a passive climate strategy since Medieval times. Depending on the composition of the textile it may have additional functionalities such as acoustic insulation, light control or serve as a screen for projections. Moreover, curtains can be used as temporary room dividers for compartmentalization. Furthermore, the fabric enables numerous design options and can be opaque, translucent or transparent.

Building physics:

By the placement of a curtain between two parallel surfaces, the exchanged radiation is drastically reduced (figure 5.16). Radiation asymmetry and low MRT levels resulting from cold surface temperatures of the enclosing building components represent a thermal comfort problem in the Stevenskerk. Thus, the application of textile as a radiation screen has a large potential. By the application of a translucent fabric, the resulting emitted radiation is reduced by 50 % . This reduction increases up to 95 % for a high emmissivity fabric (see Appendix D.1 for formulas). As the placement of a fabric next to the wall can create a risk for humidity problems, sufficient ventilation between the fabric and the wall has to be ensured by an inter-space width and ventilation openings.

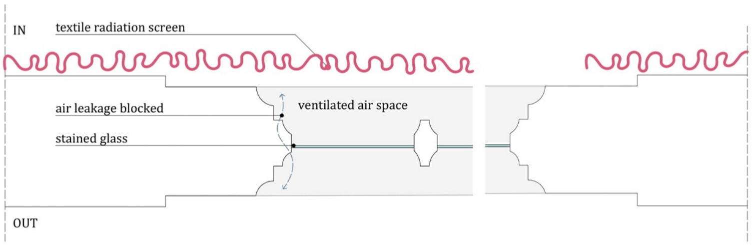


Figure 5.16: Concept radiation screen

5.4.3 Glass box

Case study project:

Figure 5.17 shows the refurbishment of retail store by UN studio where glass boxes create a second skin in front of the historic facade. During the day the pedestrians can look inside the building while during the night the glazed boxes turn into animated light installations illuminating the public space (worldarchitecture, 2020).

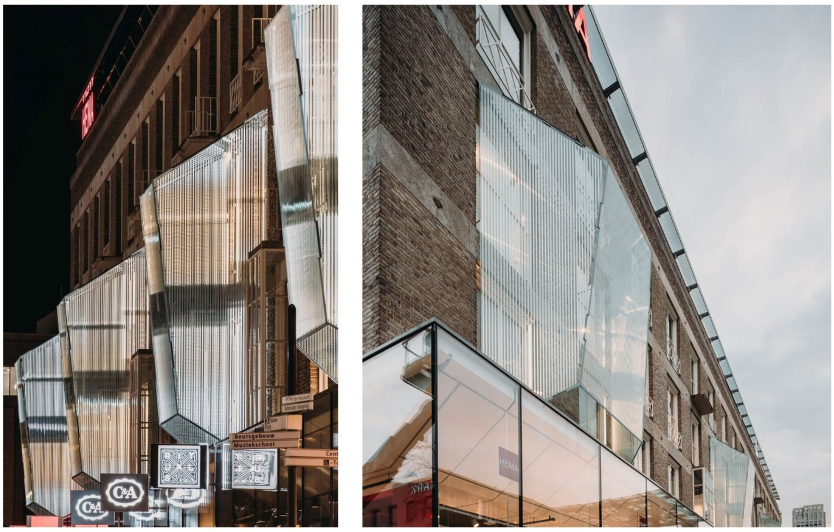


Figure 5.17: Photographs retail store in Eindhoven (worldarchitecture, 2020)

Description:

The addition of a glass box on historic windows can improve their insulation performance (application of double glazing can improve the U-value up to 1 W/m^{2}K, reduce the infiltration through cracks in the window frame and enable secondary functions such as the interaction with the public space. However, the external impression of the building is drastically changed by this measure.
Therefore, the application of glass boxes on the inside of the windows in combination with walkways is introduced as an alternative. This measure does not only lead to an increased thermal performance of the windows but also improves the accessibility and visibility of the monument for the visitor.

5.5 Summary and conclusion

Chapter 5.4 provided an overview of renovation strategies for the stained glass windows in the Stevenskerk including the application of protective glazing and alternative strategies. Furthermore, the protective glazing systems present in the Stevenskerk were examined by means of measurements and validated physical calculation models.
During the research it has become clear that there are numerous parameters influencing the suitability of a renovation method for a specific building. In order to identify the most suitable renovation strategies for the windows in the Stevenskerk, therefore, an evaluation system based on the research objectives will be introduced (chapter 8).

6 Spatial adaptations

6.1 Spatial adaptations for improving thermal comfort

Existing literature about the conversion of churches has identified different types of structural interventions including *the separation of secondary rooms, the vertical* or *the horizontal division of the space* or *the house in house principle* (Netsch, 2018). This research will investigate to what extend it is possible to improve the thermal indoor comfort in the Stevenskerk by adapting the space. Spatial adaptation measures which are in accordance with the following constraints will be illustrated by the introduction of selected case study buildings:

- Potential for the improvement of the thermal indoor comfort
- Conservation of significant monumental values (see chapter 3.3)
- Full reversibility of the intervention
- No intervention on the buildings exterior impression
- Limited intervention on the indoor space impression (in particular the lightening experience and the high vault)
- Preservation of the multi-functional, flexible, large church space and the smaller side chapels as individual spaces

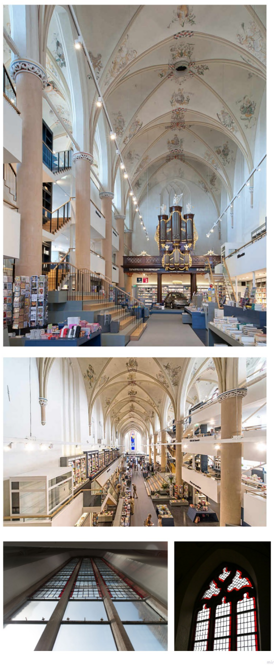


Figure 6.1: Broerenkerk in Zwolle (Parcum, n.d.-b)

Figure 6.2: St. Petruskerk in Vught (González, 2018)

6.2 Case studies

6.2.1 Floorplan adaptation or Zoning the indoor space

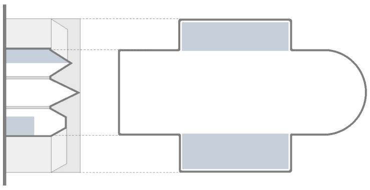


Figure 6.3: Floorplan adaptation

Description: Additional floors and separated spaces are permanently built into the church (figure 6.3). The new levels and accessible routes allow the visitors to experience the indoor space from different perspectives. The vaults and the windows can be observed more closely than from the ground floor. At the same time, the main nave remains open which ensures the conservation of the sacral indoor space impression and preserves important views in the building.

Case-study projects:
The *Broerenkerk in Zwolle* from the 15th century is a national monument and was transformed by Joop van Putten and Hans Westerink in 2013 (figure 6.1). The converted church is used as a library, for catering and for shops (Parcum, n.d.-b).
The *St. Petruskerk in Vught* is a national monument and was transformed in 2018 (figure 6.2). Today, the building contains a library, a museum and a community center (González, 2018).

Thermal comfort:
This adaptation principle has potential for improving the thermal comfort because the new built zones can be equipped with a separate heating system which can be regulated separately from the large space. As these new zones have smaller volumes their thermal comfort could be provided easier than for the large church volume. This concept could also be combined with a heated route through the primarily used spaces while the rest of the church remains unheated.

Figure 6.5: Hotel concept Heilige Nachten
(Nachten, n.d.)

Figure 6.6: Flexybox concept
(Sander Vijgen architect, n.d.)

6.2.2 The house in house or box in box principle

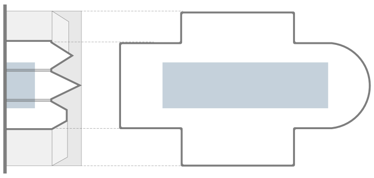


Figure 6.4: box in box principle

Description: The addition of independent spaces in the church can be realized temporarily or permanently (figure 6.4). This principle enables a clear distinction between and the separate use of the newly added elements and the historic building. Furthermore, the new internal structure does not influence the external impression and depending on the volume and the location the intervention on the indoor space impression can be influenced. Depending on the scale, additional floor space can be generated.

Case-study projects temporary (figure 6.5 and 6.6):
Hotel concept *Heilige Nachten* for overnight stay in a church building (figure 6.5): Visitors sleep in a temporarily built up space, similar to a transparent tent (Nachten, n.d.).
The design *FLEXYBOX* by Sander Vijgen Architect (figure 6.6) enables the use of flexible and temporarily placed boxes as meeting space, event location or for overnight stays (Sander Vijgen architect, n.d.). Both ideas are independent from the location of the church.

Case-study projects permanent (figure 6.7 - 6.9):
In 2014, a smaller chapel was built into the *Marien Chapel St. Johannes* in Wietmarschen from the 13th century (figure 6.7). It is equipped with a separate floor heating system. (Gantner et al., 2017).
The *St. Gertrudis van Nijvelkerk* in Heerle from 1865 was converted to a general doctors practice, a village hall and a place for the church board in 2012 by Oomen architecten (Oomen Arch., n.d.) (figure 6.8).
In 2015 a parish hall was built into the *Walloner Church* in Magdeburg to extend the use of the space (Gantner et al., 2017) (figure 6.9).

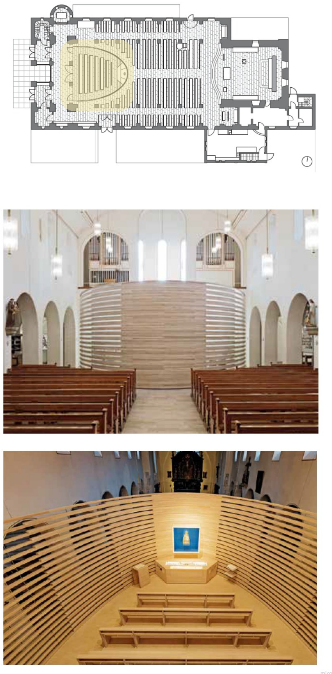


Figure 6.7: Marien Chapel St. J., Wietmarschen (Gantner et al., 2017)

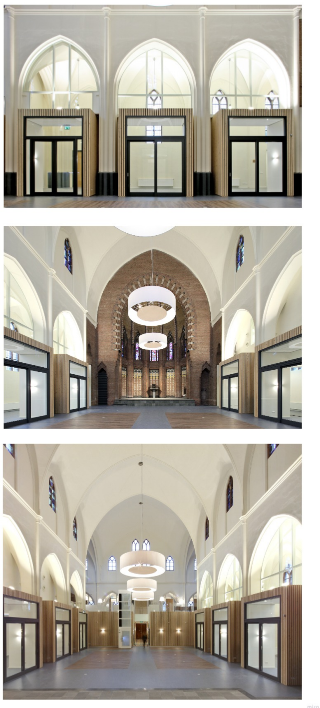


Figure 6.8: Gertrudis v. Nijvelkerk, Heerle (Oomen Arch., n.d.)

Figure 6.9: Walloner Church, Magdeburg (Gantner et al., 2017)

Thermal comfort:

The compartmentalization has potential for improving the thermal comfort because the IEQ (*Indoor Environmental Quality*) conditions for the new internal structure is separate from the large space. The manageability of the thermal conditions depends on the technical infrastructure.

A temporary tent structure for example would not have a separate heating system. However, the material of the skin in combination with a small indoor volume and the heat emitted by the occupants can create a comparably warm indoor temperature.

Permanent box in box systems can be equipped with a separate heating system enabling an independent regulation from the surrounding larger volume which may remain unheated or at a lower temperature.

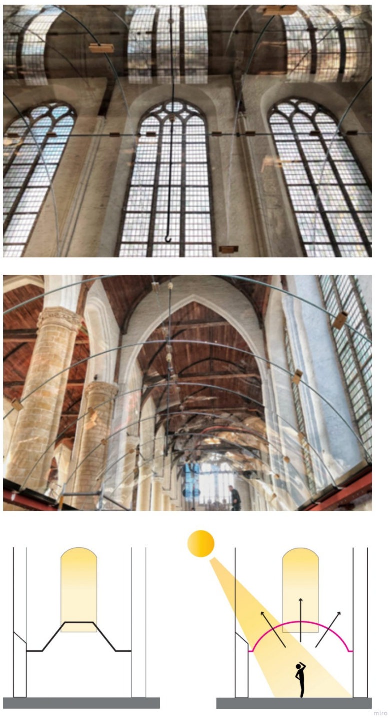


Figure 6.11: St. Janskerk, Schiedam (Mei architekten, n.d.)

Figure 6.12: St. Bernadus church, Oberhausen (Gantner et al., 2017)

6.2.3 Division indoor volume

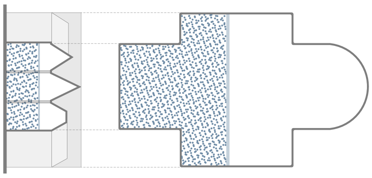


Figure 6.10: Division

Description: By dividing the indoor space of the church horizontally or vertically (figure 6.10) the large volume is split into separate zones enabling independent use. This intervention does not require a change of the building's facade. Within the separate zones the interior of the building can remain unchanged. By using transparent materials the indoor space impression of the church as a whole is insignificantly compromised.

Case-study projects:
In the *St. Janskerk*, dating from 1425 in Schiedam an opaque wooden roof was replaced by an innovative and transparent glazing construction (Mei architekten, n.d.) (figure 6.11).
In 2006, Zwo+ architects realized a use division in the *St. Bernadus church* in Oberhausen by the placement of vertical, separating glass elements. The church remains open for religious activities while the separated space is used for events (Gantner et al., 2017) (figure 6.12).

Thermal comfort:
By dividing the large indoor volume of the building, the heating load is reduced which enables an improved regulation of the thermal comfort. By dividing the indoor volume horizontally, the interior height is reduced. Thus, rising hot air from the floor heating is trapped because it cannot disappear in the high vaulted space.

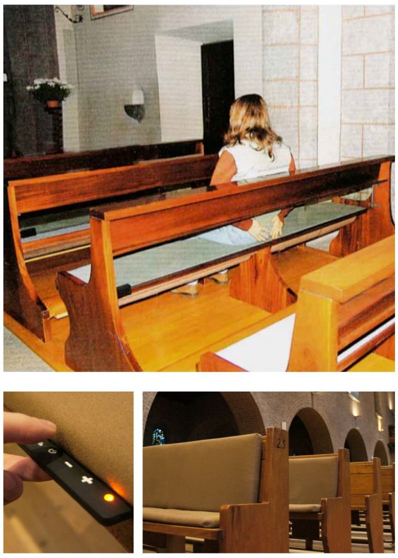


Figure 6.14: Examples pew heating (Camuffo, 2010; Sit & Heat, n.d.)

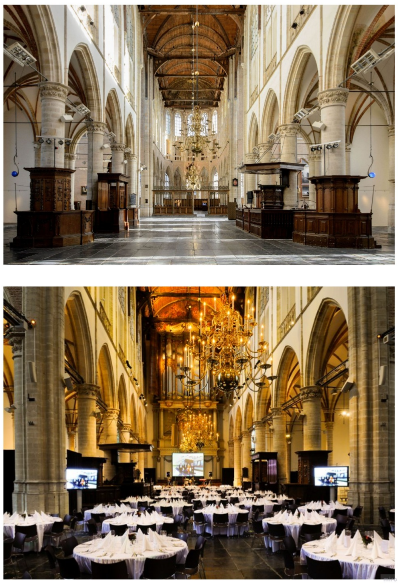


Figure 6.15: Grote Kerk Alkmaar: multi-functional use (Nationaal Monumenten Portaal, n.d.)

6.2.4 Local heating

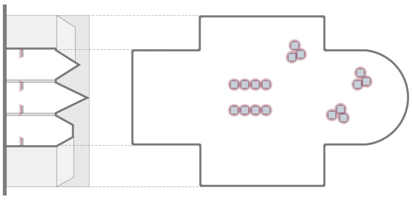


Figure 6.13: Local heating

Description:

This strategy is based on the principle « *Heating people not spaces* ». The application of local heating enables to create a comfortable environment at a specific and restricted location of a large building volume where occupants with thermal comfort requirements are situated while the remaining space is kept at a lower comfort level (figure 6.13).

Case-study projects and thermal comfort:

Local pew heating has been subject of previous research about heating and heritage conservation in churches and was identified as a suitable measure when artwork conservation is prioritized while the heating is irregular and the church benches are fixed (Camuffo, 2010). Different strategies such as low-temperature radiation heaters, heating foils placed close to the occupants (figure 6.14 top) or integration of heating wires or foil into a carpet were studied. Systems for pew heating integrated into the seating pillow are available on the market and can be supplied by batteries or a wired connection (figure 6.14 bottom) (Sit & Heat, n.d.).

The study (Camuffo, 2010) also investigated the effects of electric radiant heaters and concluded: *«When properly designed and installed, the system can provide local heating of areas where people sit or stand with small perturbations of the natural climate in the rest of church. The level of comfort depends on the homogeneity, intensity and symmetry of IR distribution, but it is never optimal, as heads are heated more than feet and the distribution is never symmetrical.»* The impact of the infrared radiation on artworks has to be avoided for damaging risks. It is suitable for churches with no or flexible pews.

The Grote Kerk in Alkmaar, for example, is equipped with infrared heating enabling the use for several functionalities and flexible spatial concepts (Nationaal Monumenten Portaal, n.d.) (figure 6.15).

7 Thermal comfort simulations

7.1 Simulation plan

7.1.1 Simulation process

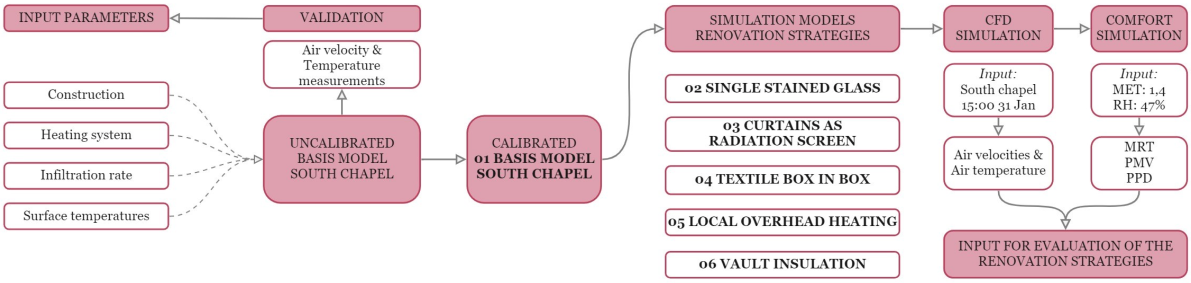


Figure 7.1: Workflow thermal comfort simulations in Design Builder

DesignBuilder was chosen as the thermal analysis tool for this project. This software performs thermal simulations to determine if the occupant in a space feels comfortable. *DesignBuilder* enables the assignment of the construction components with their materials to the 3D-model of a building and the modelling of the HVAC system under the consideration of different boundary conditions influencing the buildings energy performance.

Figure 7.1 summarizes the workflow in *DesignBuilder*: First, a basis model of the South chapel representing the current situation was constructed. It was validated with the real measurement data taken in the Stevenskerk by checking the simulation results and adapting the input parameters.

The South chapel was selected for the thermal simulations performance because real measurement data is available for the validation of the model. Furthermore, the space is equipped with an air-heating system and with a high vault which makes the South Chapel a good representation of the large church space. The simulation of the Stevenskerk as a whole would have been too complex and time consuming for the scope of this project.

First, the thermal analysis was conducted. This simulation provides information about the heating losses through the building components and the heating demand while taking into account weather data at the buildings location during a selected time period. Afterwards, an internal CFD (*Computer Fluid Dynamics*) analysis for a specific day and time (31st Jan 3pm) was conducted enabling the illustration of air velocity flows and the air temperature in the space. The following thermal simulation calculates more specific outputs regarding the thermal comfort such as the mean radiant temperature (MRT), the predicted mean vote (PMV) and the predicted percentage of people dissatisfied (PPD). Those results can be visualized for specific locations in the space by slice diagrams showing a specific colour depending on the simulation result.

After the validation of the basis simulation model, adaptations were made according to selected renovation measures and the simulation is repeated with the same boundary conditions. This enables the comparison of the resulting thermal conditions for the different renovation measures and the current situation.

7.1.2 Simulation objectives

The thermal simulations were performed in order to compare the influence of different renovation strategies on the thermal comfort in the Stevenskerk. While the improvement of the thermal comfort is the most important assessment parameter, the simulation should also take the heating demand, the spatial configuration, the climatic conditions and the building construction into account.

The assessment of the thermal comfort improvement by means of thermal simulation software takes all the mentioned parameters into one simulation and provides a comprehensive and visual result about the thermal conditions within the different zones of a space. Furthermore, the simulations were used to review the expected thermal improvement according to previous calculations and research. The desired result was a comparative analysis and visualisation of different promising renovation measures and the assessment of their thermal performance.

7.1.3 Basis model South chapel

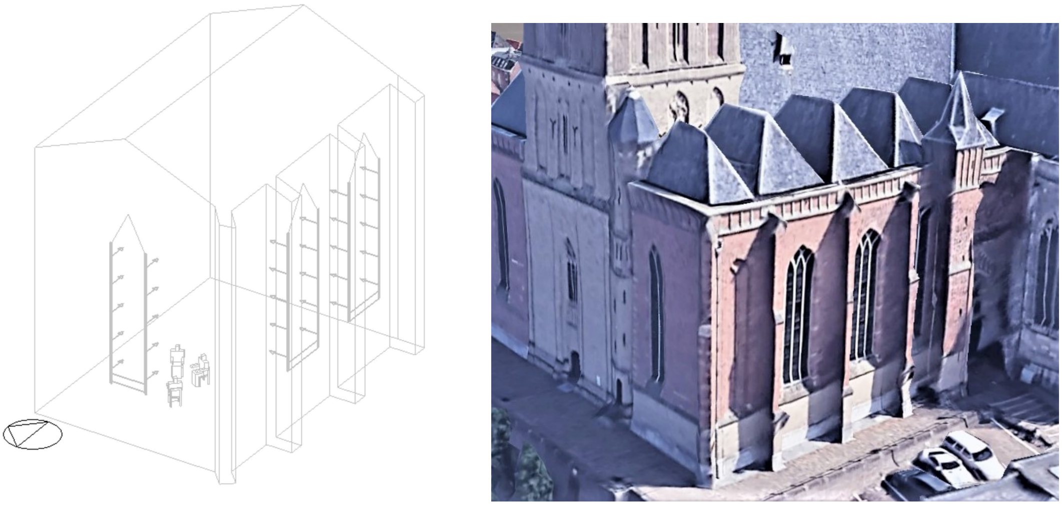


Figure 7.2: Axonometric view 3D basis model in DesignBuilder and google earth view South chapel (Google Earth, n.d.)

In order to reduce the simulation time the 3D model of the South chapel was build as a slightly simplified structure (figure 7.2). While the volume and the size of the indoor space were modelled as in reality, the exact shape of the complex vaulting was simplified to a pitched roof.

The heat resistance of the building components were adjusted according to the available building data (figure 7.3). The location and size of the windows were modelled according to the actual situation while their complex shape and structure was simplified to regular glass panes. The glazing was modeled with a closed cavity (3mm glass, 20mm closed cavity, 3mm glass). As this analysis is focused on comparing different adaptation strategies however, it was not essential to build a model which perfectly matches the existing situation.

Construction Input		R_c-value [m^2K/W]	U-value [W/m^2K]
01 Basis model South chapel			
External wall	Plaster - Natural stone (90cm)	0,66	1,51
Internal wall	Plaster - Natural stone - Plaster (40cm)	0,53	1,90
Floor	Ground floor (medium-weight)	3,18	0,31
Roof	Concrete - cavity - wood - slate tiles	0,63	1,59
Window	Double glazing with air cavity (3*20*3mm)	0,34	2,98

Figure 7.3: Overview input parameters construction for the basis model

Even though Stichting Stevenskerk is planning to change to a water-based floor-heating the simulations were conducted for the current air-heating system as this is common for church spaces and therefore the simulation results could also be applicable for other buildings.

The infiltration rate with external air was indicated according to previous research (Aarle, 2007) and the air tightness of the building was set to poor as the building skin is comparatively permeable. In order to model the cracks which have been identified along the window reveal, CFD boundary conditions with air infiltration were included in the model.

7.1.4 Evaluation simulation results

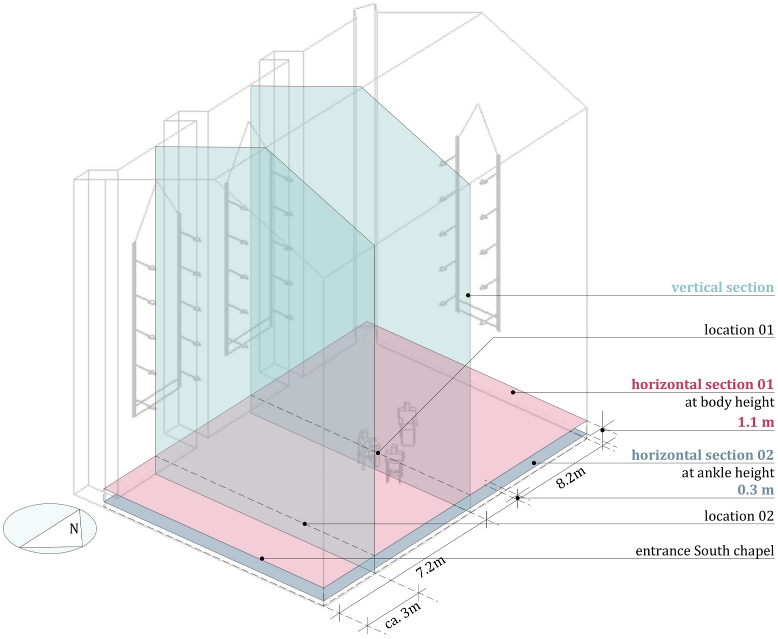


Figure 7.4: Sections and locations for evaluation simulation results

In order to evaluate the different renovation measures, locations in the simulation model for the thermal comfort assessment were defined. There are four «test locations» at which section diagrams through the model were placed: Horizontally, the ankle (30 cm above the ground) and the body height (1.1 m above the ground) level were evaluated more into detail (figure 7.4) as those locations influence the thermal sensation of the user. The vertical sections are located along the window openings as those are the thermally weakest point of the external building skin and the focus of this project.

The comparison of the same location for the different measures enables comparability of the results. Additionally, uniform bands for the different simulation results were defined in order to relate the simulation results to each other.

In Appendix B a full table of the CFD results as section diagrams can be found (figure B.5). This chapter shows selected diagrams and describes significant simulation results. The air velocity and the MRT were chosen as the main assessment parameters for the thermal comfort level in the South chapel as these were identified as critical challenges during the heating period. Additionally, the PMV and PPD levels were taken into account.

7.1.5 Validation Basis model South chapel - 01

The section diagram of the CFD analysis (figure 7.5 left) illustrates the downdraft along the internal surface of the building skin and the infiltration through cracks in the window reveal as well as the horizontal airflow in the center of the South chapel. At the body and the ankle level, the simulation shows an average airflow velocity of 0.2 m/s which represents a comfort problem. The simulated MRT lies 1 °C below the actual measured temperature level. At 1.1 m height the overall MRT level is at about 17 °C. The green colour in the MRT section diagram (figure 7.5 right) illustrates the cold radiation emitted from the exterior wall and the vault.

However, this difference is not significant and the simulated air velocities are within the range of the real measurements taken in the South chapel (see data comparison figure 7.6). Therefore, the basis model can be used as the starting point for further simulations.

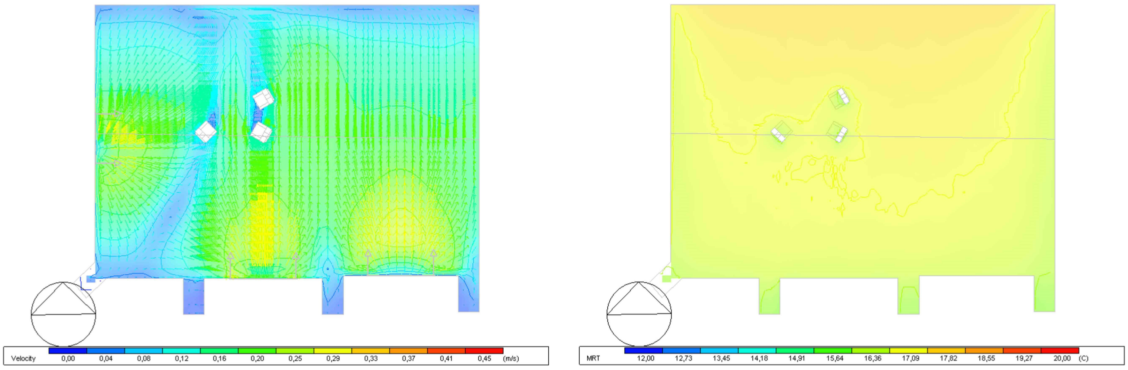
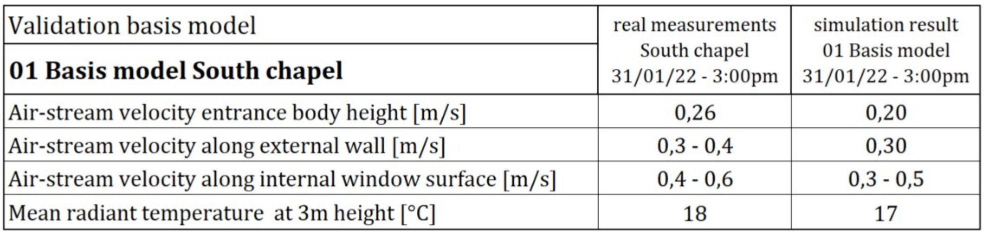


Figure 7.5: Basis model simulation air velocity at 1.1m height (l) and section MRT at location 1 (r)



Validation basis model **01 Basis model South chapel**	real measurements South chapel 31/01/22 - 3:00pm	simulation result 01 Basis model 31/01/22 - 3:00pm
Air-stream velocity entrance body height [m/s]	0,26	0,20
Air-stream velocity along external wall [m/s]	0,3 - 0,4	0,30
Air-stream velocity along internal window surface [m/s]	0,4 - 0,6	0,3 - 0,5
Mean radiant temperature at 3m height [°C]	18	17

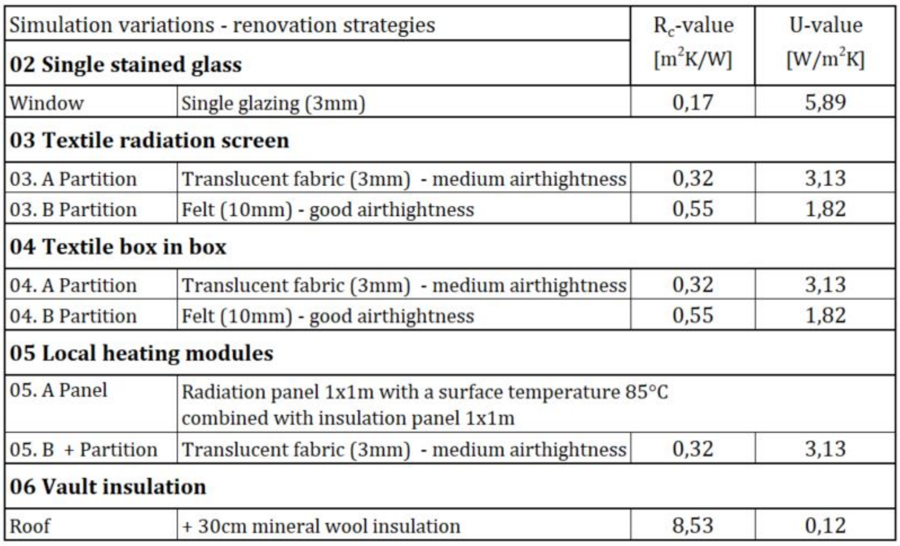
Figure 7.6: Comparison real measurement and simulation data South chapel

According to the simulation the PMV of the occupants at the «test locations» is -1 which translates into a slightly cold environment. The simulated PPD ranges from 27 % close to the facade to 20 % adjacent to the internal walls.

Overall, in accordance with the reported sensation of the building users, the simulation showed that in the current situation the temperature and air velocity levels in the South chapel do not correspond to thermal comfort requirements during winter (see chapter 3).

7.2 Comparative thermal simulations

Figure 7.7 illustrates the construction input adaptations according to the different renovation measures simulations and the according heat resistances calculated by *DesignBuilder*. The selection of the strategies was based on their estimated potential for the thermal comfort improvement in combination with their suitability for the spatial functionality in the Stevenskerk (for further explanation see chapter 8). Overall, nine different simulation variations were performed for the South chapel of the Stevenskerk (Appendix B figure B.5).



Simulation variations - renovation strategies		R_c-value [m^{2}K/W]	U-value [W/m^{2}K]
02 Single stained glass			
Window	Single glazing (3mm)	0,17	5,89
03 Textile radiation screen			
03. A Partition	Translucent fabric (3mm) - medium airthightness	0,32	3,13
03. B Partition	Felt (10mm) - good airthightness	0,55	1,82
04 Textile box in box			
04. A Partition	Translucent fabric (3mm) - medium airthightness	0,32	3,13
04. B Partition	Felt (10mm) - good airthightness	0,55	1,82
05 Local heating modules			
05. A Panel	Radiation panel 1x1m with a surface temperature 85°C combined with insulation panel 1x1m		
05. B + Partition	Translucent fabric (3mm) - medium airthightness	0,32	3,13
06 Vault insulation			
Roof	+ 30cm mineral wool insulation	8,53	0,12

Figure 7.7: Overview input parameters for the simulation variations

7.2.1 Single stained glass - 02

Introduction:
This simulation was conducted because the stained glass windows in the large church space of the Stevenskerk are not equipped with protective glazing. In order to compare the potential improvement by adapting them to a double glazed window construction, it was interesting to visualize the difference between these two stages of comfort. According to the measurements taken in the Stevenskerk the application of secondary glazing increased the surface temperature of the glass from 15 °C to 8 °C.

Air velocity:
As expected, the downdraft along the window is increased in comparison to the basis model simulation 01 (double glazed window with closed cavity). The section shows values up to 0.45 m/s (figure 7.8). This also coincides with the air velocity measurements which have been taken in the Stevenskerk and therefore validates this simulation model.
In comparison to the basis model 01 there are no significant differences in the air-flow velocity in the center of the room at body or ankle height. This simulation therefore shows that even if the thermal comfort regarding airflow along the external building skin is improved this does not significantly influence the comfort conditions in the more centrally located space.

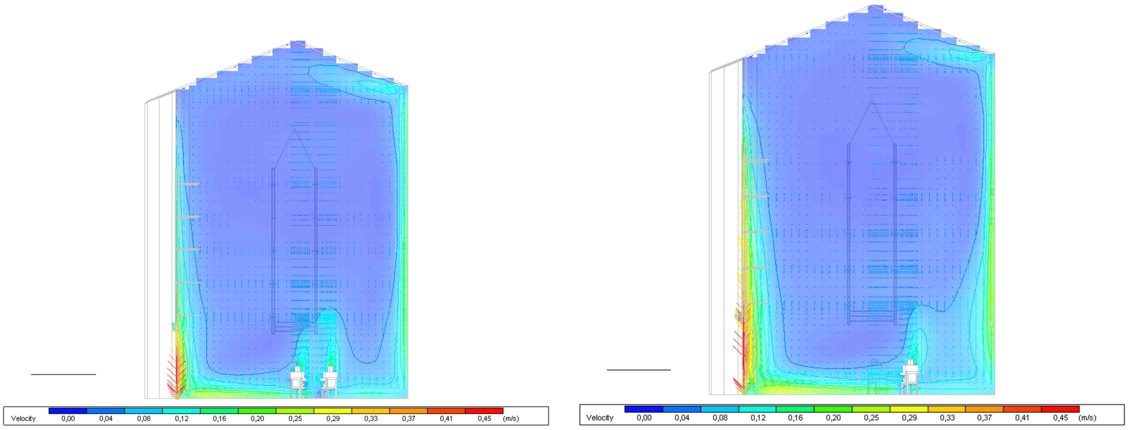


Figure 7.8: Thermal simulation velocity - Basis model (l) and single stained glass windows (r) - location 1

MRT:
The section diagrams of the MRT simulation results (figure 7.9) clearly shows that the single stained glass windows emit significantly more cold than the double glazed windows towards the indoor space. This simulation illustrates that even the placement of a glass pane between two parallel surfaces can serve as a radiation screen (chapter 5.4.2).
However, the section diagrams also make visible that the influence on the MRT at the location of the occupants in the center of the South chapel is limited as the window is located at a higher level. Nevertheless, in the area close to the window the MRT at body height is slightly decreased in comparison to the basis model simulation 01.

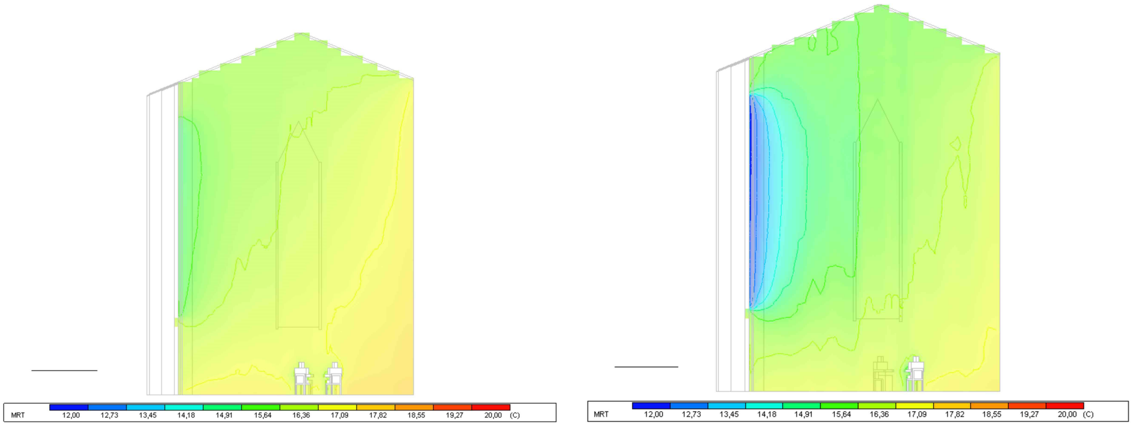


Figure 7.9: Thermal simulation MRT - Basis model (l) and single stained glass windows (r) - location 1

Conclusion:
According to the simulation with regards to the air velocity and the MRT at a location not adjacent to the window surface, the addition of internal protective glazing with a closed cavity has only a limited potential for thermal comfort improvement.
Thus, when investigating window renovation methods for thermal comfort improvement, the location with high thermal comfort requirements within the space and the layout of the room should be considered.

7.2.2 Textile radiation screen - 03

Introduction:

According to the previous approximate calculations (chapter 5.4.2), the application of a radiation screen can largely reduce the emitted radiation. Therefore, the application of textile as a radiation screen between the external wall and the occupant was simulated with two different materials: With a thin, translucent fabric with a low thermal resistance (03.A) and an insulating felt fabric (03.B). Felt fabric was chosen as an insulating textile because it is sustainable, acts sound absorbing, is durable and enables diverse designs for example regarding its colour.

Aesthetically, the transparent fabric might be more suitable as it enables light income and a view towards the surrounding church space. The felt curtain, however, might lead to a better improvement of the thermal comfort due to a better insulation performance of the fabric. The comparative simulation should enable understanding of how these two different systems perform with regard to the thermal comfort level in the space.

Overall, the provision of sufficient ventilation in the cavity between the fabric and the wall is important in order to avoid condensation. Therefore, large openings at the top and at the bottom were integrated into the curtain modelled with Design Builder and the textile was located with a distance (30 cm) to the wall (figure 7.10).

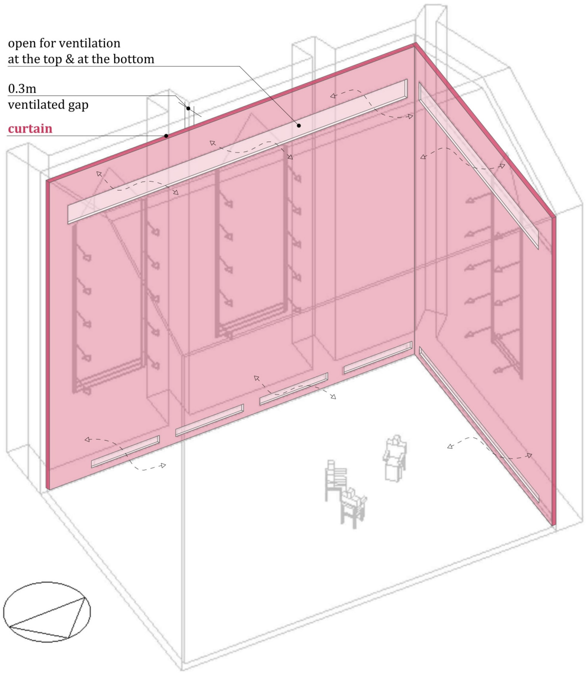


Figure 7.10: Axonometric view 3D model radiation screen simulation

Air velocity:

As expected, in comparison to the basis situation, the simulation shows a reduction of the air-stream originating from the external walls for both fabric types. Figure 7.11 - l in comparison to figure 7.13 - r illustrates that the felt fabric blocks the airflow even slightly better leading to lower air velocities in the South chapel. This difference is probably related to the air-tightness of the fabric which was indicated with «medium» for the translucent and «good» for the felt. Thus, this simulation proves that there is potential for improving thermal comfort with regards to draft in the South chapel by the placement of a textile radiation screen and that the air permeability of the fabric influences the level of draft reduction (figure 7.11 and 7.11 - l).

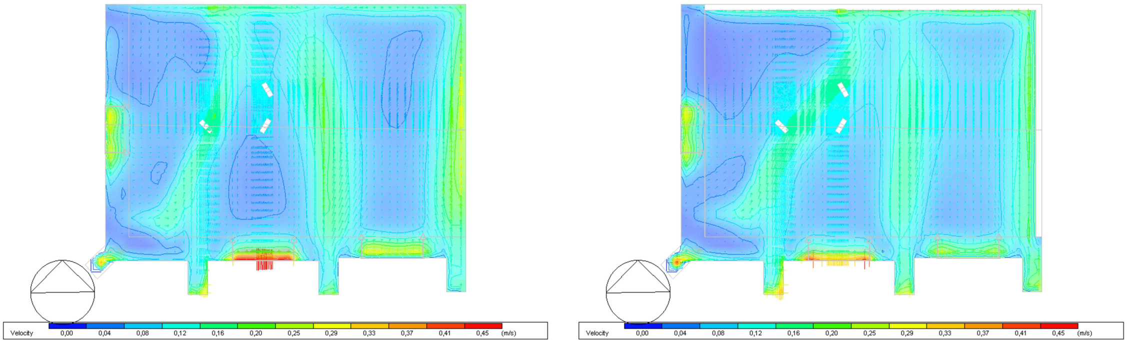


Figure 7.11: Textile radiation screen simulation air velocity - Plan view 03.A (l) and 03.B (r)

Mean radiant temperature:

The comfort simulation visualizes a significantly increased MRT at the occupants location in the South chapel compared to the basis model (figure 7.12 and 7.13 - r). As expected this improvement is slightly larger for the application of the felt fabric (Δ = ca. 2 °C) than for the translucent fabric (Δ = ca. 1 °C). Furthermore, there is a considerable temperature difference in comparison to the cavity between the facade and the textile (Δ = ca. 3 °C).

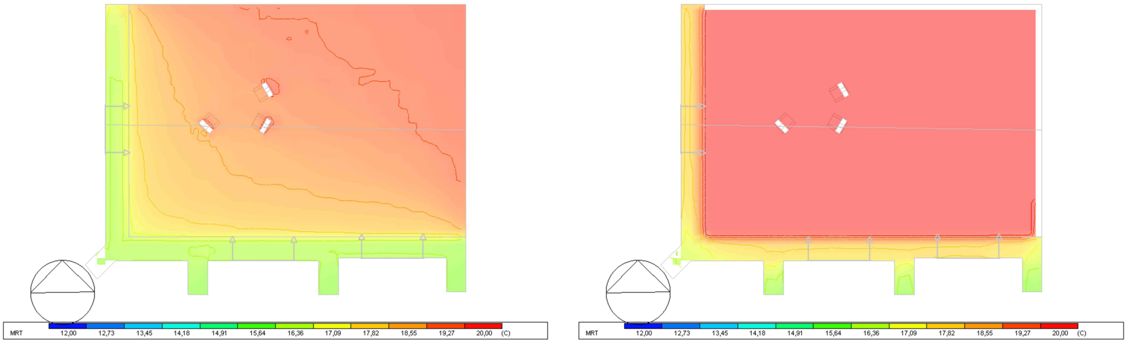


Figure 7.12: Textile radiation screen simulation MRT - Plan view 03.A (l) and 03.B (r)

Visual comparison Basis model:

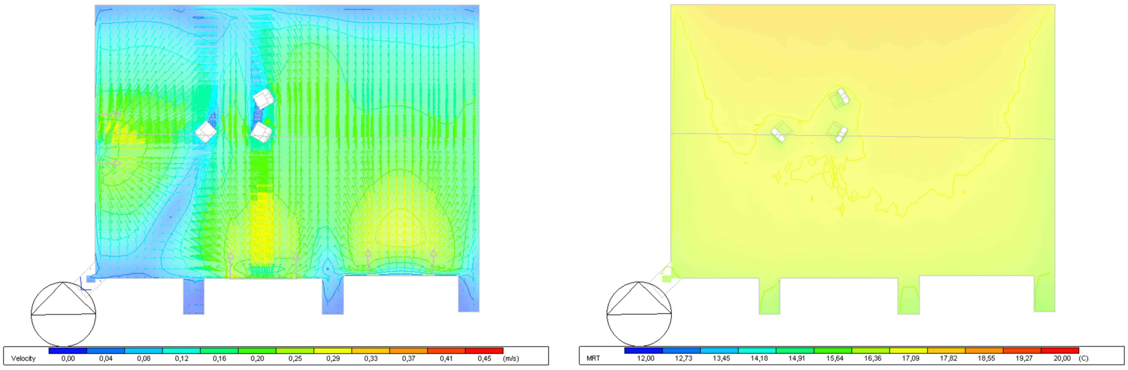


Figure 7.13: Basis model simulation - Plan view air velocity (l) and MRT (r)

<u>PPD:</u>

The comparison of the PPD ratio of the basis model and felt as radiation screen (figure 7.14) illustrates the large potential for comfort improvement by this measure. It reduces the PPD range from 20-27 % to a level of 10 % which corresponds to a building class C according to the ISO 7730 standard (ISO, 2005).

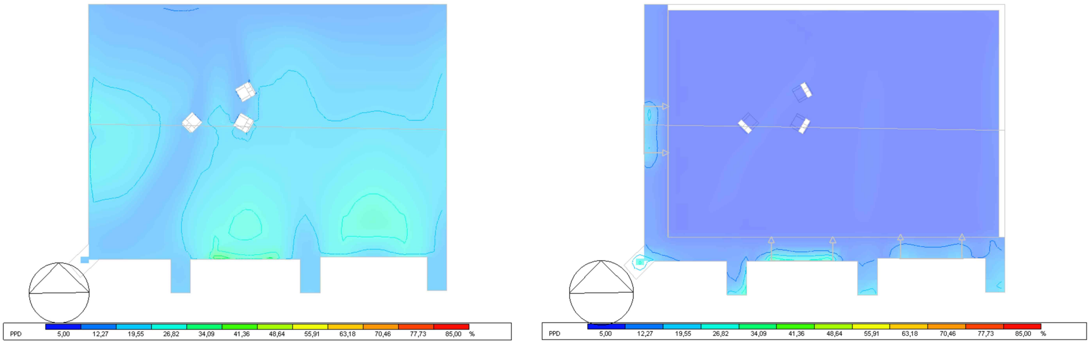


Figure 7.14: Simulation PPD - Plan view simulation Basis model 01 (l) and felt as radiation screen - 03.B (r)

7.2.3 Textile box in box - 04

Introduction:

According to the spatial adaptation principle of compartmentalization (chapter 6.2.2), the influence of the vertical division of the space into a smaller area was simulated. Textile was chosen as material for the simulation of the division because it enables the flexible and adaptive use of the space.
On the one hand, the division leads to a smaller indoor volume resulting in a smaller heating load. On the other hand, it is questionable if this really has a significant influence on thermal comfort as the space has a high vaulted roof. The simulation should help to understand these interrelations.
In order to compare the impact of two design strategies, once again the application of a translucent curtain (04.A - 3 mm) and the application of a insulating felt (04.B - 10 mm) were simulated.
The textile box was modelled in *DB* using the internal partition tool and assigning the corresponding material properties. As ventilation of the internal space is crucial and the connection of the curtain will not directly join on the floor and along the complex vault shape, large ventilation openings were integrated (figure 7.15).

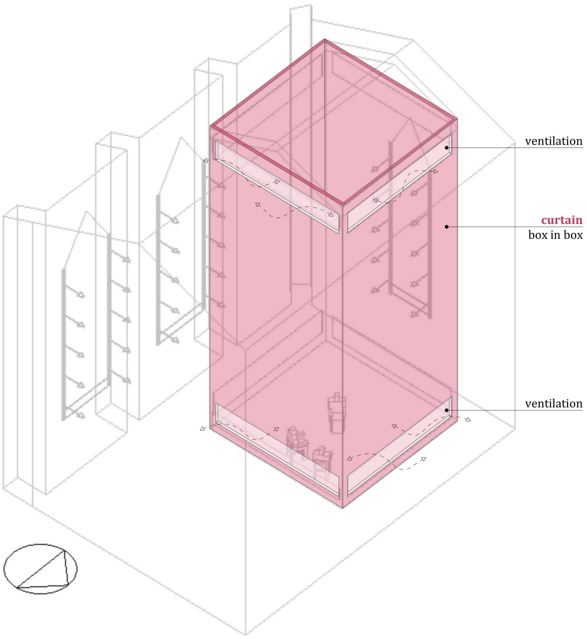


Figure 7.15: Axonometric view 3D model vertical textile room division

Air velocity

The thermal simulation shows a reduction of the horizontal air-flow velocity at body height within the textile box structure to 0.10 m/s (figure 7.16). This lies in the comfort range for winter conditions. At ankle level, however, where the ventilation openings are located, the air velocity is similar to the current situation (0.25 m/s). Against the expectations, the simulation results for the different fabric types for the box in box system were very similar (comparison figure 7.16 left and right).

MRT:

According to the thermal comfort simulation, the compartmentalization with a textile at the same heating level leads to a considerable improvement of the MRT to 19 °C within the new box in comparison to 17.5 °C outside the box (figure 7.17). This improved MRT level is vertically equally distributed over the full height of the space.

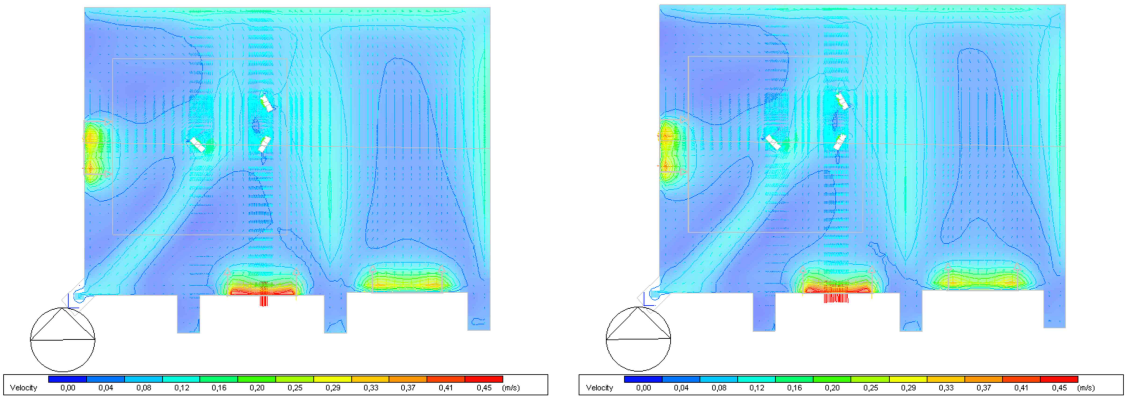


Figure 7.16: Textile box in box simulation air velocity - Plan view 04.A (l) and 04.B (r)

PPD:

Furthermore, this spatial adaptation decreased the PPD at location 01 (in the box) from 20-28 % in the basis model to 11 % in both simulation variants. Referring to the ISO 7730 standard (ISO, 2005) this space would then corresponds to the thermal comfort requirements for building class C.

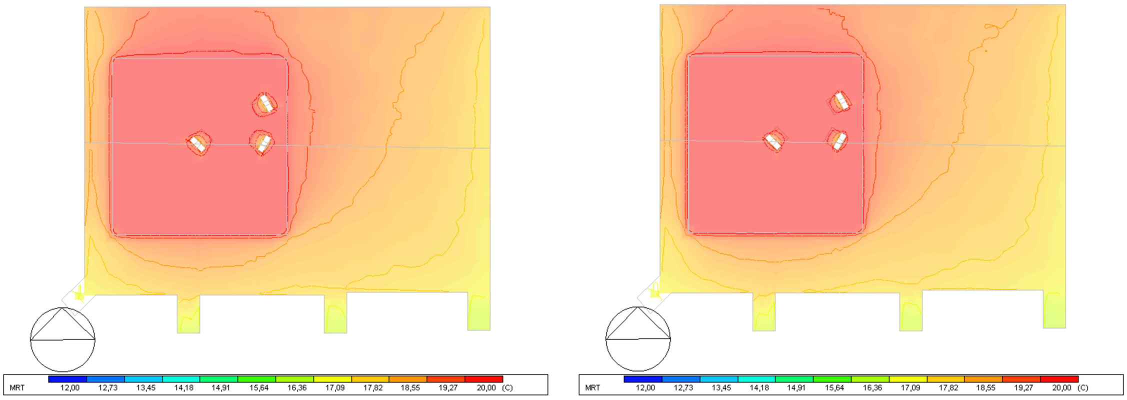


Figure 7.17: Textile box in box - Thermal simulation MRT - Plan view 04.A (l) and 04.B (r)

Conclusion:

It was unexpected that the thermal comfort improvement by two textiles with different insulation properties showed similar results. Therefore, further investigation and more simulations with different textile properties should be performed.

The significant improvement of the thermal comfort conditions within the smaller space in the South chapel model could be proven as expected. To conclude, the compartmentalization results in less draft and higher temperature levels leading to better thermal comfort. Therefore this strategy has a lot of potential.

7.2.4 Local heating - 05

Introduction:

This simulation was based on the principle of local heating (chapter 6.2.4). It was performed in order to investigate to what extent radiation panels which are located above the occupants can improve their thermal comfort condition. The idea of a modular system of heating panels at different locations in the space was simulated.

The panels were constructed as building components with an area of 1x1 m and a surface temperature of 85 °C which is common for infrared heaters. Per module two heating panels were combined with two insulation modules of the same size and one large insulating component from the top in order to distribute the heat downwards. Thus, the complete module size is 2x2 m. For this simulation in total 3 heating modules were placed at 2.5 m above floor level in the center of the space (figure 7.18).

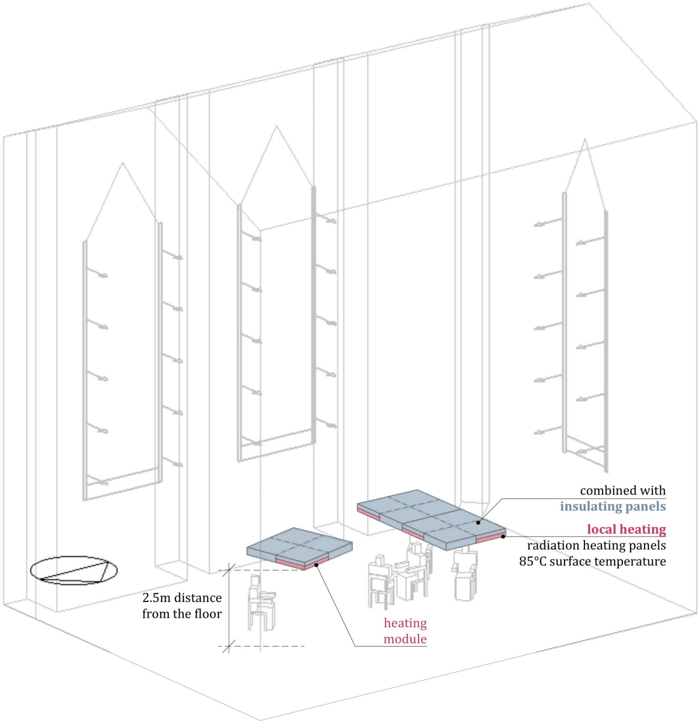


Figure 7.18: Axonometric view 3D model 05.A with local heating modules

Air velocity:

According to the thermal simulation the air-stream velocity at body level is slightly increased (ca. 0.25 m/s). With regard to draft the simulation of this strategy does show comfort improvement.

MRT:

As expected the thermal simulation clearly shows a locally increased MRT below the heating modules (ca. 19.5-20 °C) while the space outside remains at a colder temperature level (figure 7.19). Thus, as desired this strategy achieves the heating of the occupant below the module instead of heating the larger space and can therefore be suitable for the application in large church volumes. However, to a certain extent figure 7.19 shows a horizontal heat distribution in the space which raises the question if the heat could be better locally concentrated. Therefore, the following simulation (05.B) tested the impact of an additional textile compartmentalization enclosing the heated volume aiming at reduced air-flow velocities and better local heat conservation.

PPD:

The PPD below the localised heating modules has decreased to 12% (figure 7.20). This corresponds to a significantly higher thermal comfort and according to the ISO 7730 standard(ISO, 2005) the space could be rated as building class C.

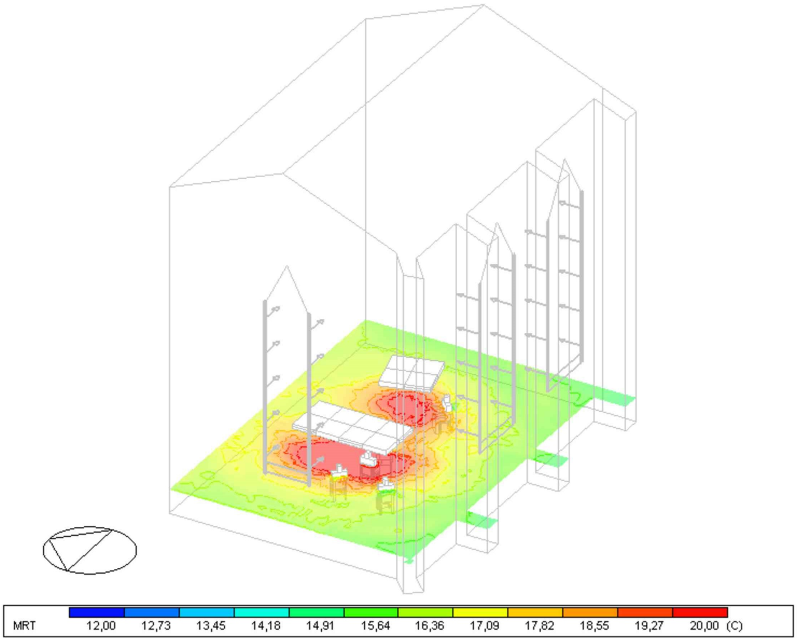


Figure 7.19: Local heating - Thermal simulation MRT - Axonometric view

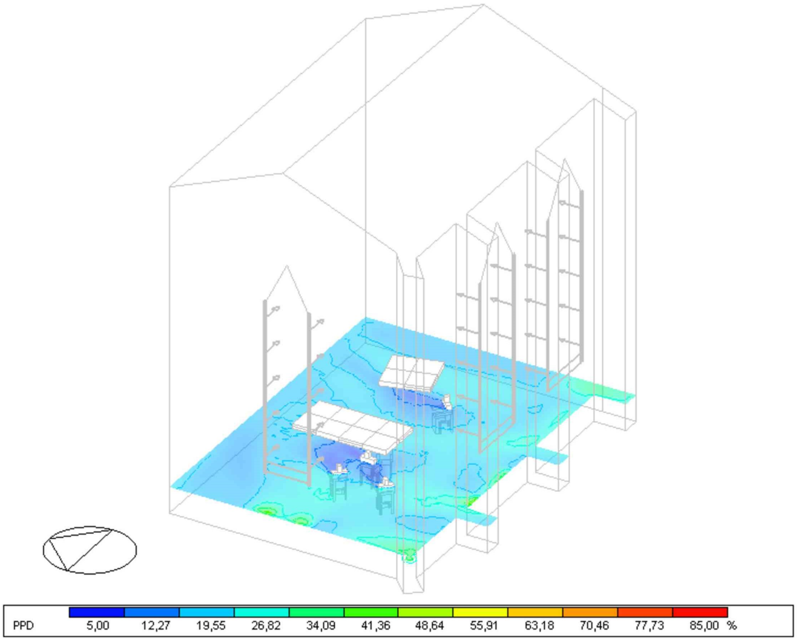


Figure 7.20: Local heating - Thermal simulation PPD - Axonometric view

Introduction local heating with curtains - 05.B

This renovation strategy can be described as a combination of simulation 05.A (*local heating*) and 04.A (*textile box in box with translucent fabric*) in order to increase their impact on thermal comfort improvement even further (figure 7.21).

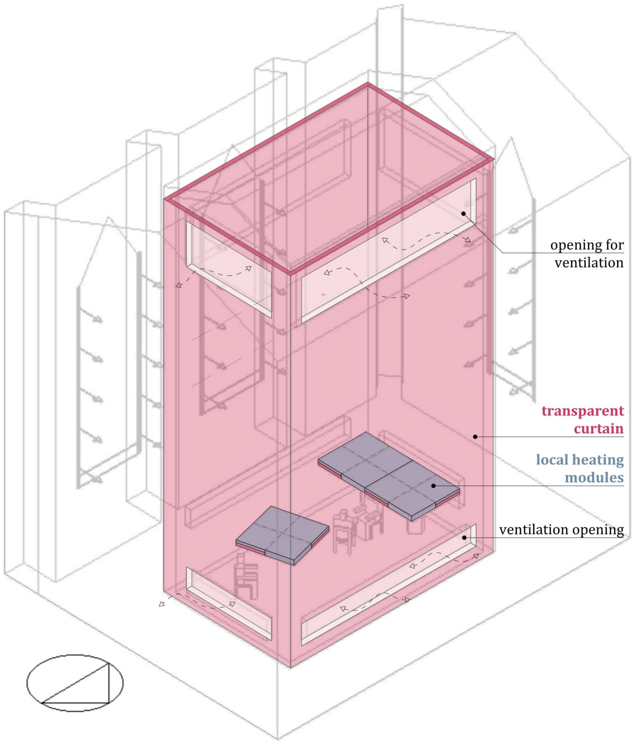


Figure 7.21: Axonometric view 3D model 05.B with local heating modules and curtains

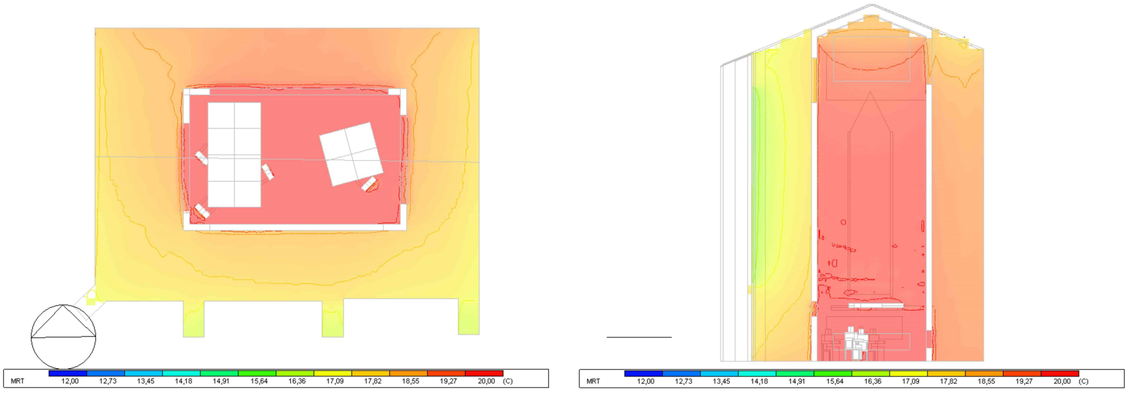


Figure 7.22: Local heating with curtains - Thermal simulation MRT - Plan view (l) and vertical section (r)

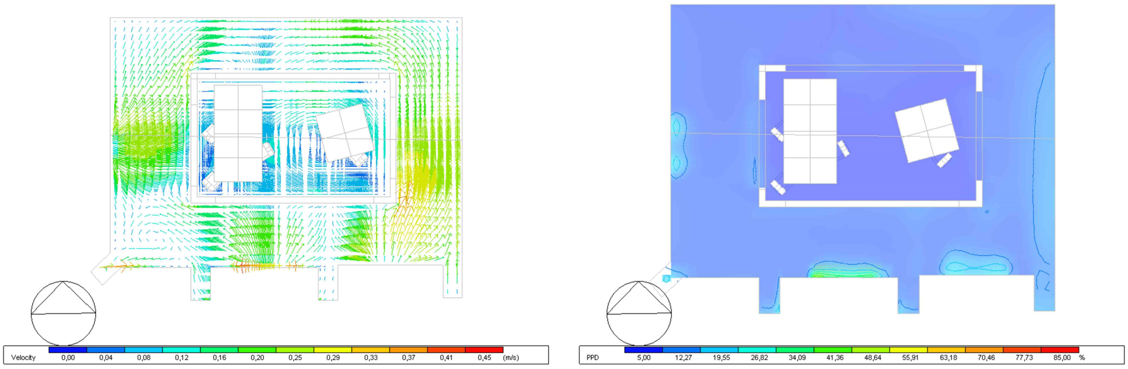


Figure 7.23: Local heating with curtains - Thermal simulation velocity and PPD - Plan view at body height

Visual comparison Basis model:

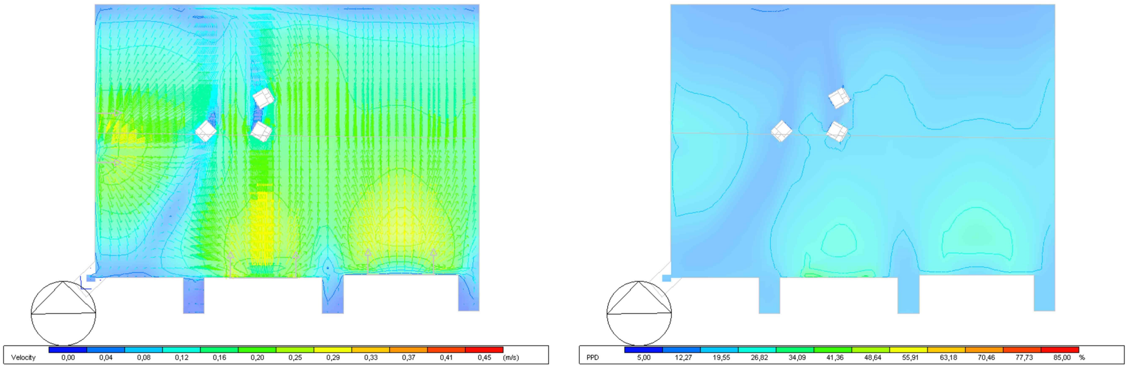


Figure 7.24: Basis model simulation - Plan view air velocity (l) and PPD (r)

Simulation results and conclusion:

The simulation results illustrate how the integration of the heating modules leads to a high local MRT while the vertical textile compartmentalization prevents the dissipation of the heat into the large space (figure 7.22). Furthermore, the air velocity at body height was significantly reduced to 0.10 m/s (figure 7.23 and 7.24 left). According to the simulated PPD, only 7% of the occupants located in the box space would feel discomfort which corresponds to a building class B (ISO, 2005) and represents a very significant thermal comfort improvement compared to the basis situation with a PPD level up to 27% (figure 7.23 and 7.24 right). To conclude, this simulation adaptation shows how a purposeful combination of different renovation strategies can lead to a better outcome.

7.2.5 Vault insulation - 06

Introduction:

This measure is not related to the renovation of the stained glass windows or to spatial adaptation strategies. However, the insulation of the vault has been identified as an effective measure for reducing the heating demand in the Stevenskerk by 25 % (Nusselder & Zandijk, 2015). The application of two layers of aluminium-covered mineral wool with staggered joints was suggested in this previous research. Regarding the concern of condensation, a vapour permeable solution with fibre materials such as Pavaflex could be chosen (Nusselder & Zandijk, 2015). See chapter 9.3.3 and 9.4.1 for more information regarding the application of vault insulation.

In comparison to the work-intensive window renovation the placement of insulation material on top of the vaults in the accessible roof spaces appears as a relatively simple measure. Therefore, the effect of the vault insulation on the thermal comfort was tested by means of thermal simulation.

A 30 cm layer of Rock-wool insulation was added to the roof construction of the *DesignBuilder* basis model of the South chapel, leading to a very well insulated structure with a thermal resistance of 8.5 W/m^{2}K (before: 1.6 W/m^{2}K). Even though it is questionable if mineral wool is the most suitable insulation material for this application, the focus of this simulation is to assess the impact on the thermal comfort which can be assessed independently from the detailed material properties.

MRT:

Although the insulation is applied on the high roof, the thermal simulation illustrates an increase of the MRT in the entire indoor space from 17 °C to 17.8 °C. The comparison of the vertical sections (figure 7.25 and 7.26 right) clearly shows that the reduced MRT level resulting from the cold vault surface temperature disappeared due to the insulation. In this situation mainly the cold surface temperatures of the external walls and windows lead to a reduced MRT. According to the simulation the internal surface temperature of the vault is increased from 16 °C to 18 °C.

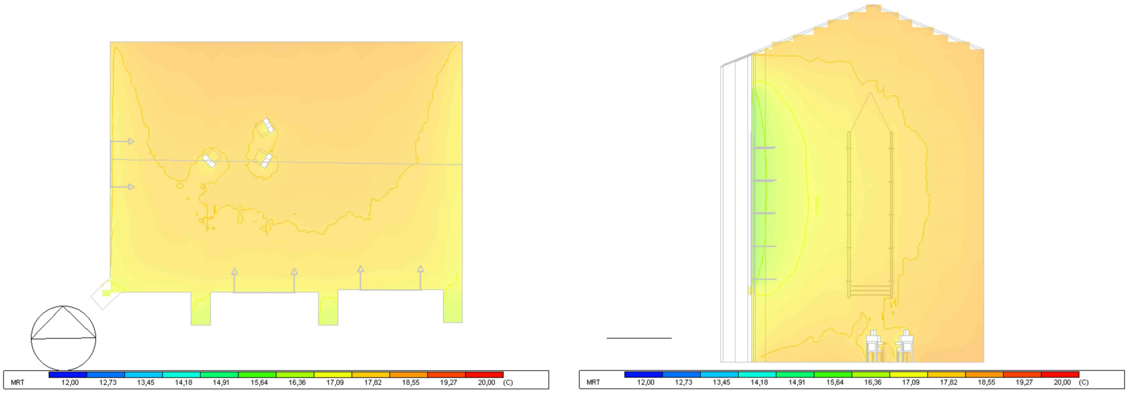


Figure 7.25: Vault insulation - Thermal simulation MRT - Plan view (l) and vertical section location 01 (r)

Visual comparison Basis model:

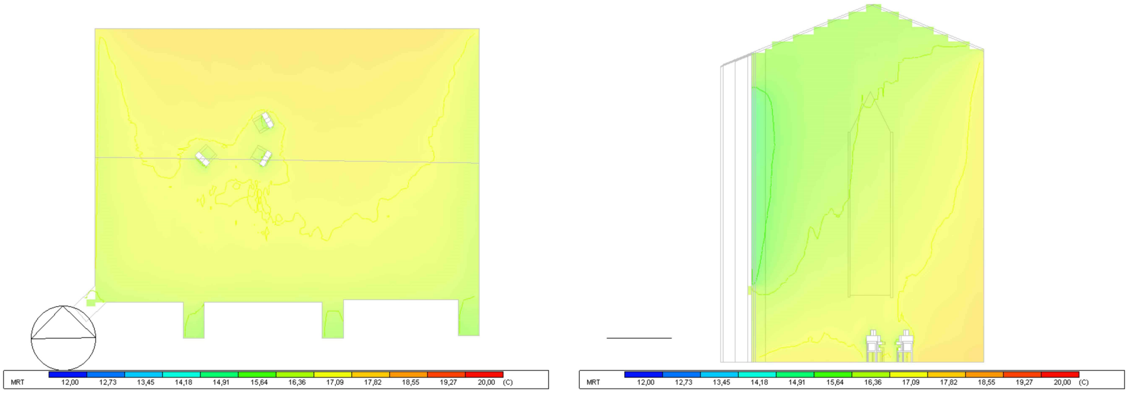


Figure 7.26: Basis model simulation - MRT plan view (l) and section (r)

Velocity and PPD:

It was unexpected that according to the simulation the application of insulation on the roof space even has a beneficial impact on reducing the air velocity stream at body height from 0.25 m/s to 0.10 m/s (figure 7.27 and 7.28 left).

Furthermore, the PPD is decreased to 15 % (Building category C) (figure 7.27 and 7.28 right).

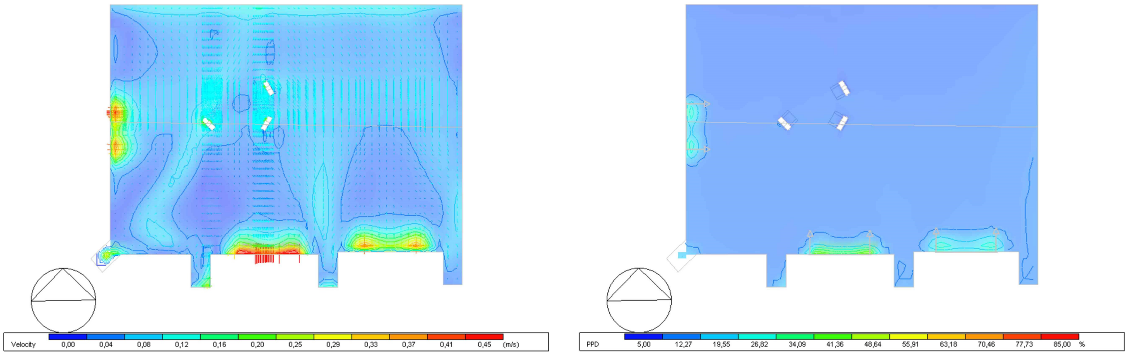


Figure 7.27: Vault insulation - Thermal simulation velocity (l) and PPD (r) - Plan view

Visual comparison Basis model:

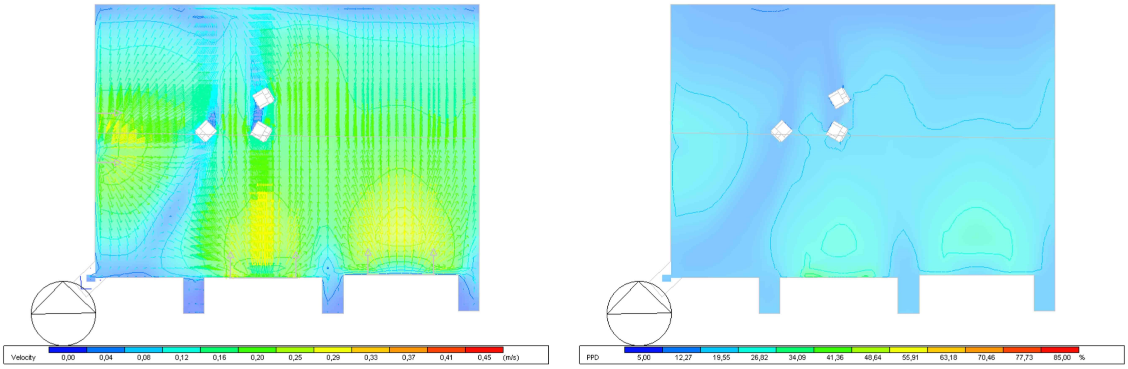


Figure 7.28: Basis model simulation - Plan view air velocity (l) and PPD (r)

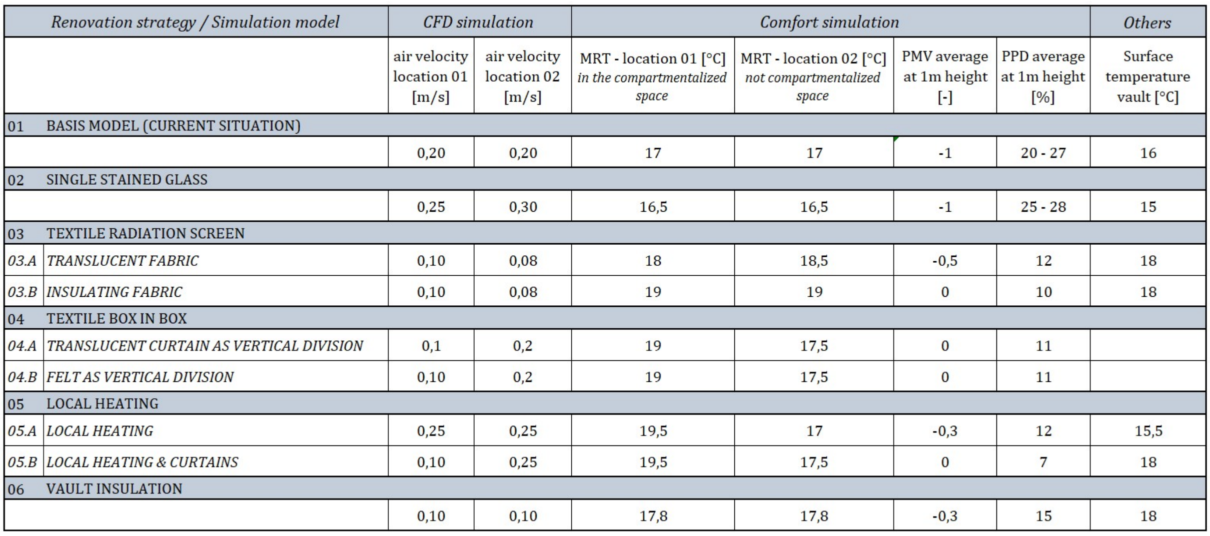
Conclusion:

The computer simulations confirmed the assumption and the outcome of previous research that the application of roof insulation has a considerable positive impact on the thermal comfort in the South chapel. Doubts regarding the limitation of the impact of this intervention due to the high vaulted space were not illustrated in the simulation.

Overall, the vault insulation could be combined together with other introduced renovation strategies to achieve an even more effective thermal comfort improvement.

7.3 Conclusion

The overview of the CFD analysis for the different renovation strategies provides a good basis for the assessment of their effect on thermal comfort improvement. Figure 7.29 provides a short overview of the most significant simulations results for thermal comfort assessment.



Renovation strategy / Simulation model		*CFD simulation*		*Comfort simulation*				*Others*
		air velocity location 01 [m/s]	air velocity location 02 [m/s]	MRT - location 01 [°C] *in the compartmentalized space*	MRT - location 02 [°C] *not compartmentalized space*	PMV average at 1m height [-]	PPD average at 1m height [%]	Surface temperature vault [°C]
01	BASIS MODEL (CURRENT SITUATION)							
		0,20	0,20	17	17	-1	20 - 27	16
02	SINGLE STAINED GLASS							
		0,25	0,30	16,5	16,5	-1	25 - 28	15
03	TEXTILE RADIATION SCREEN							
03.A	*TRANSLUCENT FABRIC*	0,10	0,08	18	18,5	-0,5	12	18
03.B	*INSULATING FABRIC*	0,10	0,08	19	19	0	10	18
04	TEXTILE BOX IN BOX							
04.A	*TRANSLUCENT CURTAIN AS VERTICAL DIVISION*	0,1	0,2	19	17,5	0	11	
04.B	*FELT AS VERTICAL DIVISION*	0,10	0,2	19	17,5	0	11	
05	LOCAL HEATING							
05.A	*LOCAL HEATING*	0,25	0,25	19,5	17	-0,3	12	15,5
05.B	*LOCAL HEATING & CURTAINS*	0,10	0,25	19,5	17,5	0	7	18
06	VAULT INSULATION							
		0,10	0,10	17,8	17,8	-0,3	15	18

Figure 7.29: Table overview simulation results for thermal comfort improvement

During the simulation process it has become clear that a targeted combination of different measures can lead to an even more effective strategy as they tackle different aspects of the problem. Furthermore, the thermal simulations can support decision making for the design process. For example, the analysis has shown that the impact on thermal comfort improvement by the application of a translucent textile is smaller than by insulating textile, however, the effect is still considerable. Thus, after further testing and re-evaluating the renovation objective, the fabric could be chosen in accordance with the aesthetic and the design requirements.

The simulation results were used as an input for the evaluation of the different renovation strategies (chapter 8) and the development of a renovation proposal for the Stevenskerk (chapter 9).

Overall, the simulation results can also serve as an estimation for the influence of renovation measures on the thermal comfort in other buildings which have a similar building structure and are exposed to the same climatic conditions as the Stevenskerk.

8 Evaluation and application strategies

8.1 Evaluation framework

In accordance with the research ambitions, a framework based on several performance criteria and corresponding evaluation parameters was developed for the introduced renovation strategies (figure 8.1 and 8.2). Their assessment based on this framework resulted in a comparable overview in a matrix.

The performance criteria include the functional compatibility, the influence on thermal comfort and the heating demand, the impact on heritage values, the life cycle and durability of the renovation method, financial investment and indoor environmental quality regarding acoustic and lighting performance.

The main objective of this evaluation framework is to enable the comparability of the different measures. Therefore, it is possible to assess some parameters not in a quantitative manner depending on exact numbers, but comparatively to the other strategies. Furthermore, measures which are not suitable because they perform very bad in a specific evaluation criteria can be eliminated.

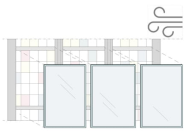
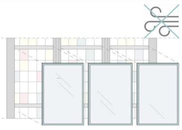
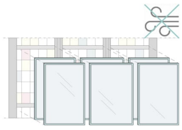
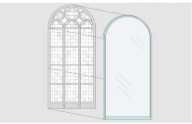
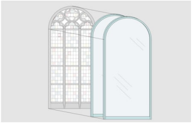
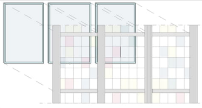
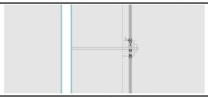
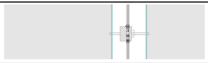
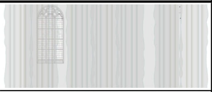
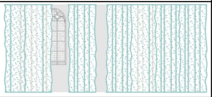
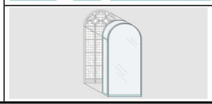
NOW		**0.1**	Single stained glass window *current situation large church space Stevenskerk*	*Single stained glass*
A INTERNAL SECONDARY GLAZING		**A.1**	Secondary single glass cavity ventilated with indoor air *Gerfkamer & Side chapels*	*inside* *stained glass* 10mm ventilated cavity 3mm*safety foil*3mm glass *outside*
		**A.2**	Secondary single glass closed cavity *tested on one window in the Gerfkamer & Side chapels*	*inside* *stained glass* cavity closed 3mm*safety foil*3mm glass *outside*
		**A.3**	Secondary double glazing	*inside* *stained glass* 10mm unventilated cavity 4mm glass 6mm closed window cavity with gas 4mm glass *outside*
B INTERNAL WINDOW		**B.1**	Single glazed window	*inside* *stained glass* 200mm unventilated space thin glass window *outside*
		**B.2**	Double glazed window	*inside* *stained glass* 200mm unventilated space double glazed window *outside*
C EXTERNAL SECONDARY GLAZING		**C.1**	External secondary single glazing *covering the lead connections, fitted between the natural stone frame*	*inside* 3mm*safety foil*3mm glass 200mm unventilated space *stained glass* *outside*
		**C.2**	External secondary double glazing *covering the lead connections, fitted between the natural stone frame*	*inside* 3mm*safety foil*3mm glass 150mm unventilated space *stained glass* *outside*
		**C.3**	Museum arrangement	*inside* Double glazing 10mm ventilated cavity *stained glass* *outside*
		**C.4**	Bonded glazing	*inside* Double glazing with stained glass in the cavity *outside*
D OTHERS		**D.1**	Curtain as radiation screen	*inside* *stained glass* 300mm cavity low emissivity fabric (translucent) *outside*
		**D.2**	Curtain as textile wall insulation	*inside* *stained glass* 50mm cavity insulating fabric (felt) *outside*
		**D.3**	Internal glass box	*inside* stained glass 300mm unventilated space (possibly outside infiltration) 10mm structural glazing box *outside*

Figure 8.1: Tabular overview evaluated window renovation strategies

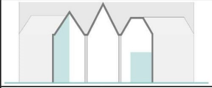
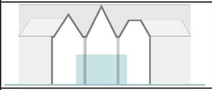
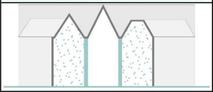
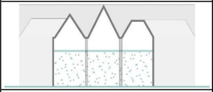
NOW		**0.1**	*DesignBuilder* *South chapel basis model simulation*	
E INDOOR SPACE ADAPTATION		**E.1**	Floorplan adaptation or Zoning the indoor space	permanent internal division(s) and/or built in new storeys and spaces
		**E.2**	Box in Box temporary *(Design Builder simulation 04)*	flexible, temporary tent or box in box structure
		E.3	Box in Box permament	permanent box in box structure
		**E.4**	Vertical division	vertical divison (e. g. textile or glass material) for compartmentalization of the occupied space
		**E.5**	Horizontal division	horizontal transparent disivison (e. g. textile or glass material)
		**E.6**	Local heating modules *(Design Builder simulation 05.A)*	radiative heating panels above the occupied space for localized heating
		**E.7**	Local heating modules in combination with textile vertical division *(Design Builder simulation 05.B)*	radiative heating panels above the occupied space in combination with temporary vertical textile division for localized heating & compartmentalization

Figure 8.2: Tabular overview evaluated spatial adaptation strategies

8.2 Performance criteria and evaluation

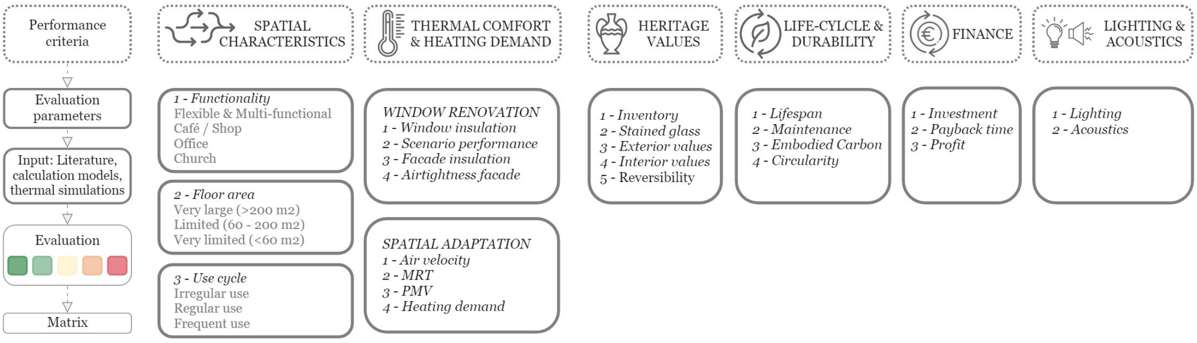


Figure 8.3: Structure evaluation framework

This chapter explains and illustrates the assessment of the renovation strategies according to different performance criteria. Their development was based on the Stevenskerk as a case-study building. In order to enable the application of the evaluation outcome also on other multi-functional and monumental church buildings, these criteria were defined as universal performance parameters.

The evaluation is based on an assessment question and is reviewed according to an evaluation method and classification (figure 8.3). The assessment is based on literature review, measurements taken in the Stevenskerk, physical calculations and thermal simulations with *DB*.

In order to obtain a comprehensive assessment overview a colour code according to the traffic light system was introduced. As the renovation strategies tackle different challenges regarding the thermal comfort in the Stevenskerk the definition of comprehensive assessment parameters which are applicable to all renovation methods was difficult. Therefore, some of the evaluation parameters for the window renovation (A-D) and the spatial adaptation concepts (E) differ.

8.2.1 Spatial characteristics

Functionality:

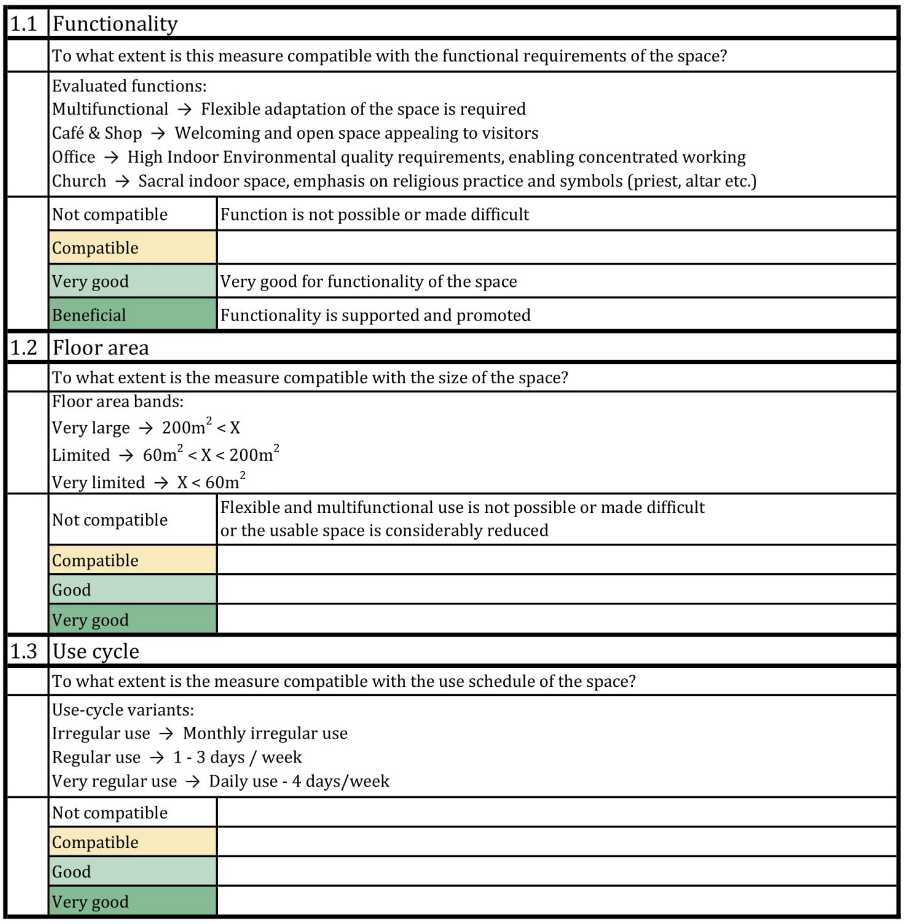
The renovation measure should support the desired functionality of the space to be renovated. Based on the use-cases present in the Stevenskerk different functionalities were defined: *Multi-functional use, cafe and shop, office* and the use as a *church* (figure 8.4). The introduced renovation strategies were evaluated based on their compatibility with those. The further development of the matrix could include other relevant use-cases for multi-functional churches.

Floor area:

According to the available floor area different renovation strategies are more suitable for a space than others (figure 8.4). When the floor area is very limited, for example, the renovation measure should not decrease the usable area. Bands of room sizes were defined as categories for the evaluation.
The more extensive the space to the facade is used (probably small spaces), the more significant are renovation measures focused on the insulation performance of the windows.

Use cycle:

Depending on how regular and how often a space is used, different renovation interventions are more compatible (figure 8.4). Local heating, for example, is very suitable for the application in an irregularly used space as it enables the flexible adaptation of local comfort conditions.

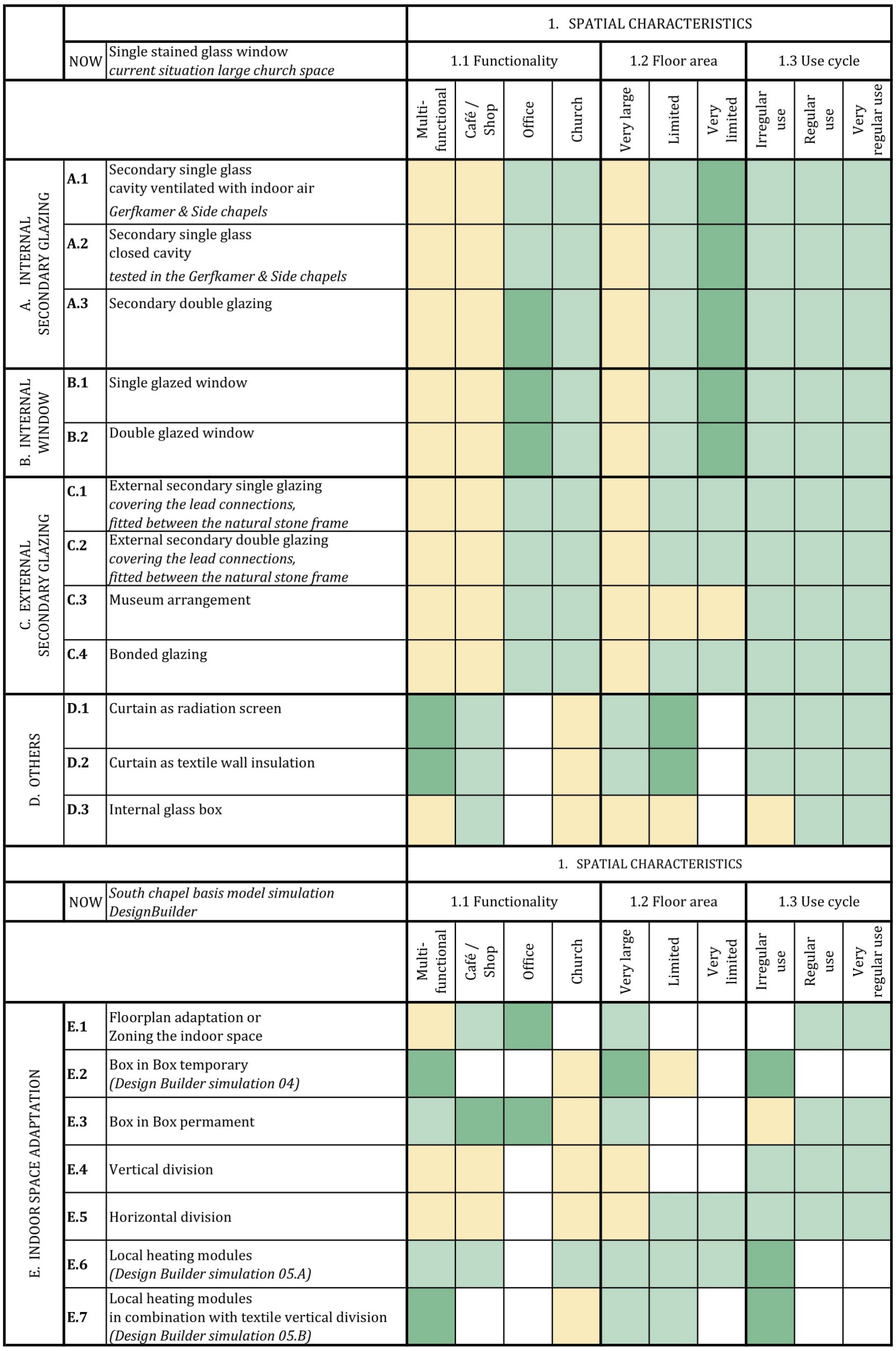


1.1	Functionality	
	To what extent is this measure compatible with the functional requirements of the space?	
	Evaluated functions: Multifunctional → Flexible adaptation of the space is required Café & Shop → Welcoming and open space appealing to visitors Office → High Indoor Environmental quality requirements, enabling concentrated working Church → Sacral indoor space, emphasis on religious practice and symbols (priest, altar etc.)	
	Not compatible	Function is not possible or made difficult
	Compatible	
	Very good	Very good for functionality of the space
	Beneficial	Functionality is supported and promoted
1.2	Floor area	
	To what extent is the measure compatible with the size of the space?	
	Floor area bands: Very large → $200m^2 < X$ Limited → $60m^2 < X < 200m^2$ Very limited → $X < 60m^2$	
	Not compatible	Flexible and multifunctional use is not possible or made difficult or the usable space is considerably reduced
	Compatible	
	Good	
	Very good	
1.3	Use cycle	
	To what extent is the measure compatible with the use schedule of the space?	
	Use-cycle variants: Irregular use → Monthly irregular use Regular use → 1 - 3 days / week Very regular use → Daily use - 4 days/week	
	Not compatible	
	Compatible	
	Good	
	Very good	

Figure 8.4: Evaluation and colour code spatial characteristics

<u>Evaluation overview:</u>

Figure 8.5 illustrates the assessment of the window renovation and indoor space adaptation strategies in regard to the spatial characteristics.



			1. SPATIAL CHARACTERISTICS									
	NOW	Single stained glass window *current situation large church space*	1.1 Functionality				1.2 Floor area			1.3 Use cycle		
			Multi-functional	Café / Shop	Office	Church	Very large	Limited	Very limited	Irregular use	Regular use	Very regular use
A. INTERNAL SECONDARY GLAZING	**A.1**	Secondary single glass cavity ventilated with indoor air *Gerfkamer & Side chapels*	🟨	🟨	🟩	🟩	🟨	🟩	▩	🟩	🟩	🟩
	A.2	Secondary single glass closed cavity *tested in the Gerfkamer & Side chapels*	🟨	🟨	🟩	🟩	🟨	🟩	▩	🟩	🟩	🟩
	A.3	Secondary double glazing	🟨	🟨	▩	🟩	🟨	🟩	▩	🟩	🟩	🟩
B. INTERNAL WINDOW	**B.1**	Single glazed window	🟨	🟨	▩	🟩	🟨	🟩	▩	🟩	🟩	🟩
	B.2	Double glazed window	🟨	🟨	▩	🟩	🟨	🟩	▩	🟩	🟩	🟩
C. EXTERNAL SECONDARY GLAZING	**C.1**	External secondary single glazing *covering the lead connections,* *fitted between the natural stone frame*	🟨	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩
	C.2	External secondary double glazing *covering the lead connections,* *fitted between the natural stone frame*	🟨	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩
	C.3	Museum arrangement	🟨	🟨	🟩	🟩	🟨	🟨	🟨	🟩	🟩	🟩
	C.4	Bonded glazing	🟨	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩
D. OTHERS	**D.1**	Curtain as radiation screen	▩	🟩		🟨	🟩	▩		🟩	🟩	🟩
	D.2	Curtain as textile wall insulation	▩	🟩		🟨	🟩	▩		🟩	🟩	🟩
	D.3	Internal glass box	🟨	🟩		🟨	🟨	🟨		🟨	🟩	🟩
			1. SPATIAL CHARACTERISTICS									
	NOW	*South chapel basis model simulation* *DesignBuilder*	1.1 Functionality				1.2 Floor area			1.3 Use cycle		
			Multi-functional	Café / Shop	Office	Church	Very large	Limited	Very limited	Irregular use	Regular use	Very regular use
E. INDOOR SPACE ADAPTATION	**E.1**	Floorplan adaptation or Zoning the indoor space	🟨	🟩	▩		🟩				🟩	🟩
	E.2	Box in Box temporary *(Design Builder simulation 04)*	▩			🟨	▩	🟨		▩		
	E.3	Box in Box permament	🟩	▩	▩	🟨	🟩			🟨	🟩	🟩
	E.4	Vertical division	🟨	🟨		🟨	🟨			🟩	🟩	🟩
	E.5	Horizontal division	🟨	🟨		🟨	🟨	🟩	🟩	🟩	🟩	🟩
	E.6	Local heating modules *(Design Builder simulation 05.A)*	🟩	🟩		🟩	🟩	🟩	🟩	▩		
	E.7	Local heating modules in combination with textile vertical division *(Design Builder simulation 05.B)*	▩			🟨	🟩	🟩		▩		

Figure 8.5: Matrix evaluation spatial characteristics

8.2.2 Thermal comfort & Heating demand

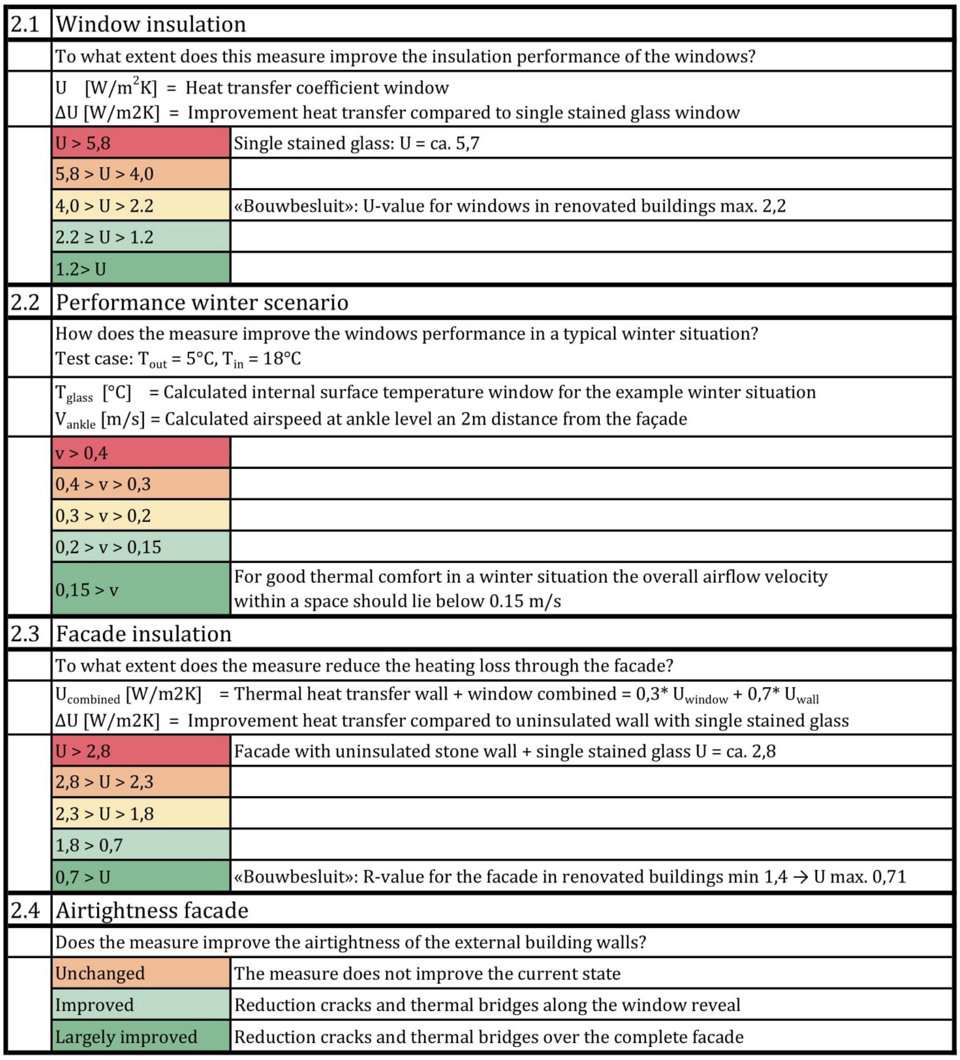
Window renovation (figure 8.6)

Window insulation:
An improved insulation of the windows reduces the heating losses and therefore enables the same indoor air temperature at a lower heating level. This saves energy and reduces the heating time during cold seasons.
The classification of the window performance is based on the comparison to single stained glass and the requirements for renovated buildings according to the Dutch building decree, chapter 5 (*Bouwbesluit 2012 Hoofdstuk 5.*, 2011).

Performance winter scenario:
The assessment values filled in the matrix are based on the physical calculations models (Appendix C). The influence of sun energy or air-heating flows are not considered in the model. Therefore, the surface temperature of the open cavity construction is in this case lower than the surface temperature of the closed cavity. This differs from the measurement data which includes the effect of hot heating air entering the cavity.
The low surface temperatures of the windows lead to radiation asymmetry and an unpleasant downdraft. Formula D.3 (Appendix D) for calculating the air velocity at ankle level is based on a formula from previous research (Menchaca-Brandan, Baranova, Petermann, Koltun, & Mackey, 2017).

Façade insulation:
The reduction of the heating demand in order to reach a comfortable temperature is required for financial and sustainability reasons. This assessment is based on the insulation performance of the building skin which is composed by the heat resistance of the wall and the window and calculated according to a window to wall ratio of 30% in the Stevenskerk (Nusselder & Zandijk, 2015). For other churches this ratio might differ.
The classification of the thermal performance of the façade is based on the comparison to the current situation and the requirements for renovated buildings according to the Dutch building decree, chapter 5 (*Bouwbesluit 2012 Hoofdstuk 5.*, 2011).

Air-tightness facade:
The presence of cracks and air leakages in the building skin mainly along the window reveals as well as the cold bridges of the non-insulated natural stone window frame enable infiltration with cold outdoor air which leads to drafts. The reduction of those drafts improves the thermal comfort level.



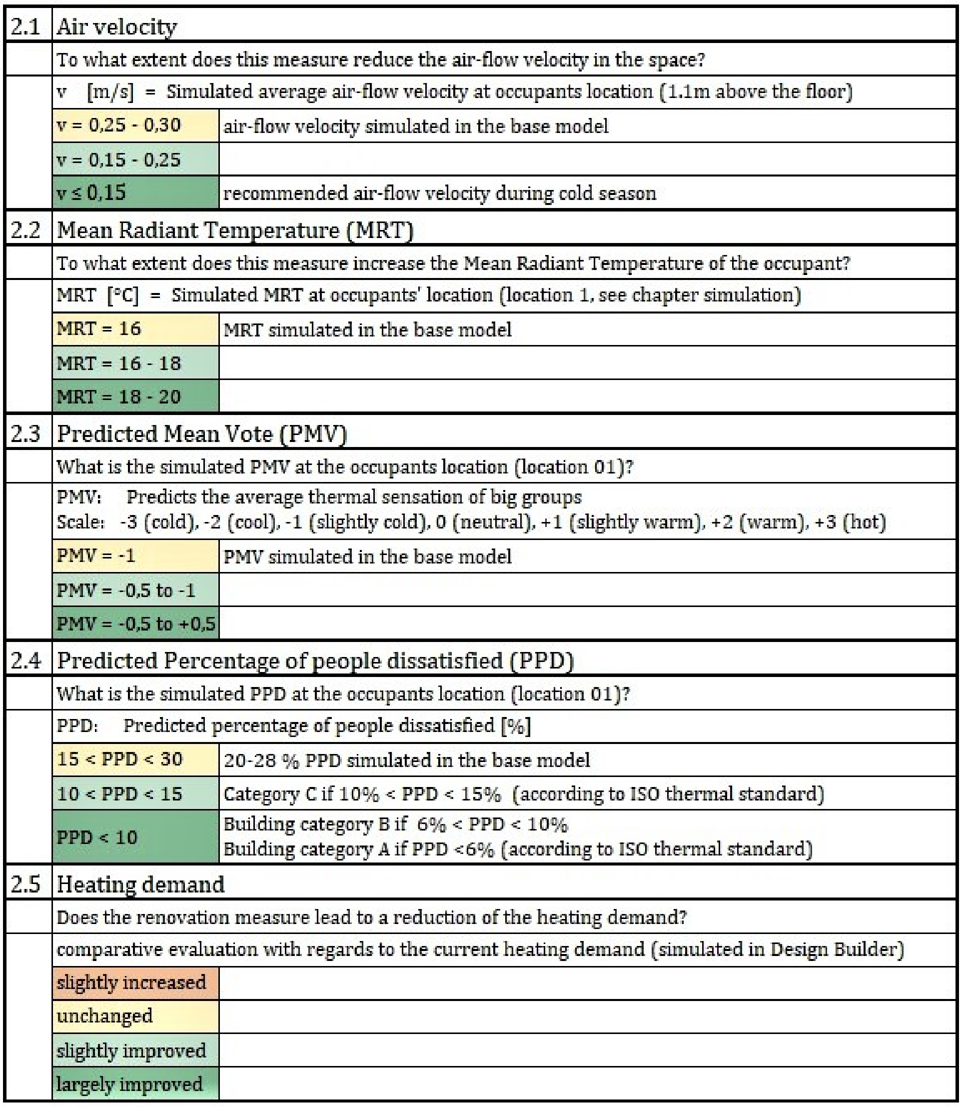
2.1	Window insulation	
	To what extent does this measure improve the insulation performance of the windows?	
	U [W/m^{2}K] = Heat transfer coefficient window ΔU [W/m2K] = Improvement heat transfer compared to single stained glass window	
	U > 5,8	Single stained glass: U = ca. 5,7
	5,8 > U > 4,0	
	4,0 > U > 2.2	«Bouwbesluit»: U-value for windows in renovated buildings max. 2,2
	2.2 ≥ U > 1.2	
	1.2> U	
2.2	Performance winter scenario	
	How does the measure improve the windows performance in a typical winter situation? Test case: T_{out} = 5°C, T_{in} = 18°C	
	T_{glass} [°C] = Calculated internal surface temperature window for the example winter situation V_{ankle} [m/s] = Calculated airspeed at ankle level an 2m distance from the façade	
	v > 0,4	
	0,4 > v > 0,3	
	0,3 > v > 0,2	
	0,2 > v > 0,15	
	0,15 > v	For good thermal comfort in a winter situation the overall airflow velocity within a space should lie below 0.15 m/s
2.3	Facade insulation	
	To what extent does the measure reduce the heating loss through the facade?	
	$U_{combined}$ [W/m2K] = Thermal heat transfer wall + window combined = 0,3* U_{window} + 0,7* U_{wall} ΔU [W/m2K] = Improvement heat transfer compared to uninsulated wall with single stained glass	
	U > 2,8	Facade with uninsulated stone wall + single stained glass U = ca. 2,8
	2,8 > U > 2,3	
	2,3 > U > 1,8	
	1,8 > 0,7	
	0,7 > U	«Bouwbesluit»: R-value for the facade in renovated buildings min 1,4 → U max. 0,71
2.4	Airtightness facade	
	Does the measure improve the airtightness of the external building walls?	
	Unchanged	The measure does not improve the current state
	Improved	Reduction cracks and thermal bridges along the window reveal
	Largely improved	Reduction cracks and thermal bridges over the complete facade

Figure 8.6: Evaluation and colour code thermal comfort and heating demand for window renovation

Spatial adaptation strategies (figure 8.7)

For the spatial adaptation strategies, different performance criteria which were the outcome from the thermal comfort simulations were chosen: The air velocity, the MRT, the PMV, the PPD and the heating demand (figure 8.7). Thus, for the spatial strategies which were no simulated, these criteria were not assessed.

The selected performance criteria are commonly used for the assessment of thermal indoor thermal comfort as they relate to draught, the perceived temperature level and the dissatisfaction of the occupant (Itard & Bluyssen, 2004). Furthermore, the evaluation takes the heating demand in relation to the current demand into account.



2.1	**Air velocity**	
	To what extent does this measure reduce the air-flow velocity in the space?	
	v [m/s] = Simulated average air-flow velocity at occupants location (1.1m above the floor)	
	v = 0,25 - 0,30	air-flow velocity simulated in the base model
	v = 0,15 - 0,25	
	v ≤ 0,15	recommended air-flow velocity during cold season
2.2	**Mean Radiant Temperature (MRT)**	
	To what extent does this measure increase the Mean Radiant Temperature of the occupant?	
	MRT [°C] = Simulated MRT at occupants' location (location 1, see chapter simulation)	
	MRT = 16	MRT simulated in the base model
	MRT = 16 - 18	
	MRT = 18 - 20	
2.3	**Predicted Mean Vote (PMV)**	
	What is the simulated PMV at the occupants location (location 01)?	
	PMV: Predicts the average thermal sensation of big groups Scale: -3 (cold), -2 (cool), -1 (slightly cold), 0 (neutral), +1 (slightly warm), +2 (warm), +3 (hot)	
	PMV = -1	PMV simulated in the base model
	PMV = -0,5 to -1	
	PMV = -0,5 to +0,5	
2.4	**Predicted Percentage of people dissatisfied (PPD)**	
	What is the simulated PPD at the occupants location (location 01)?	
	PPD: Predicted percentage of people dissatisfied [%]	
	15 < PPD < 30	20-28 % PPD simulated in the base model
	10 < PPD < 15	Category C if 10% < PPD < 15% (according to ISO thermal standard)
	PPD < 10	Building category B if 6% < PPD < 10% Building category A if PPD <6% (according to ISO thermal standard)
2.5	**Heating demand**	
	Does the renovation measure lead to a reduction of the heating demand?	
	comparative evaluation with regards to the current heating demand (simulated in Design Builder)	
	slightly increased	
	unchanged	
	slightly improved	
	largely improved	

Figure 8.7: Evaluation and colour code thermal comfort and heating demand for indoor space adaptations

Evaluation overview:

Figure 8.8 illustrates the assessment of the window renovation and indoor space adaptation strategies in regard to the thermal comfort and heating demand.

			2. THERMAL COMFORT & HEATING DEMAND							THERMAL COMFORT & ENERGY DEMAND
	NOW	Single stained glass window *current situation large church space*	5,76		8,3	0,42	2,78		Cracks / Thermal bridges	
			2.1 Window insulation		2.2 Performance winter scenario		2.3 Facade insulation		2.4 Airtightness facade	
			U [W/m^{2}K]	ΔU	T_{glass}[°C]	v_{ankle} [m/s]	$U_{combined}$	ΔU		
A. INTERNAL SECONDARY GLAZING	**A.1**	Secondary single glass cavity ventilated with indoor air *Gerfkamer & Side chapels*	3,98	1,78	14,3	0,26	2,25	0,53	unchanged	🟧
	A.2	Secondary single glass closed cavity *tested in the Gerfkamer & Side chapels*	3,69	2,07	16,1	0,19	2,16	0,62	unchanged	🟨
	A.3	Secondary double glazing	1,01	4,75	16,7	0,16	1,36	1,42	unchanged	🟩
B. INTERNAL WINDOW	**B.1**	Single glazed window	3,02	2,74	14,1	0,27	1,96	0,82	improved	🟨
	B.2	Double glazed window	1,01	4,75	16,7	0,16	1,36	1,42	improved	🟩
C. EXTERNAL SECONDARY GLAZING	**C.1**	External secondary single glazing *covering the lead connections,* *fitted between the natural stone frame*	3,69	2,07	16,1	0,19	2,16	0,62	unchanged	🟧
	C.2	External secondary double glazing *covering the lead connections,* *fitted between the natural stone frame*	1,01	4,75	16,7	0,16	1,36	1,42	unchanged	🟩
	C.3	Museum arrangement	1,49	4,26			1,51	1,28	unchanged	🟨
	C.4	Bonded glazing	2,78	2,98			1,89	0,89	unchanged	🟧
D. OTHERS	**D.1**	Curtain as radiation screen	4,88	0,88	13,2	0,29	2,52	0,26	largely improved	🟨
	D.2	Curtain as textile wall insulation	2,51	3,25	13,8	0,28	1,81	0,97	largely improved	🟨
	D.3	Internal glass box	1,01	4,75	16,7	0,16	1,36	1,42	improved	🟩

			2. THERMAL COMFORT & HEATING DEMAND					THERMAL COMFORT & ENERGY DEMAND
	NOW	*South chapel basis model simulation DesignBuilder*	0,25 - 0,30	16	-1	20 - 28	basis	
			2.1 Air velocity [m/s]	2.2 MRT [°C]	2.3 PMV *(-3 to +3)*	2.4 PPD [%]	2.5 Heating demand	
E. INDOOR SPACE ADAPTATION	**E.1**	Floorplan adaptation or Zoning the indoor space	*no thermal comfort simulations performed*					
	E.2	Box in Box temporary *(Design Builder simulation 04)*	0,15	19	0	11	unchanged	🟩
	E.3	Box in Box permament	*no thermal comfort simulations performed*					
	E.4	Vertical division	*no thermal comfort simulations performed*					
	E.5	Horizontal division	*no thermal comfort simulations performed*					
	E.6	Local heating modules *(Design Builder simulation 05.A)*	0,25	19,5	-0,3	12	locally increased	🟩
	E.7	Local heating modules in combination with textile vertical division *(Design Builder simulation 05.B)*	0,10	19,5	0	7	locally increased	🟩

Figure 8.8: Matrix evaluation thermal comfort and heating demand

8.2.3 Heritage values

Conservation risks for building and inventory:

A stable temperature and RH level (40 - 60%) on building level have been identified as suitable circumstances for preserving monuments and their inventory (see chapter 3 and 4). Thus, the renovation measure should enable the compliance with these boundary conditions (figure 8.9). A good insulation performance of the building skin means that the room temperature can be kept on the same level with less heating which also leads to a more stable RH level. Therefore, the assessment of this criterion is also related to the criteria *2.1 Window insulation* and *2.3 Facade insulation* (figure 8.6).

Conservation stained glass windows:

Renovation strategies applied on the stained glass windows change the building physical conditions. They might increase the risk for condensation which is a disadvantage for the conservation of the stained glass windows as it can lead to damage on the lead, the connections, the coloured glass or adjacent building components. Furthermore, the change of the position of the stained glass window can lead to damages. Additionally, outside degradation can occur without external protection of the windows.

Exterior monumental values:

The most significant monumental values of the Stevenskerk which are visible from the outside contain the plasticity of the façade, the visibility and fragmentation of the lead windows. These elements have been identified during the heritage value analysis and by means of the heritage values matrix (see chapter 3). The conservation of those elements is significant for the role of the Stevenskerk as an iconic historic building in the center of Nijmegen (figure 8.9).

Interior monumental values:

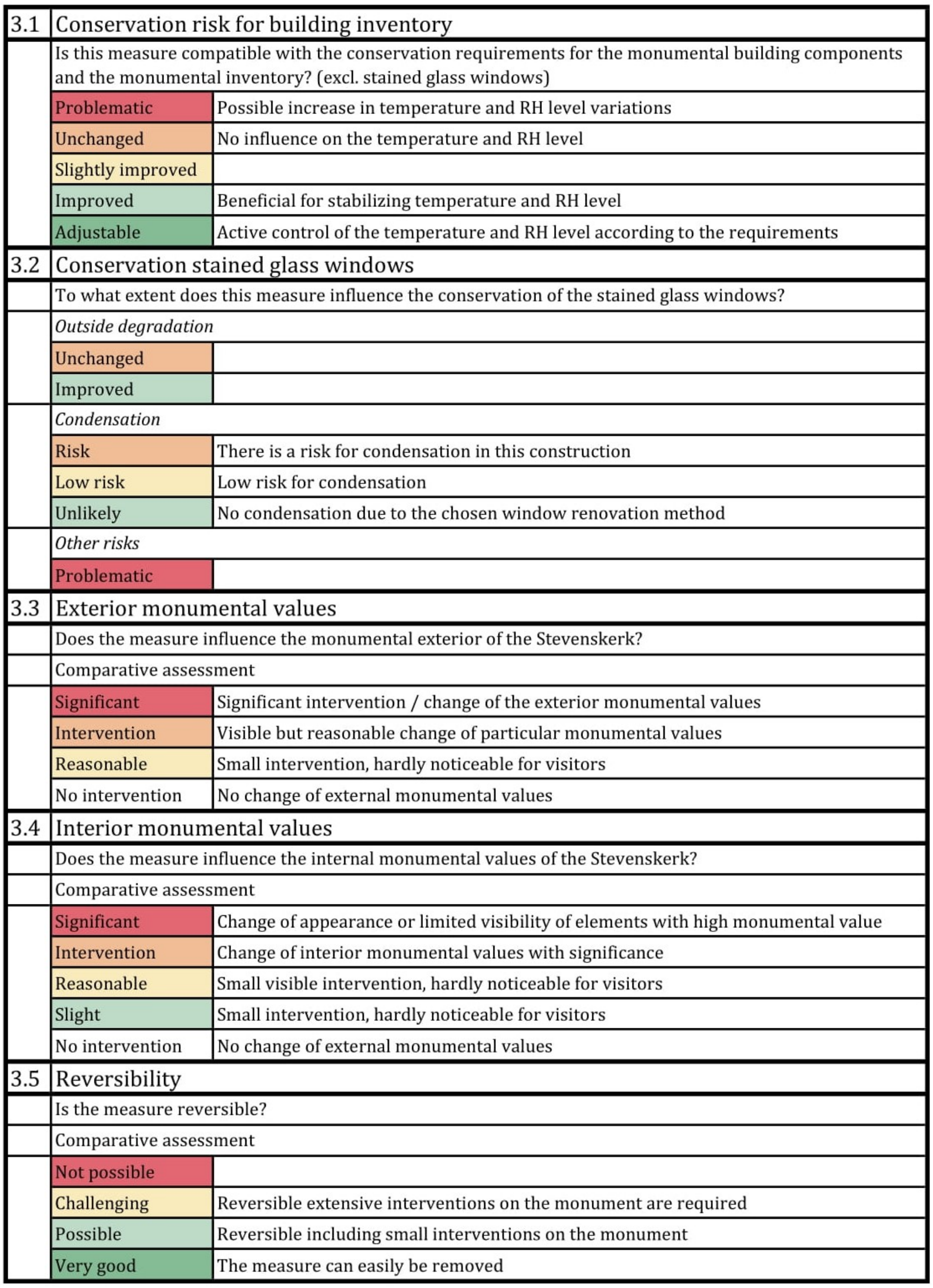
The visibility of the monumental inventory and the monumental building elements is crucial for the Stevenskerk and, thus, should be visually and spatially experienced by the visitors. The most significant monumental building values include the indoor spatial impression (high vaults, pillars), the large open space, the floorplan of the church, the sacral atmosphere of the indoor space and the lighting experience. The monumental inventory with high monumental value includes the organs, tomb stones and wall paintings. From the heritage conservation point of view the least intervention on those values is preferable (figure 8.9).

Reversibility:

Dependent on the impact caused by the renovation measure as well as the monumental significance of the affected building component its reversibility might be a requirement for the application in the Stevenskerk or another monumental church. According to the Burra Charter: *«Changes which reduce cultural significance should be reversible, and be reversed when circumstances permit.»* (Australian National Committee of ICOMOS, 2013)

Furthermore, the weighting of the parameters influencing the significance of a monumental attribute can change over time leading to changing requirements for the building components. The stained glass windows for example, which are currently not part of the monumental description could become part of it leading to the necessity to change them back to their original condition. Furthermore, the function of the church could change leading to an adaptation of the spatial requirements as well.

Therefore, from a heritage conservation perspective, the reversibility of the renovation measure is desired (figure 8.9).

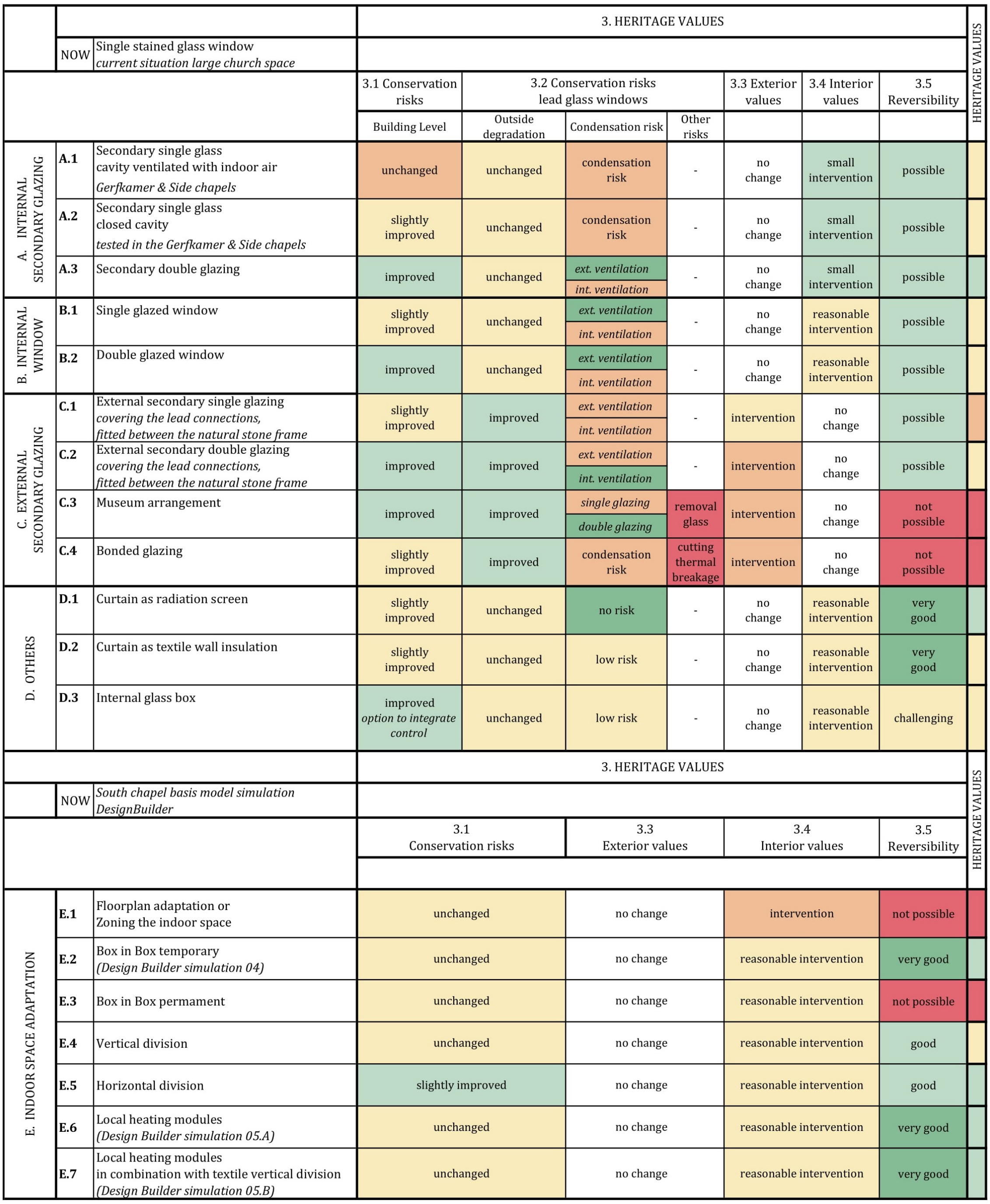


3.1	Conservation risk for building inventory	
	Is this measure compatible with the conservation requirements for the monumental building components and the monumental inventory? (excl. stained glass windows)	
	Problematic	Possible increase in temperature and RH level variations
	Unchanged	No influence on the temperature and RH level
	Slightly improved	
	Improved	Beneficial for stabilizing temperature and RH level
	Adjustable	Active control of the temperature and RH level according to the requirements
3.2	Conservation stained glass windows	
	To what extent does this measure influence the conservation of the stained glass windows?	
	Outside degradation	
	Unchanged	
	Improved	
	Condensation	
	Risk	There is a risk for condensation in this construction
	Low risk	Low risk for condensation
	Unlikely	No condensation due to the chosen window renovation method
	Other risks	
	Problematic	
3.3	Exterior monumental values	
	Does the measure influence the monumental exterior of the Stevenskerk?	
	Comparative assessment	
	Significant	Significant intervention / change of the exterior monumental values
	Intervention	Visible but reasonable change of particular monumental values
	Reasonable	Small intervention, hardly noticeable for visitors
	No intervention	No change of external monumental values
3.4	Interior monumental values	
	Does the measure influence the internal monumental values of the Stevenskerk?	
	Comparative assessment	
	Significant	Change of appearance or limited visibility of elements with high monumental value
	Intervention	Change of interior monumental values with significance
	Reasonable	Small visible intervention, hardly noticeable for visitors
	Slight	Small intervention, hardly noticeable for visitors
	No intervention	No change of external monumental values
3.5	Reversibility	
	Is the measure reversible?	
	Comparative assessment	
	Not possible	
	Challenging	Reversible extensive interventions on the monument are required
	Possible	Reversible including small interventions on the monument
	Very good	The measure can easily be removed

Figure 8.9: Evaluation and colour code heritage values

Evaluation overview:

Figure 8.10 illustrates the assessment of the window renovation and indoor space adaptation strategies in regard to the conservation of heritage values.



			3. HERITAGE VALUES							HERITAGE VALUES
	NOW	Single stained glass window *current situation large church space*								
			3.1 Conservation risks	3.2 Conservation risks lead glass windows			3.3 Exterior values	3.4 Interior values	3.5 Reversibility	
			Building Level	Outside degradation	Condensation risk	Other risks				
A. INTERNAL SECONDARY GLAZING	**A.1**	Secondary single glass cavity ventilated with indoor air *Gerfkamer & Side chapels*	unchanged	unchanged	condensation risk	-	no change	small intervention	possible	🟨
	A.2	Secondary single glass closed cavity *tested in the Gerfkamer & Side chapels*	slightly improved	unchanged	condensation risk	-	no change	small intervention	possible	🟨
	A.3	Secondary double glazing	improved	unchanged	*ext. ventilation* *int. ventilation*	-	no change	small intervention	possible	🟩
B. INTERNAL WINDOW	**B.1**	Single glazed window	slightly improved	unchanged	*ext. ventilation* *int. ventilation*	-	no change	reasonable intervention	possible	🟨
	B.2	Double glazed window	improved	unchanged	*ext. ventilation* *int. ventilation*	-	no change	reasonable intervention	possible	🟨
C. EXTERNAL SECONDARY GLAZING	**C.1**	External secondary single glazing *covering the lead connections,* *fitted between the natural stone frame*	slightly improved	improved	*ext. ventilation* *int. ventilation*	-	intervention	no change	possible	🟧
	C.2	External secondary double glazing *covering the lead connections,* *fitted between the natural stone frame*	improved	improved	*ext. ventilation* *int. ventilation*	-	intervention	no change	possible	🟨
	C.3	Museum arrangement	improved	improved	*single glazing* *double glazing*	removal glass	intervention	no change	not possible	🟥
	C.4	Bonded glazing	slightly improved	improved	condensation risk	cutting thermal breakage	intervention	no change	not possible	🟥
D. OTHERS	**D.1**	Curtain as radiation screen	slightly improved	unchanged	no risk	-	no change	reasonable intervention	very good	🟩
	D.2	Curtain as textile wall insulation	slightly improved	unchanged	low risk	-	no change	reasonable intervention	very good	🟨
	D.3	Internal glass box	improved *option to integrate control*	unchanged	low risk	-	no change	reasonable intervention	challenging	🟨

			3. HERITAGE VALUES				HERITAGE VALUES
	NOW	*South chapel basis model simulation DesignBuilder*					
			3.1 Conservation risks	3.3 Exterior values	3.4 Interior values	3.5 Reversibility	
E. INDOOR SPACE ADAPTATION	**E.1**	Floorplan adaptation or Zoning the indoor space	unchanged	no change	intervention	not possible	🟥
	E.2	Box in Box temporary *(Design Builder simulation 04)*	unchanged	no change	reasonable intervention	very good	🟩
	E.3	Box in Box permament	unchanged	no change	reasonable intervention	not possible	🟥
	E.4	Vertical division	unchanged	no change	reasonable intervention	good	🟨
	E.5	Horizontal division	slightly improved	no change	reasonable intervention	good	🟩
	E.6	Local heating modules *(Design Builder simulation 05.A)*	unchanged	no change	reasonable intervention	very good	🟩
	E.7	Local heating modules in combination with textile vertical division *(Design Builder simulation 05.B)*	unchanged	no change	reasonable intervention	very good	🟩

Figure 8.10: Matrix evaluation heritage values

8.2.4 Life cycle & Durability

Lifespan:

The longer the estimated lifespan of the measure, the more attractive becomes the financial investment for the strategy because as long as the measure is functioning no further investment apart from the maintenance is necessary (figure 8.11). Most importantly, the estimated lifespan should be higher than the estimated payback period of the evaluated measure. Additionally, a measure with the same level of embodied carbon also becomes more sustainable when the lifespan is longer.

Nonetheless, to some extent it could be advantageous to select a renovation strategy with a shorter lifespan as this enables the possibility to think about new strategies for the monument and develop new ideas when the requirements change. In this case the parameters re-usability and circularity of the used materials become important. As it is difficult to predict the lifespan for some of the strategies it is indicated as a range.

Maintenance:

Building components which can easily be maintained have a longer lifespan because they can be cleaned, maintained or repaired and broken elements can be replaced instead of replacing the whole system. This leads to slower degradation of the building components and is therefore related to the sustainability of the renovation method. The feasibility of maintenance includes the accessibility and the option for disassembly. This is related to the detailing of the building component and therefore difficult to assess during this phase of the project. Therefore, this evaluation is based on the feasibility of maintenance compared to the other strategies (figure 8.11).

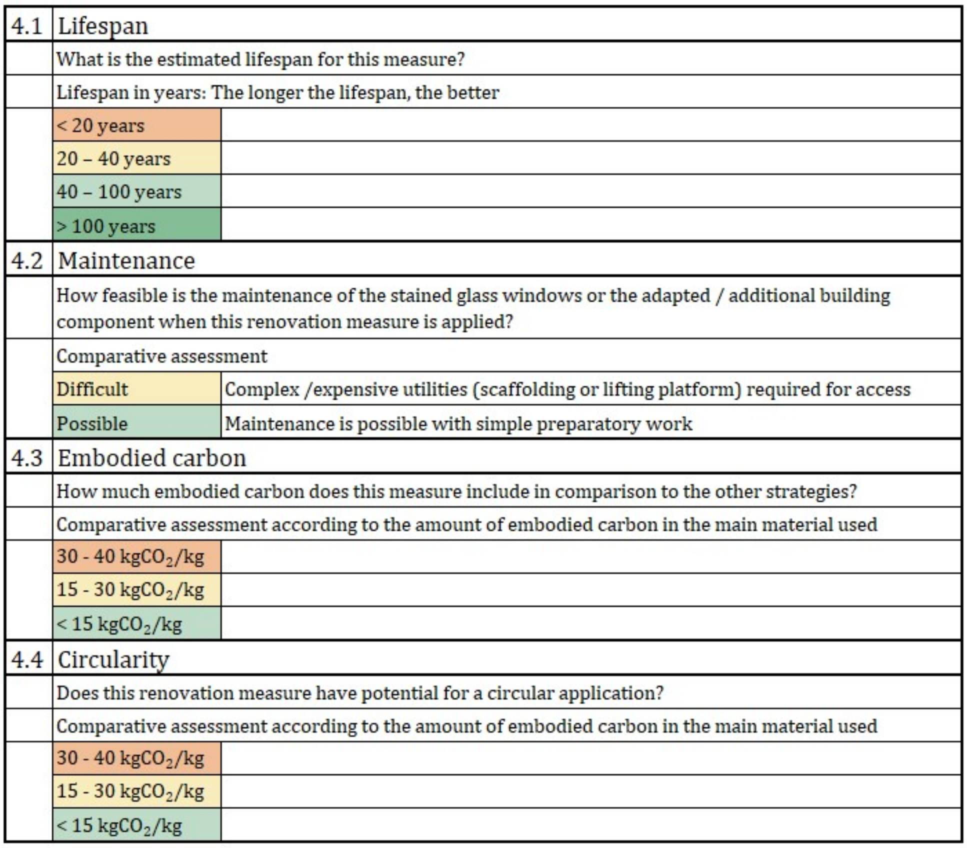
Embodied carbon material:

«Embodied carbon is the carbon dioxide (CO2) emissions associated with materials and construction processes throughout the whole life-cycle. It includes any CO2 created during the manufacturing of building materials (material extraction, transport to manufacturer, manufacturing), the transport of those materials to the job site, and the construction practices used.»(Cure, 2020).

Therefore, materials with a low embodied carbon are more sustainable and the re-use of old materials has a better CO2 balance than the use of virgin materials. This evaluation considers the main material(s) used in the renovation method and assesses its embodied carbon in comparison to the other materials used. This assessment was only done for those strategies where the main material can be defined at this stage of the project.

Circularity:

A circular building component could be dismounted and dismantled for re-use in another project when it becomes unnecessary in its current function. Thus, this evaluation parameter is closely related to *the reversibility of the renovation measure (3.5)* which was introduced with regards to its significance for the monument conservation. For sustainability reasons the application of a circular building system is desired (figure 8.11). This potential depends on the detailing of the building component but also on the type of materials used.



4.1	Lifespan	
	What is the estimated lifespan for this measure?	
	Lifespan in years: The longer the lifespan, the better	
	< 20 years	
	20 – 40 years	
	40 – 100 years	
	> 100 years	
4.2	Maintenance	
	How feasible is the maintenance of the stained glass windows or the adapted / additional building component when this renovation measure is applied?	
	Comparative assessment	
	Difficult	Complex /expensive utilities (scaffolding or lifting platform) required for access
	Possible	Maintenance is possible with simple preparatory work
4.3	Embodied carbon	
	How much embodied carbon does this measure include in comparison to the other strategies?	
	Comparative assessment according to the amount of embodied carbon in the main material used	
	30 - 40 kgCO$_2$/kg	
	15 - 30 kgCO$_2$/kg	
	< 15 kgCO$_2$/kg	
4.4	Circularity	
	Does this renovation measure have potential for a circular application?	
	Comparative assessment according to the amount of embodied carbon in the main material used	
	30 - 40 kgCO$_2$/kg	
	15 - 30 kgCO$_2$/kg	
	< 15 kgCO$_2$/kg	

Figure 8.11: Evaluation and colour code life cycle and durability

Evaluation overview:

Figure 8.12 illustrates the assessment of the window renovation and indoor space adaptation strategies in regard to their life cycle and durability.

			4. LIFE CYCLE & DURABILITY				DURABILITY
	NOW	Single stained glass window *current situation large church space*					
			4.1 Lifespan	4.2 Maintenance	4.3 Embodied Carbon	4.4 Circularity	
					EC [kgCO2/m^2 or kg]		
A. INTERNAL SECONDARY GLAZING	**A.1**	Secondary single glass cavity ventilated with indoor air *Gerfkamer & Side chapels*	40 - 100	difficult	21,6/m^2 6mm single glazing, ex frame	possible	🟩
	A.2	Secondary single glass closed cavity *tested in the Gerfkamer & Side chapels*	40 - 100	difficult	21,6/m2 6mm single glazing, ex frame	possible	🟩
	A.3	Secondary double glazing	20 -40	difficult	32,5/m2 8mm double glazing, ex cavity & frame	difficult	🟧
B. INTERNAL WINDOW	**B.1**	Single glazed window	40 - 100	difficult	21,6/m2 6mm single glazing, ex frame	possible	🟨
	B.2	Double glazed window	20 - 40	difficult	32,5/m2 8mm double glazing, ex cavity, ex frame	difficult	🟧
C. EXTERNAL SECONDARY GLAZING	**C.1**	External secondary single glazing *covering the lead connections,* *fitted between the natural stone frame*	40 - 100	difficult	21,6/m2 6mm single glazing, ex frame	possible	🟨
	C.2	External secondary double glazing *covering the lead connections,* *fitted between the natural stone frame*	20 - 40	difficult	32,5/m2 8mm double glazing, ex cavity, ex frame	difficult	🟨
	C.3	Museum arrangement	40 - 100	difficult	32,5/m2 8mm double glazing, ex cavity, ex frame	difficult	🟨
	C.4	Bonded glazing	40 - 100	difficult	32,5/m2 8mm double glazing, ex cavity, ex frame	difficult	🟨
D. OTHERS	**D.1**	Curtain as radiation screen	< 20	possible		possible	🟨
	D.2	Curtain as textile wall insulation	< 20	possible	11/m^2 wool	possible	🟩
	D.3	Internal glass box	20 - 40	difficult	32,5 8mm double glazing, ex cavity, ex frame	difficult	🟧
			4. LIFE CYCLE & DURABILITY				DURABILITY
	NOW	*South chapel basis model simulation DesignBuilder*					
			4.1 Lifespan	4.2 Maintenance		4.4 Circularity	
E. INDOOR SPACE ADAPTATION	**E.1**	Floorplan adaptation or Zoning the indoor space	40 - 100	possible		difficult	🟨
	E.2	Box in Box temporary *(Design Builder simulation 04)*	< 20	possible		possible	🟨
	E.3	Box in Box permament	40- 100	possible		possible	🟨
	E.4	Vertical division	20 - 40	possible		possible	🟨
	E.5	Horizontal division	20 - 40	difficult		possible	🟨
	E.6	Local heating modules *(Design Builder simulation 05.A)*	20 - 40	possible		possible	🟨
	E.7	Local heating modules in combination with textile vertical division *(Design Builder simulation 05.B)*	20 - 40	possible		possible	🟨

Figure 8.12: Matrix evaluation life cycle and durability

8.2.5 Finance

Investment costs:

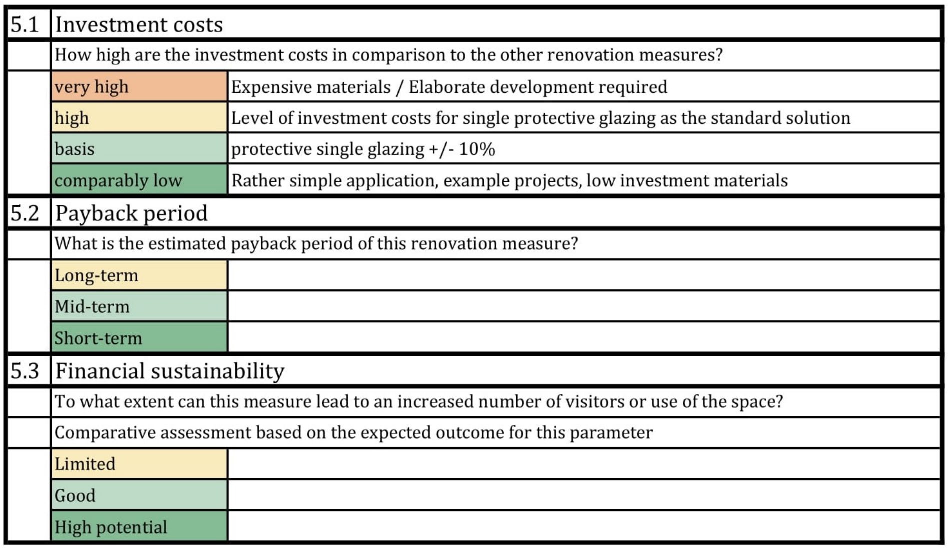
The proposed measure has to be be economically realizable for the *Stichting* of the Stevenskerk or the building owner of other churches. Less expensive measures could be realized more easy than very expensive strategies (figure 8.13).

Payback period:

The payback period is calculated by the estimated financial investment divided by the financial gains from this strategy. Both of these parameters are difficult to predict and therefore this evaluation is based on the difference of payback periods between the different measures but does not give an exact estimation of the payback period for the different strategies. When assessing the payback period more in detail different parameters such as the estimated savings by the reduced heating demand and the additional gains by increased visitors need to be considered.

Financial sustainability:

The renovation strategy could lead to an increase in the income of the building owner via entrance fees as one objective is to increase the accessibility by opening the church during the whole year (figure 8.13). Additionally, the improved thermal conditions would lead to an increase of the number of days when the spaces can be rented. Furthermore, the application of innovative renovation methods can increase the attraction of the Stevenskerk or another multi-functional church for a larger number of visitors paying entrance fee or donating to the Stichting. Additionally to the financial benefit of the increase in the number of visitors this would lead to an improved visibility of this monument in the society which is a cultural gain that can not be measured.



5.1	Investment costs	
	How high are the investment costs in comparison to the other renovation measures?	
	very high	Expensive materials / Elaborate development required
	high	Level of investment costs for single protective glazing as the standard solution
	basis	protective single glazing +/- 10%
	comparably low	Rather simple application, example projects, low investment materials
5.2	Payback period	
	What is the estimated payback period of this renovation measure?	
	Long-term	
	Mid-term	
	Short-term	
5.3	Financial sustainability	
	To what extent can this measure lead to an increased number of visitors or use of the space?	
	Comparative assessment based on the expected outcome for this parameter	
	Limited	
	Good	
	High potential	

Figure 8.13: Evaluation and colour code finance

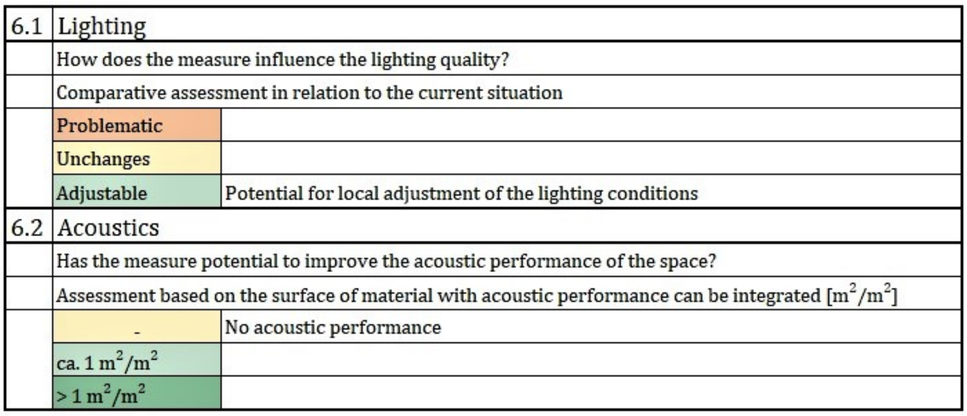
8.2.6 Lighting & Acoustics

Lighting:

As the daylight entrance reduces the need for artificial lighting and creates a pleasant indoor space it is desired to achieve the same natural daylight income as in the current situation or to keep the reduction of the natural daylight income at a low level (figure 8.14). Additionally, the measures could include an option for the adjustment of the natural daylight income or an additional lighting source for he space according to the current use.

Acoustics:

An improved acoustic performance of the enclosing surfaces by reducing reverberation-time, absorbing sound and improving comprehension leads to a more comfortable noise level and promotes the use of the space for concerts or other acoustic performances (figure 8.14).
This parameter is assessed according to the area of acoustic performing surface which can be integrated per m^2 floor surface when this strategy is applied.

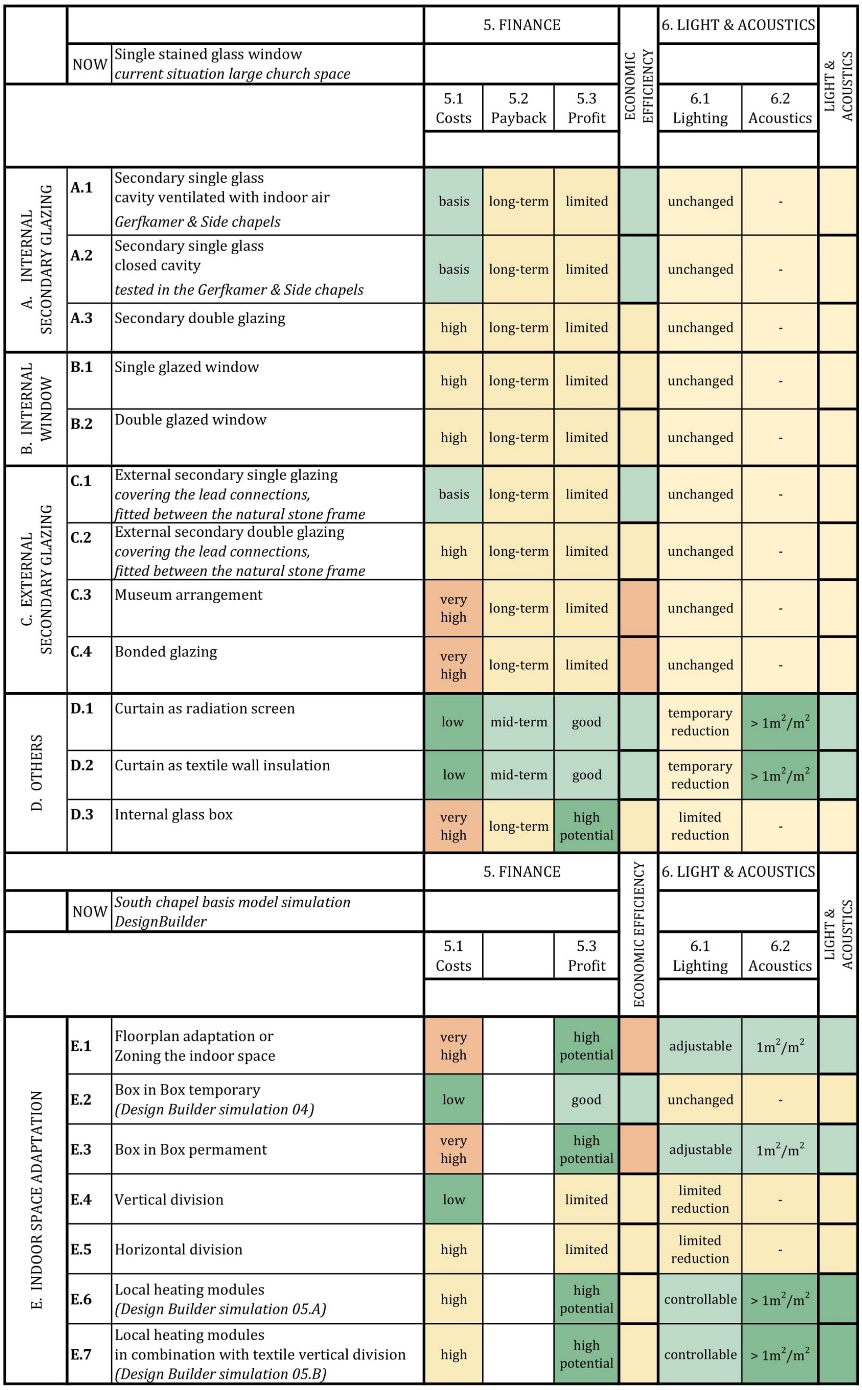


6.1	Lighting	
	How does the measure influence the lighting quality?	
	Comparative assessment in relation to the current situation	
	Problematic	
	Unchanges	
	Adjustable	Potential for local adjustment of the lighting conditions
6.2	Acoustics	
	Has the measure potential to improve the acoustic performance of the space?	
	Assessment based on the surface of material with acoustic performance can be integrated [m^2/m^2]	
	-	No acoustic performance
	ca. 1 m^2/m^2	
	> 1 m^2/m^2	

Figure 8.14: Evaluation and colour code lighting and acoustics

Evaluation overview:

Figure 8.15 illustrates the assessment of the window renovation and indoor space adaptation strategies in regard to their financial feasibility as well as their lighting and acoustic performance.



			5. FINANCE			ECONOMIC EFFICIENCY	6. LIGHT & ACOUSTICS		LIGHT & ACOUSTICS
	NOW	Single stained glass window *current situation large church space*							
			5.1 Costs	5.2 Payback	5.3 Profit		6.1 Lighting	6.2 Acoustics	
A. INTERNAL SECONDARY GLAZING	**A.1**	Secondary single glass cavity ventilated with indoor air *Gerfkamer & Side chapels*	basis	long-term	limited	🟩	unchanged	-	🟨
	A.2	Secondary single glass closed cavity *tested in the Gerfkamer & Side chapels*	basis	long-term	limited	🟩	unchanged	-	🟨
	A.3	Secondary double glazing	high	long-term	limited	🟨	unchanged	-	🟨
B. INTERNAL WINDOW	**B.1**	Single glazed window	high	long-term	limited	🟨	unchanged	-	🟨
	B.2	Double glazed window	high	long-term	limited	🟨	unchanged	-	🟨
C. EXTERNAL SECONDARY GLAZING	**C.1**	External secondary single glazing *covering the lead connections, fitted between the natural stone frame*	basis	long-term	limited	🟩	unchanged	-	🟨
	C.2	External secondary double glazing *covering the lead connections, fitted between the natural stone frame*	high	long-term	limited	🟨	unchanged	-	🟨
	C.3	Museum arrangement	very high	long-term	limited	🟧	unchanged	-	🟨
	C.4	Bonded glazing	very high	long-term	limited	🟧	unchanged	-	🟨
D. OTHERS	**D.1**	Curtain as radiation screen	low	mid-term	good	🟩	temporary reduction	> $1m^2/m^2$	🟩
	D.2	Curtain as textile wall insulation	low	mid-term	good	🟩	temporary reduction	> $1m^2/m^2$	🟩
	D.3	Internal glass box	very high	long-term	high potential	🟨	limited reduction	-	🟨

			5. FINANCE			ECONOMIC EFFICIENCY	6. LIGHT & ACOUSTICS		LIGHT & ACOUSTICS
	NOW	*South chapel basis model simulation DesignBuilder*							
			5.1 Costs		5.3 Profit		6.1 Lighting	6.2 Acoustics	
E. INDOOR SPACE ADAPTATION	**E.1**	Floorplan adaptation or Zoning the indoor space	very high		high potential	🟧	adjustable	$1m^2/m^2$	🟩
	E.2	Box in Box temporary *(Design Builder simulation 04)*	low		good	🟩	unchanged	-	🟨
	E.3	Box in Box permament	very high		high potential	🟧	adjustable	$1m^2/m^2$	🟩
	E.4	Vertical division	low		limited	🟨	limited reduction	-	🟨
	E.5	Horizontal division	high		limited	🟨	limited reduction	-	🟨
	E.6	Local heating modules *(Design Builder simulation 05.A)*	high		high potential	🟨	controllable	> $1m^2/m^2$	🟩
	E.7	Local heating modules in combination with textile vertical division *(Design Builder simulation 05.B)*	high		high potential	🟨	controllable	> $1m^2/m^2$	🟩

Figure 8.15: Matrix evaluation finance, lighting and acoustics

8.3 Application

8.3.1 Evaluation matrix

The evaluation matrix provides a comparative overview of different strategies for the renovation of the stained glass windows and spatial adaptations. The assessment framework is based on the Stevenskerk as a case-study, but universal evaluation parameters were defined to make the matrix applicable for other multi-functional and monumental church buildings in the Netherlands.
The complete table illustrating the performance overview of the renovation strategies in all assessment criteria can be found in the Appendix B (figure B.6).

8.3.2 Stepped approach towards identifying suitable renovation strategies

This chapter explains how the evaluation matrix can serve as a tool for supporting the identification of suitable renovation strategies by introducing a stepped approach which is suggested on the basis of the development of a renovation proposal for the Stevenskerk (figure 8.16).

Step 1: Relevance and applicability evaluation matrix

Firstly, it is necessary to understand and investigate if the evaluation matrix is relevant and applicable for the examined building. The matrix is applicable for monumental church buildings with large stained glass or lead windows which are located in a heating dominated climate similar to the Netherlands.
The matrix is relevant for buildings which are dealing with a thermal comfort challenge that would be solved by the renovation strategies evaluated (window renovation and spatial indoor adaptation). An investigation about previously applied renovation measures and other potentially suitable renovation methods such as an adaptation of the heating system, vault insulation etc. are part of this step.
If this assessment shows that the matrix is not applicable for the building, the evaluation framework should be adapted and extended in order to be applicable for different boundary conditions.

Step 2: Identify building and user requirements

Secondly, different requirements concerning the space (building needs), such as conservation requirements and the user (human needs), such as the IEQ requirements should be identified as boundary conditions for interventions. Therefore, an elaborated analysis and inventory of the building is necessary. For a monumental building this includes a heritage value assessment.

Step 3: Define renovation objective(s)

The decision-making in favour or against a renovation method should be based on the motivation for the renovation. Therefore, it is important to clearly define the renovation objective(s) before assessing the suitability of a strategy.
Thus, a future vision for the building regarding its functionality, its use-cycle, the user-groups and accordingly the spatial or thermal requirements and other relevant parameters should be developed . Respectively, the significance of the performance criteria evaluated in the matrix can be weighted.
For this project for example, the suitability for the functionality of the space and the improvement of the thermal comfort have been identified as the most important objectives because they are most beneficial for the accessibility and the usability of the Stevenskerk.
As the future vision is different for every case-study it may contain parameters which are not listed as evaluation parameters and therefore requires further extension of the assessment framework.

Step 4: Select and combine renovation strategies

Based on the weighting of the evaluation criteria, some renovation strategies can be identified as more suitable than others. The evaluation matrix provides an overview of the performance of the strategies to support and simplify this selection.

Furthermore, it the combination of different renovation strategies and its influence on the renovation objective should be investigated.

During the research and evaluation process of this project it has become clear that there cannot be one renovation solution for several buildings and that even within one building such as the Stevenskerk, depending on the requirements of the different spaces, different renovation methods can be suitable.

Step 5: Adapt renovation strategies

After selecting suitable renovation strategies those should be adapted to the specific circumstances and requirements of the building. This step includes the further development and design of the selected renovation method in consideration of the case study building and its characteristics.

The final outcome of this process is a renovation proposal for the specific case-study building. A renovation proposal for the Stevenskerk will be introduced in the following chapter 9.

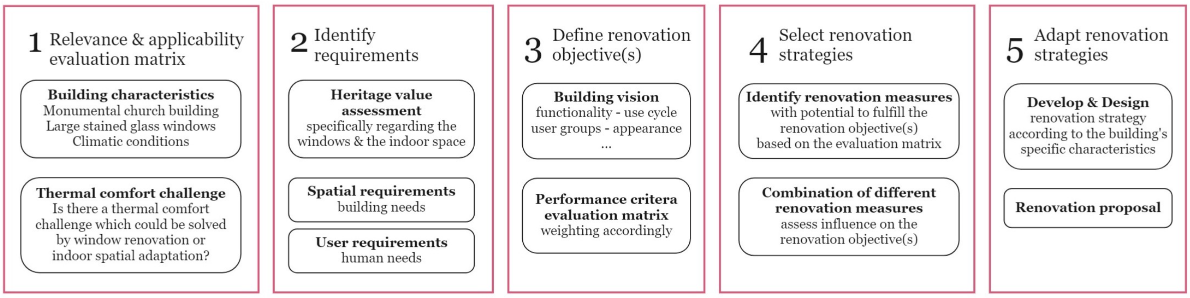


Figure 8.16: Overview of the steps for identifying and developing suitable renovation strategies

9 Renovation strategy Stevenskerk

9.1 Designs for the Stevenskerk

9.1.1 Local heating modules

The indoor space adaptation strategy *Local heating* (chapter 6.2.4), is suitable for the large church space of the Stevenskerk because it is beneficial for flexible, multi-functional and irregular use.
Based on this strategy and in accordance with step 5 of the introduced stepped approach (chapter 8.3), the design of a local heating and acoustic module was developed for the Stevenskerk. The design is inspired by the delicate and elegant Gothic architecture and its geometric patterns as well as the opening and closing movement of flowers (figure 9.1). The module is composed of radiative heating and insulation panels in combination with acoustic performing, non-inflammable textile (figure 9.2). Additionally, lighting could be integrated in the module.

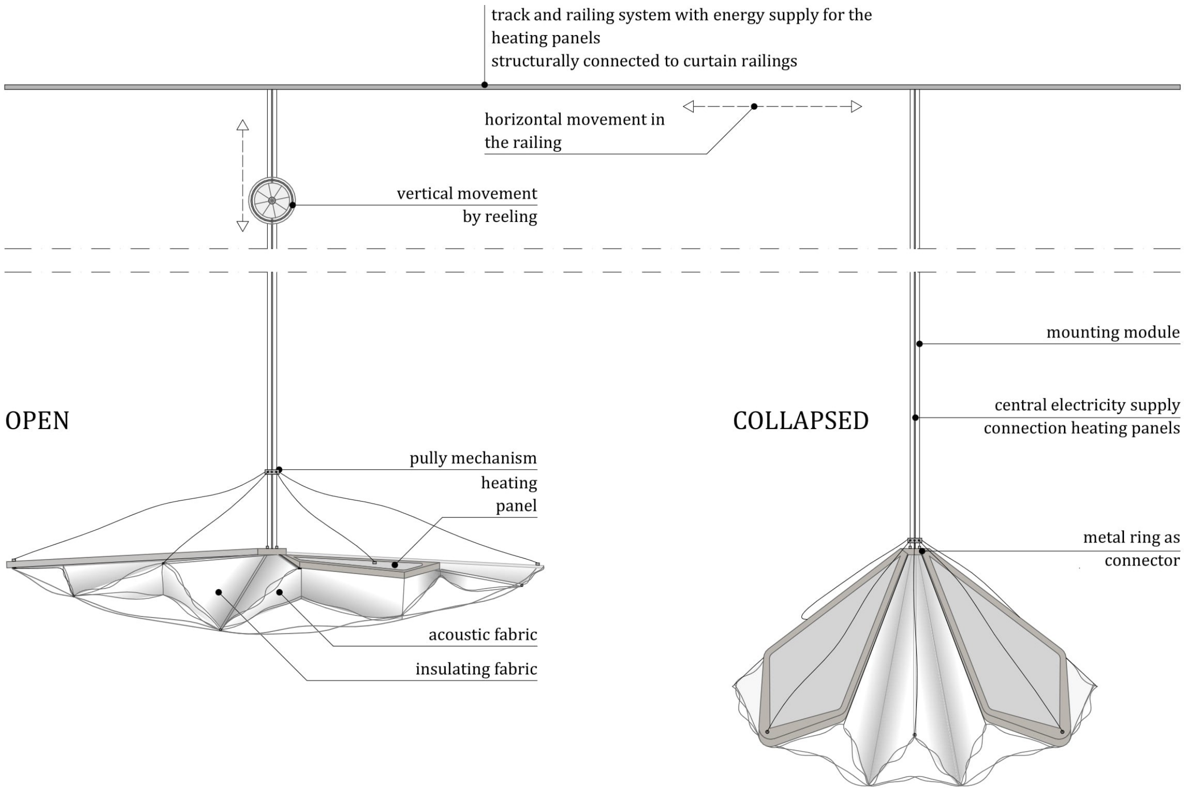


Figure 9.1: Local heating modules side view

A pulley mechanism enables the folding of the module similar to an umbrella principle. The module is vertically mounted to a railing system with electricity supply. Furthermore, the vertical movement of the modules allows them to be pulled up into the high vaulted space. Thus, when no heating is required the view towards the indoor space remains open. By this means the heating supply, the size and the arrangement of the modules can be adapted according to the flexible use of the space. The electrical connection and supply of the modules from the roof space is not possible due to fire protection and restriction to low voltage in the roof space of the Stevenskerk.

The lightweight and transparent design is aesthetically pleasant and emphasizes the light and vertical indoor space impression of the Stevenskerk. The application of these heating modules in the Stevenskerk does not only promote the multi functional usability by improved acoustic and thermal conditions but additionally it emphasizes the special characteristics of the impressive indoor space.

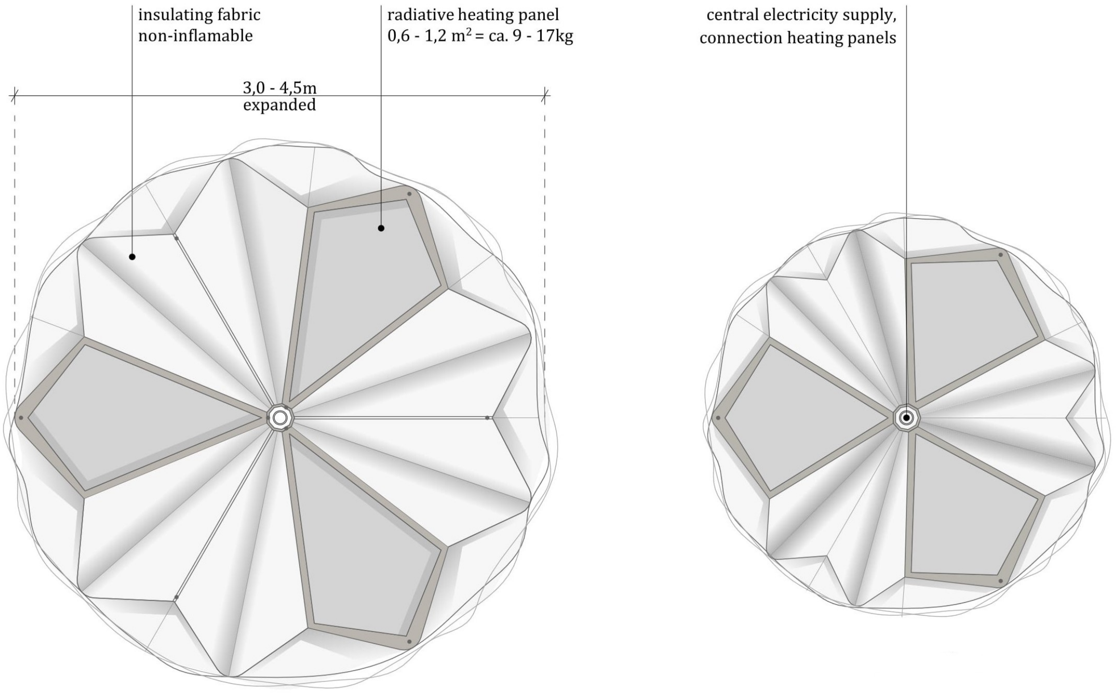


Figure 9.2: Local heating modules top view - Open and collapsed

9.1.2 Curtains

Figure 9.3: Combination vertical textile division and local heating modules Stevenskerk

In order to enhance the multi-functional use of the Stevenskerk, the application of vertical textile room divisions to enable compartmentalization of the large space was further developed in line with the local heating modules (figure 9.3). Furthermore, the thermal simulations have shown that the combination of local heating with textile compartmentalization of the space has a large potential for thermal comfort improvement (chapter 7.2.4).

The curtains are placed according to the space that is already formed by the pillars. Because these span up to 8 m from each other, the curtain railings are fixed to a steel beam which is connected to the columns (figure 9.4). As this intervention has a significant impact on the heritage values of the indoor space of the Stevenskerk, the reversibility of this intervention is crucial. Therefore, the steel beam is not directly fixed to the decorated fluted pillars, but to a ring that can be adjusted and is thereby clamped to the pillar. The surface of the column is protected by a wooden fitting, shaped to the shape of the fluted column and covered with an elastic gasket. The metal ring and the steel beams can easily be removed by opening the bolted connections.

A translucent fabric was chosen in order to enable natural daylight passing through and to emphasize the lightweight and elegant aesthetics of the heating modules. The acoustic performance of the textile supports the multi-functional usability of the space.

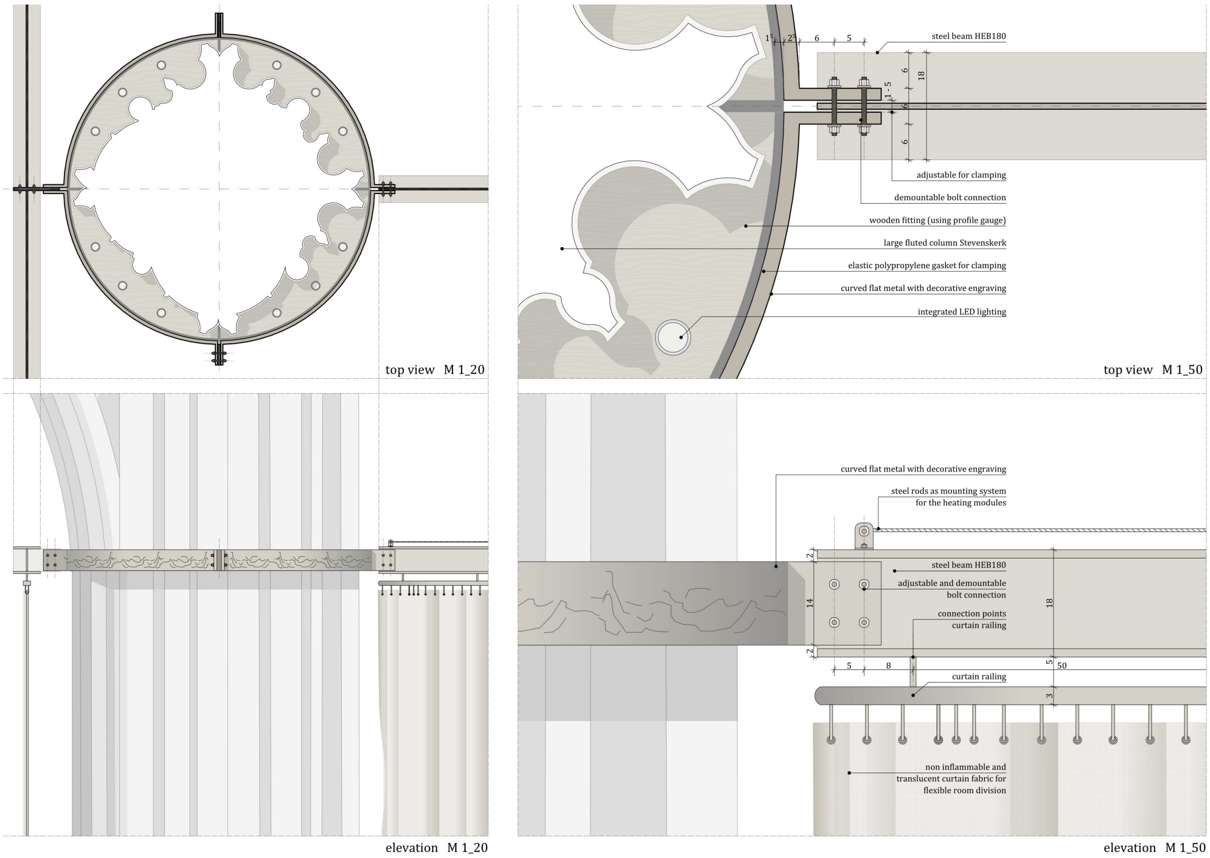


Figure 9.4: Detail connection curtain to column Stevenskerk

9.2 Framework renovation strategy

9.2.1 Objective

The proposed renovation strategies should improve the accessibility of the monumental Stevenskerk enabling its usability during the whole year, also during winter. On the one hand, this requires comfortable thermal conditions for the users with a reasonable heating input. On the other hand, the multi-functional usability of the space is crucial for the accessibility and the active use by different user groups. Therefore, the introduced renovation plan aims at promoting the multi-functionality of the Stevenskerk by providing strategies which enable the flexible adaptation of the space according to the use requirements. Furthermore, the improved accessibility of the Stevenskerk should embrace its historical origin as a building which was built for communal use. Enabling several functionalities in the Stevenskerk leads to a greater visibility of the monument and its heritage values because it will be experienced by people who would not visit a church building for religious reasons.

9.2.2 Monumental boundary conditions

Renovation measures lead to interventions on the monumental values of the Stevenskerk. In order to develop suitable renovation strategies, boundary conditions for the designs were defined in accordance with the most significant heritage values (chapter 3). The spatial experience when entering the Stevenskerk resulting from the very high vaulted space, the Gothic vault patterns, the oak barrel vault and the vertical pillars has very high monumental value. The large number and size of the stained glass windows allows natural light to enter the building and creates a light and open atmosphere resulting in an unique and valuable spirit of the place. As the spatial as well as the lighting experience have very high monumental value, the renovation concepts should compromise those to a very limited extend. The monumental inventory including tomb stones, chandeliers and the organs has to remain accessible and visible for the visitors of the Stevenskerk. The external appearance of the Stevenskerk is defined by its historic impression with aged stone facades, its Gothic ornaments and the plasticity and fragmentation of the façade. This results from the deep natural stone windows reveals, the visible lead connections and fragmentation of the window elements and should therefore be preserved. Furthermore, the usability of the Stevenskerk as a multi-functional space for cultural and religious activities as well as a place of reflection and the community can be defined as a significant monumental value which has to preserved. Additionally, these functionalities and a large visitor number is essential for the economic existence of the Stevenskerk. Therefore, the aim is to develop a renovation strategy which supports the flexibility of use where needed and adds a value to the user's experience when visiting the church. This should emphasize the building's uniqueness as a multi-functional monument balancing historic values and present use requirements.

9.2.3 Step-by-step strategy

The renovation proposal for the Stevenskerk resulting from the investigations in the scope of this graduation thesis was developed as a step-by-step plan for several reasons. Firstly, the design, the development and the application of the different renovation measures is related to a certain time frame. Secondly, it was assumed that the extension of the use of the Stevenskerk will grow steadily and therefore as the time passes more space for multi-functional use will be required.

The proposed strategies are grouped into two main steps according to an ambitious time plan for the renovation of the whole Stevenskerk depending on the time which is required to develop the strategies for their application. As the literature review has shown, there are currently subsidies available for such church renovation projects which could be used for realising the project within a limited time frame of 10 years. Additionally, the short-term application of the strategies would enable testing the impact of the introduced measures as a case study which could then be applied on comparable monumental buildings as a contribution to the urgent need of a sustainable transformation of the built environment.

The varying use of the spaces in the Stevenskerk results in distinctive requirements for functionality, thermal comfort and spatial quality. Therefore, the application and combination of different renovation strategies within this one building is appropriate. The suggested renovation measures are introduced according to the following spaces: The Gerfkamer, the South chapel, the North chapel and the large church space. On the basis of the vision of the Stichting Stevenskerk (Stichting Stevenskerk, 2005) different use-cases are related to the different zones to develop strategies in accordance with the functionality.

Furthermore, for some zones alternative strategies are suggested as at this state of the project a definite decision for or against some renovation measures is not possible as there are too many uncertainties about measures which have not yet been applied.

9.2.4 Internal interventions

The analysis of common protective glazing methods on monuments has shown that the application of glazing on the outside largely influences the external impression of the building. This method is suitable for windows with a very high artistic value such as coloured stained glass windows. Therefore, this method was also applied on the painted glass windows by Marc Mulders in the Stevenskerk.

One the one hand, for the external impression of the Stevenskerk the monumental value of the historic façade with the plasticity of the other stained glass windows and the visibility of the lead connections can be rated higher than the external protection of these windows which have a special artistic value. On the other hand, from the inside, the adaptation of the aesthetic appearance of the windows and to a certain extent the spatial impression can be explained with the adaptation of the use of the internal space.

Therefore, my renovation proposal is focused on the internal renovation and adaptation of the windows and the space with the aim to improve the thermal comfort.

9.3 Renovation proposal - Step 1

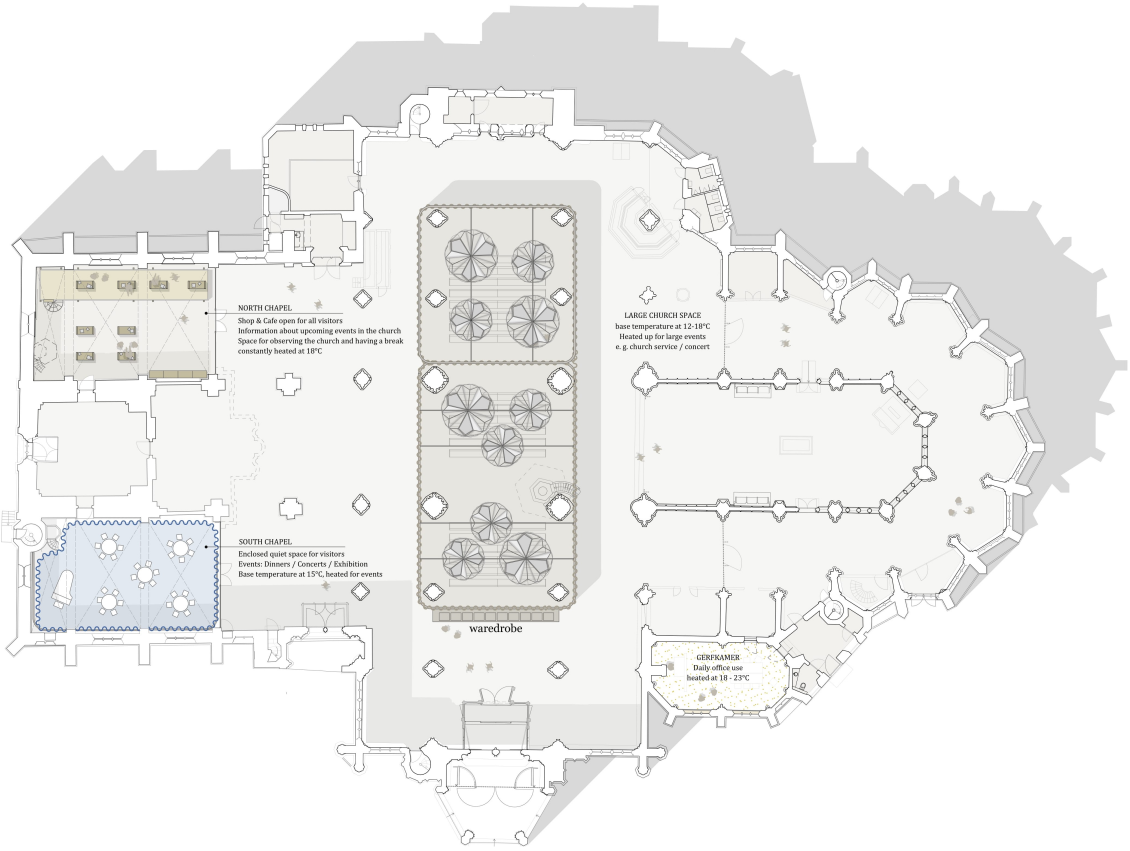


Figure 9.5: Floorplan Stevenskerk renovation proposal - Step 1

Short-term renovation proposal which could be applied within 2 to 5 years (figure 9.5):

- Gerfkamer: Internal double glazed window & Roof insulation
- Large church space - Transept: Local heating with curtains & Roof insulation
- South chapel: Closing ventilation gap windows & Curtain as radiation screen & Roof insulation
- North chapel: Internal double glazed window & Internal walkways & Roof insulation

9.3.1 Gerfkamer

- Constant heating (18 - 23 °C)
- High comfort requirements for daily office use
- Limited floor area

Selection and evaluation combined renovation strategies

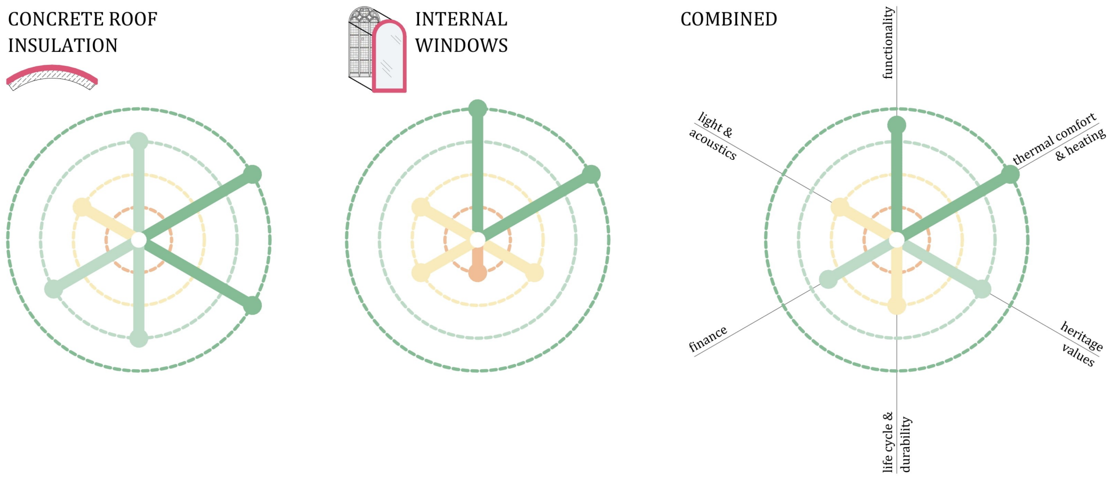


Figure 9.6: Gerfkamer: Selection and evaluation renovation strategies

The renovation strategies for the Gerfkamer are suggested based on the evaluation framework (figure 9.6). Both measures have a very good performance in *thermal comfort* improvement and in maintaining the spatial *functionality* of the Gerfkamer as an office with very limited floor area and a daily use-schedule because they don't intervene with the space.

The external impression of the Stevenskerk is not influenced by the proposed strategies. The addition of an internal secondary window leads to an intervention on internal *heritage values* as it will cover the ornamented window frame and the stained glass (figure 9.7). However, the accordance with thermal and functional requirements for the office use in the Gerfkamer can be rated higher than the conservation of the internal wall elevation as a *heritage value*. Furthermore, in case of the change of functionality or weighting of the heritage value assessment, the windows could be converted to their original state as this measure can be applied reversible.

The roof insulation has no visual impact on the *heritage values* while it is beneficial for their conservation requirements (steady RH and T-level).

The *lifespan* for double glazing and the roof insulation is estimated to be 20-40 years. The embodied carbon for double glazing is comparably high.

Also the *financial investment* for double glazing per m^2 is relatively high, but is in this case limited by comparatively small window area in the Gerfkamer (ca. 17 m^2 in total).

Furthermore, the costs for roof insulation are comparatively low and the expected savings due to a decreased heating demand are significant as the Gerfkamer is heated daily, which leads to a reasonable payback period.

The selected measures have no influence on the *light* condition in the Gerfkamer. If required, printed glass could be used as a sunscreen to reduce glare. The strategies don't include *acoustic* performing surfaces. The application of new glazing would change the reverberation time of the internal window surface but this was not investigated in this project.

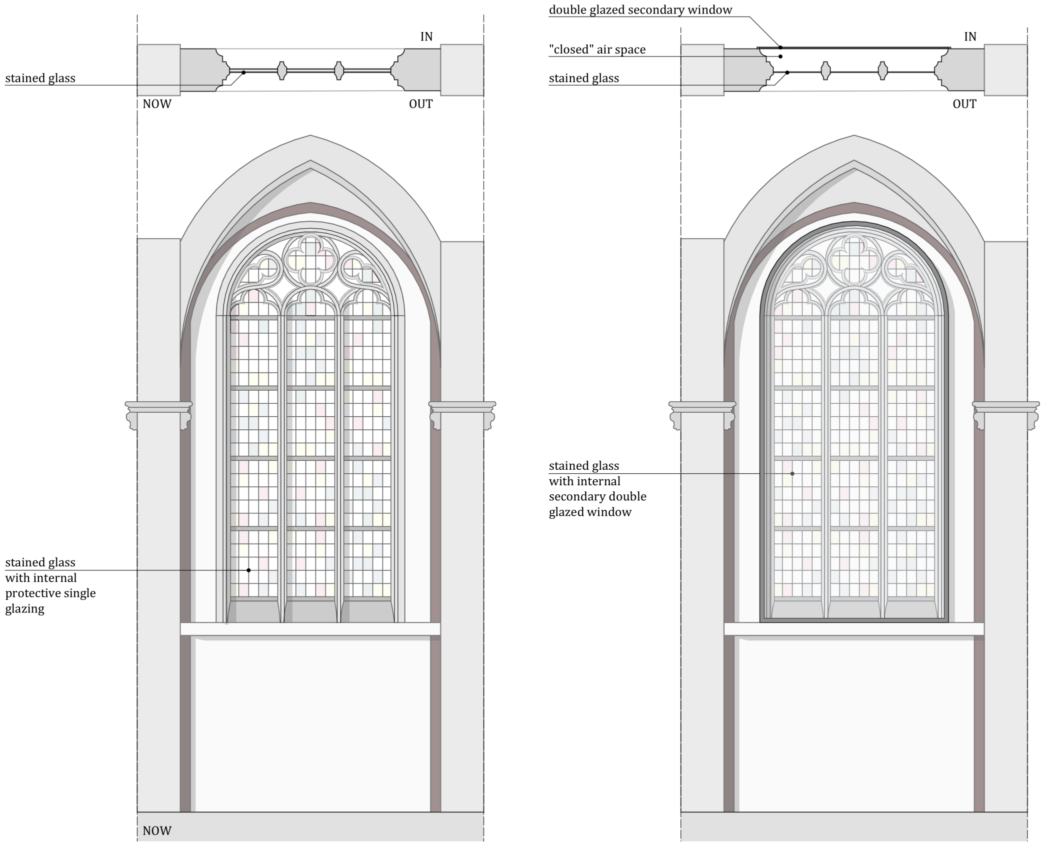


Figure 9.7: Illustration internal elevation window Gerfkamer now and with internal secondary window

Double glazed internal secondary window

The double glazing significantly improves the insulation performance of the window construction to a U-value of 1 W/m^{2}K. Secondly, the cold bridges resulting from the window frame and cold draft due to air leakage in the window reveal are eliminated by covering the cracks. A non-ventilated system with a closed cavity is proposed because this leads to the best insulation performance. However, it is questionable if a fully airtight construction can be achieved due to leakages in the building fabric.

If indoor air would enter the cavity this leads to a very high condensation risk on the stained glass: For the test case scenario (T_{in} = 18 °C and T_{out} = 5 °C), the maximum calculated RH for the Gerfkamer to avoid condensation in the cavity is 40 % which is less than the values measured at this temperature (ca. 48 % - chapter 5.2). If outside air would enter the cavity, however, the cold air will slightly warm up in the cavity which decreases its RH level, reducing the condensation risk. To conclude, if it is not possible to construct an airtight system, the infiltration from the outside should predominate in comparison to the ventilation from the inside in order to reduce condensation risks in the cavity.

There was no case study found for the application of this system in a church building. Therefore, the detailing regarding for example the connection of the window to the wall or the window frame design requires further investigation.

If the building owner prefers the application of a window renovation strategy where experience from previous application is available, the application of internal double glazing as protective glazing is suggested. This system significantly improves the insulation of the glass, however, is does not reduce the thermal bridges and the cracks in the natural stone.

Roof insulation

The roof of the Gerfkamer is made of concrete which enables the application of an insulation layer within the roof space without the risk of damage by condensation. Additionally, the vault height in the Gerfkamer is lower than in the South chapel and therefore the insulation will have an even more significant impact compared to the thermal simulation (chapter 7.2.5).

Ventilation

The ventilation of the Gerfkamer is currently controlled by an exhaust fan which extracts air from the space, leading to infiltration with fresh air through the permeable building skin.

The proposed measures would lead to an immense improvement of the air-tightness of the openings and the roof. Nevertheless, it should be considered that sufficient ventilation is required. It should be investigated if the remaining infiltration through the door and leakages in the walls, supported by the exhaust fan could be sufficient.

9.3.2 Large church space - Transept

- Large church space: rough climate (12-15 °C) and transept: local heating for specific use
- Irregular comfort requirements for multi-functional use: Services, concerts, visitor tours, events etc.
- Extremely large and open floor area, high vaults

Selection and evaluation combined renovation strategies (figure 9.8)

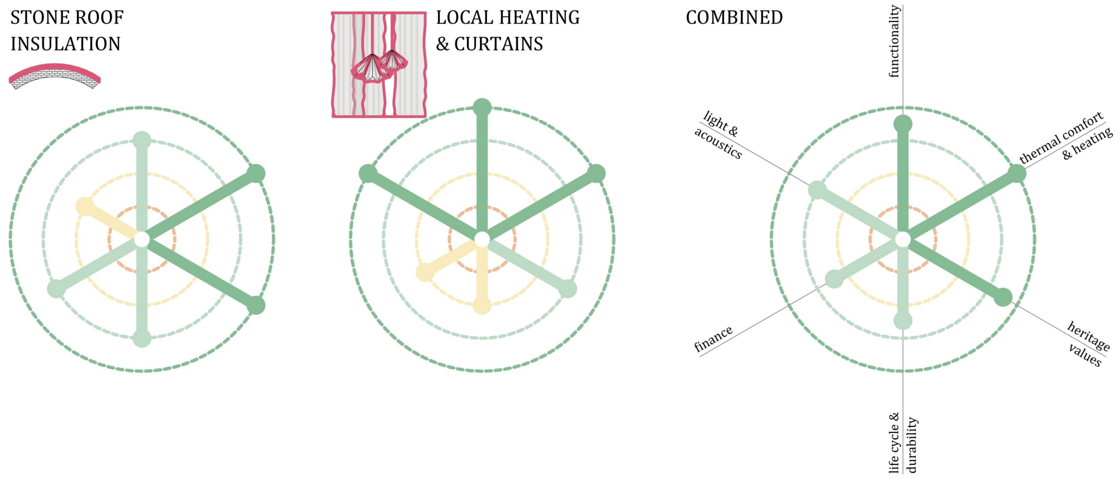


Figure 9.8: Large church space: Selection and evaluation renovation strategies

The combination of local heating modules with curtains enables the flexible configuration and the independent heating of differently sized spaces within the transept depending on the use. This facilitates the *multi functionality* of the large church space with an irregular use-cycle.
The large potential for *thermal comfort* improvement by roof insulation was shown in the thermal simulation. Additionally, overhead heating modules provide flexible and short-term local thermal conditions for different use cases without heating the large church volume. The combination with curtains prevents that heat is dispersed into the large space by buffering.
The insulation of the stone vault (in the side naves and the choir of the large church space) from above has no visual influence on the *heritage values*. By enabling more constant heating at a medium temperature (13-15 °C) due to improved insulation, the conservation conditions for the monumental inventory is improved due to less RH and temperature fluctuations.
According to previous research, local heating can help to avoid conservation risks for monuments (Camuffo, Schellen, Limpens-Neilen, & Kozlowski, 2006). However it is very important to avoid the direct impact of radiative heating on the monumental inventory because local heating up for monumental inventory such as the pulpit in the transept leads to degradation. Additionally, large fluctuations in temperature and RH levels due to cyclic heating up can lead to damage. The heating modules and curtains have a visual impact on the internal *heritage values*. However, they can be clearly distinguished from the historic interior. Furthermore, the application of visual attracting overhead heating modules leads to an increased perception of the impressive height of the space and the vault.
The financial investment for the roof insulation is comparatively low, whereas it has a limited payback by the reduced heating demand when large space is heated. The financial investment for the heating modules is comparatively high, whereas it leads to considerable payback as it improves the conditions for more frequent use of the space relating to financial income by an increased number of visitors. The selected strategies include a considerable potential for the integration of *acoustic* performing surfaces which is beneficial for the use of the space for audio performances of any kind.

Figure 9.9: Section transept Stevenskerk - now and after measures applied

Local heating in combination with textile room division

The integration of translucent curtains connected to railings enables the subdivision into one large (300 m^2) or two smaller spaces (100 m^2 and 200 m^2).

The location for this intervention was chosen for the spatial functionality: The flexible placement of seating and the location of the pulpit enable different types of gatherings and activities such as services or concerts. The spatial design enables to move around the complete church while the spaces are separated. The combination with the local heating modules enables the creation of different levels of comfort in the different zones (figure 9.9 - 9.11).

The curtains are located on the external side of the pillars which includes them into the inter-space. Thereby the fluted surface is visible from the inside and can be experienced by the user as a significant element of Gothic architecture.

Figure 9.10: Indoor perspective now - Thermal discomfort during winter

Figure 9.11: Indoor perspective multi functional use with local heating modules and translucent curtains

Stone vault insulation

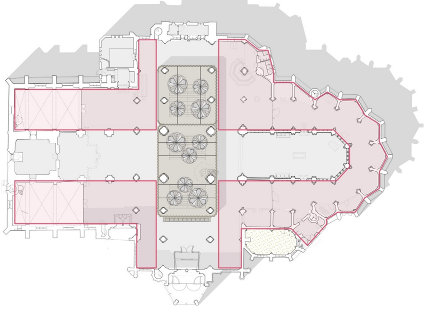


Figure 9.12: Stone vaults Stevenskerk

The vaults of the side naves, the side chapels and the ambulatory are made of stone (figure 9.12) (Nusselder & Zandijk, 2015). Investigations about the Stevenskerk and the thermal simulation showed that the insulation of the vaults have considerable potential for thermal comfort improvement (chapter 7.2.5). The roof spaces of these vaults are accessible and spacious (figure 9.13). Furthermore, in comparison to the wooden vault, the stone material is not as damageable by the appearance of moisture. Therefore, the insulation of the stone vaults which will not be visible for the user is suggested as part of the first renovation step.

Figure 9.13 illustrates how this insulation could be applied. During the reconstruction phase in the 20th century, a concrete ring beam was added to the stone walls (Appendix B figure B.9). Expansion bolts can be attached to the concrete to connect steel cables on which a metal grid is placed. This serves as the bearing for the insulation blanket which can then be applied without bending according to the complex vault shape. The insulation material should be moisture permeable as the roof structure and the stone vault are permeable for humidity and condensation has to be avoided. In previous research the application of fibre materials such as Pavaflex was suggested (Nusselder & Zandijk, 2015) To eliminate cold bridge at the non-insulated stone facade could be insulated from the inside.

Figure 9.13 is an approach towards insulating the stone vaults in the Stevenskerk. Nevertheless, the different roof spaces have distinctive characteristics, shapes and requirements which are not included in this consideration and are to be considered in a detailed assessment during future research.

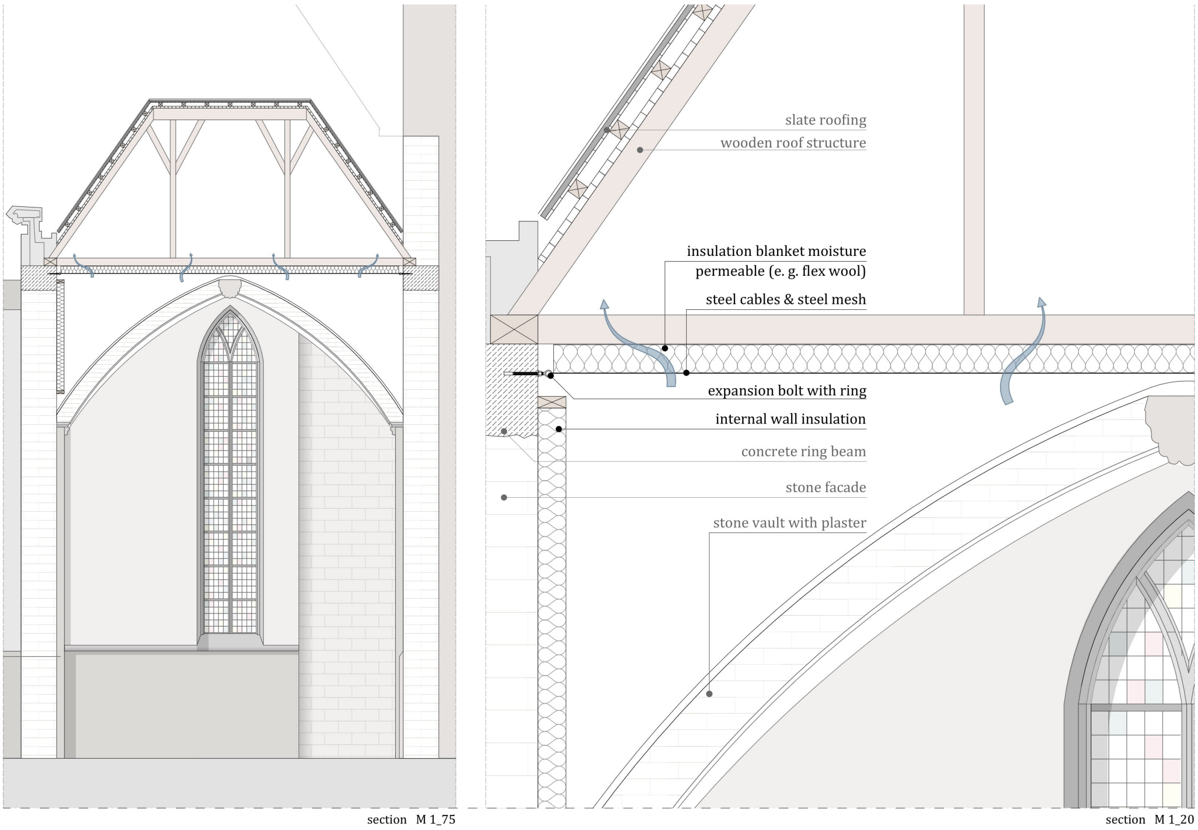


Figure 9.13: Detail stone roof insulation - exemplary for the Side chapels

9.3.3 South chapel

Selection and evaluation combined renovation strategies (figure 9.14)

- Irregular heating cycle: 12-15 °C base temperature, up to 23 °C during use
- Irregular comfort requirements for multi-functional use: Exhibitions, concerts, private events etc.
- Limited floor area

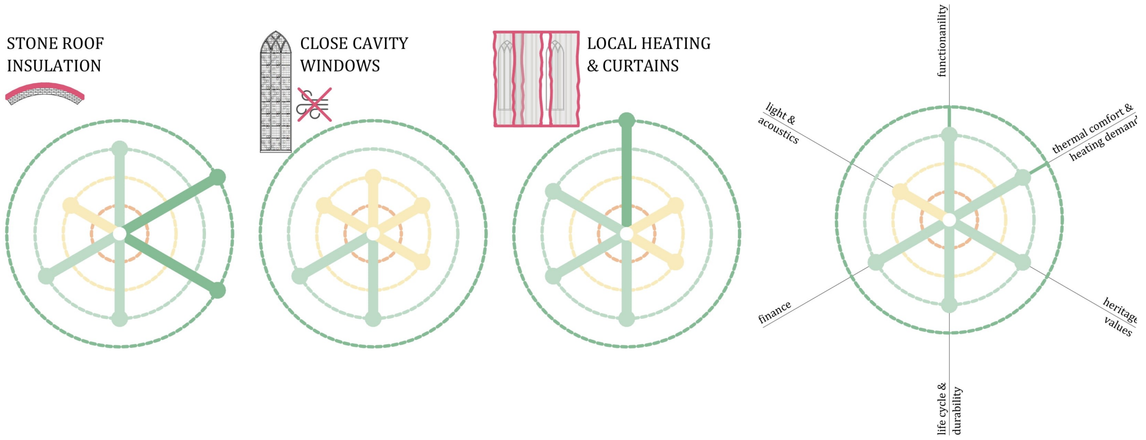


Figure 9.14: South chapel: Selection and evaluation renovation strategies

Closing the ventilation openings of the windows and insulating the vault has no significant influence on the *functionality* of the chapel with a limite floor area and an irregular use-cycle. The application of curtains as enclosing wall surfaces is beneficial for multi functional use as its appearance and thereby the atmosphere of the space can be adapted according to the current use and include secondary functions such as acoustic performance or display of exhibition content.

Converting the current protective glazing system into a non ventilated construction slightly improves the *thermal comfort* in the zones close to the facade as it increases the heat resistance of the glazing. Additionally there is a good *thermal comfort* improvement by the vault insulation.

Thermal simulation have shown that the application of textile as radiation screen can significantly improve the MRT and reduce discomfort due to draft. Furthermore it is a good addition to the window renovation as the fabric will cover the cracks in the natural stone and thereby limit draft by natural infiltration. Overall, the impact of the radiation screen depends on the type of fabric which is applied. The better the insulation and the air tightness of the textile, the larger the impact. While the vault insulation has only beneficial influence on the *heritage* conservation, the window renovation leads to a condensation risk in the cavity.

The curtains largely change the visual appearance of the internal wall and window surfaces by covering the wall layout, the window frame and thereby the plasticity of the wall. This visual impact also on the *heritage values*, the *lighting conditions* and the *acoustics* largely depends on the applied textile. Sufficient ventilation is required in order to avoid conservation risks between the curtain and the wall surface. All selected measures have relatively low *investment* costs.

Change windows to non-ventilated system

This measure is comparatively simple as the glazing is already applied. It improves thermal comfort by eliminating the cold draft from the ventilation openings and slightly improving the insulation performance from a U-value of about 4 to 3.7 W/m^{2}K. Compared to the current RH level in the

cavity, the closing of the ventilation openings slightly increases the condensation risk. However, the improvement for the thermal comfort and the reduction of the heating load justify this adaptation.
Nonetheless, the risk of condensation is present. For the test case scenario (T_{in} = 18 °C and T_{out} = 5 °C), the calculated RH_{max} for the South chapel is 50 % which is close to the RH which was measured in the South chapel at 18 °C. Accordingly, when there are small deviations and indoor air enters the cavity, which can then not leave the inter-space, condensation will occur. Therefore, the entrance of indoor air in the cavity has to be prevented. If this cannot be realised, more external than internal air should enter the cavity space. This could be achieved by creating ventilation openings in the stained glass windows which would however limit the insulating performance. Furthermore, rain or insects might enter through those openings.
In previous research, the installation of drainage into the inter-space has been identified as a suitable strategy for the deduction of humidity (Curteis & Seliger, 2017). The integration of such inter-space drainage could also be implemented in the windows in the South chapel and prevent damage to the window and adjacent building components. Overall, it is recommended to observe the test-case window in the South chapel for a longer period and to observe if condensation is present continuously. From the experiments which have been performed within the scope of this project it is not possible to make a definitive statement about the air-tightness of the stained glass windows or how much indoor air is entering the cavity through leakages in the natural window frame.

Curtain design

The application of opaque and insulating curtains is suggested for an improved comfort level in the South chapel and for creating an introverted, calm space where the visitors can take some time to rest. The functionality of the chapel could be extended with meditation sessions for people to rest from their every day life. For smaller events such as concerts or dinners, the acoustic absorption of the textile will be beneficial for the noise level in the space and the illumination of the space by the monumental chandeliers will be underlined by the dark enclosing surfaces (figure 9.15).
Furthermore, the connection of the textile to the walls with curtain railings enables the exchange or temporary removal of the fabric when necessary. Thus, during summer for example, the South chapel can be reset to its current appearance. Furthermore, different layouts of the curtains could be chosen and changed according to different functionalities.

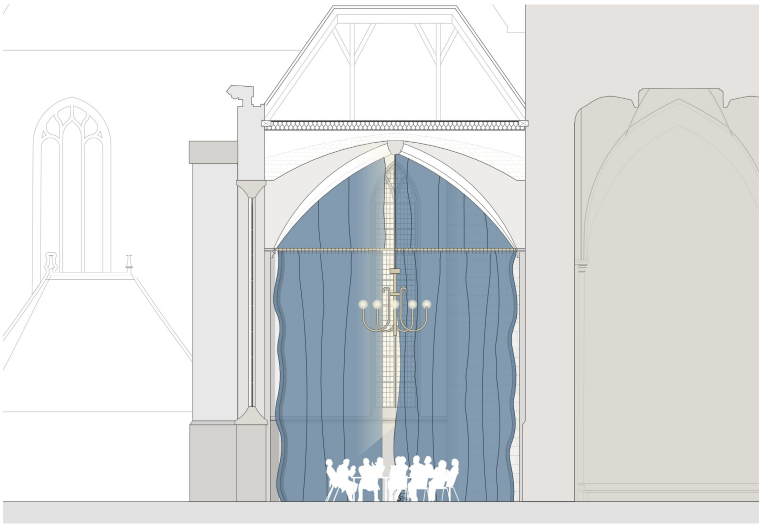


Figure 9.15: Elevation internal West facade South chapel with curtains

9.3.4 North chapel

Selection and evaluation combined renovation strategies (figure 9.16)

- New function: Cafe and shop
- Continuous high thermal comfort requirements
- Limited floor area

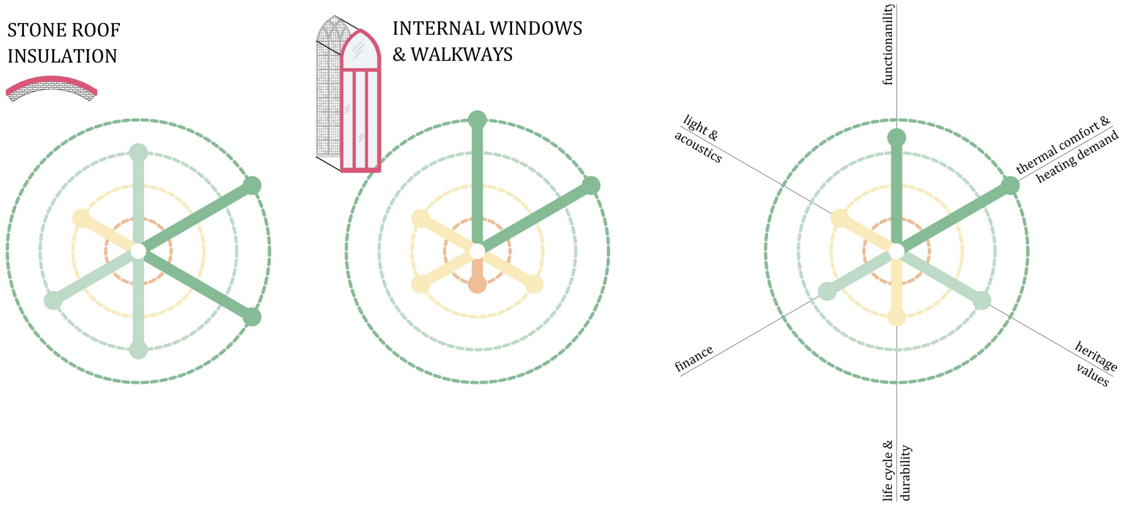


Figure 9.16: North chapel: Selection and evaluation renovation strategies

The integration of galleries into the North chapel is suggested as part of its conversion to a café. This has a positive impact on the *functionality* as a cafe and shop with a regular use-cycle because it creates an exceptional spatial experience for the visitor and thereby supports the goal to attract people for having a break in the cafe or visiting the shop.
The vault insulation has a very high potential for *thermal comfort* improvement while the walkways are an exclusively spatial intervention. As the gallery is located adjacent to the windows surface an improvement of their insulation performance is particularly important. Therefore, the application of internal secondary windows is suggested (see 9.2.1 for more information).
The intervention on the internal *heritage values* can be justified by the continuous thermal requirements and the new functionality of the chapel.
The high *financial investment* for the application of internal secondary windows in combination with the walkways is balanced by the expected payback due to an increased number of visitors.
The selected strategies do not included *acoustic* performing surfaces as this is no specific requirement for the functionality in the North chapel.

New gallery

The new walkways include seating elements for the visitors from where they can observe the indoor space of the chapel and the vault on the one side and the stained glass windows on the other side (figure 9.17). Furthermore, the large church space will be visible through the currently built glazed door. This will enable the visitor to get into closer contact with the monument.

Figure 9.18 illustrates how the detailing of the walkway could lead to an integration as a visibly new and reversible addition in the historic environment.

The foundation points, for example, are not hidden into the ground but are standing on top of the floor to emphasize the intervention. Furthermore, there is a seam clearly visible between the old and the new elements.

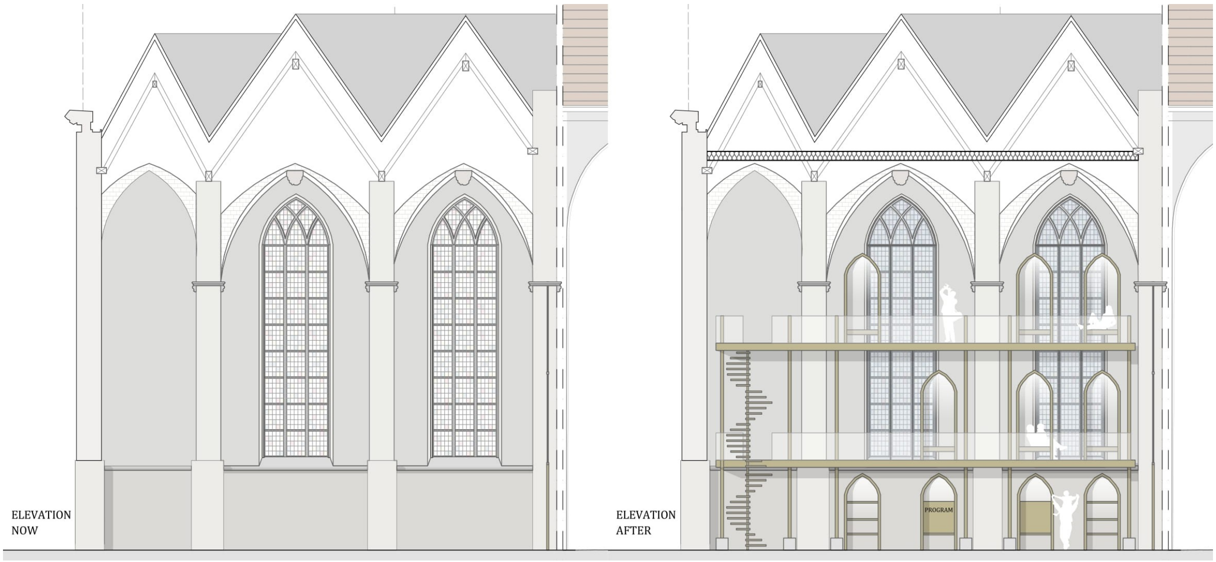


Figure 9.17: Elevation internal North facade North chapel Stevenskerk before and after

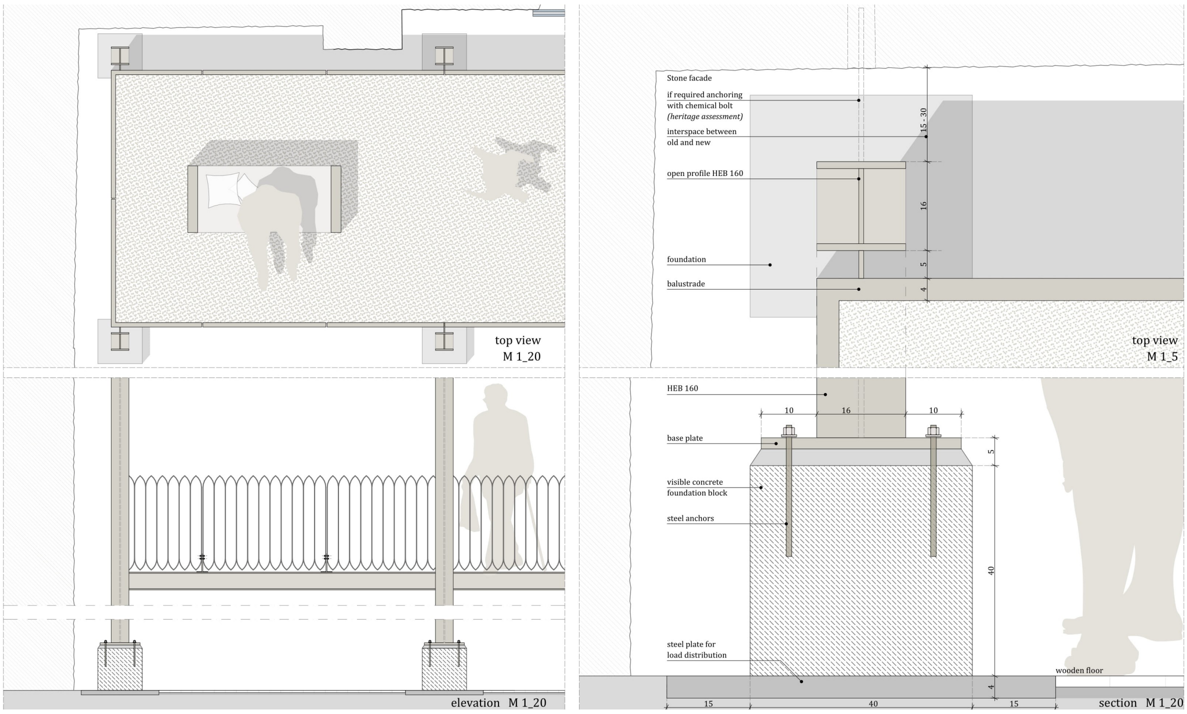


Figure 9.18: Details walkway North chapel

9.4 Renovation proposal - Step 2

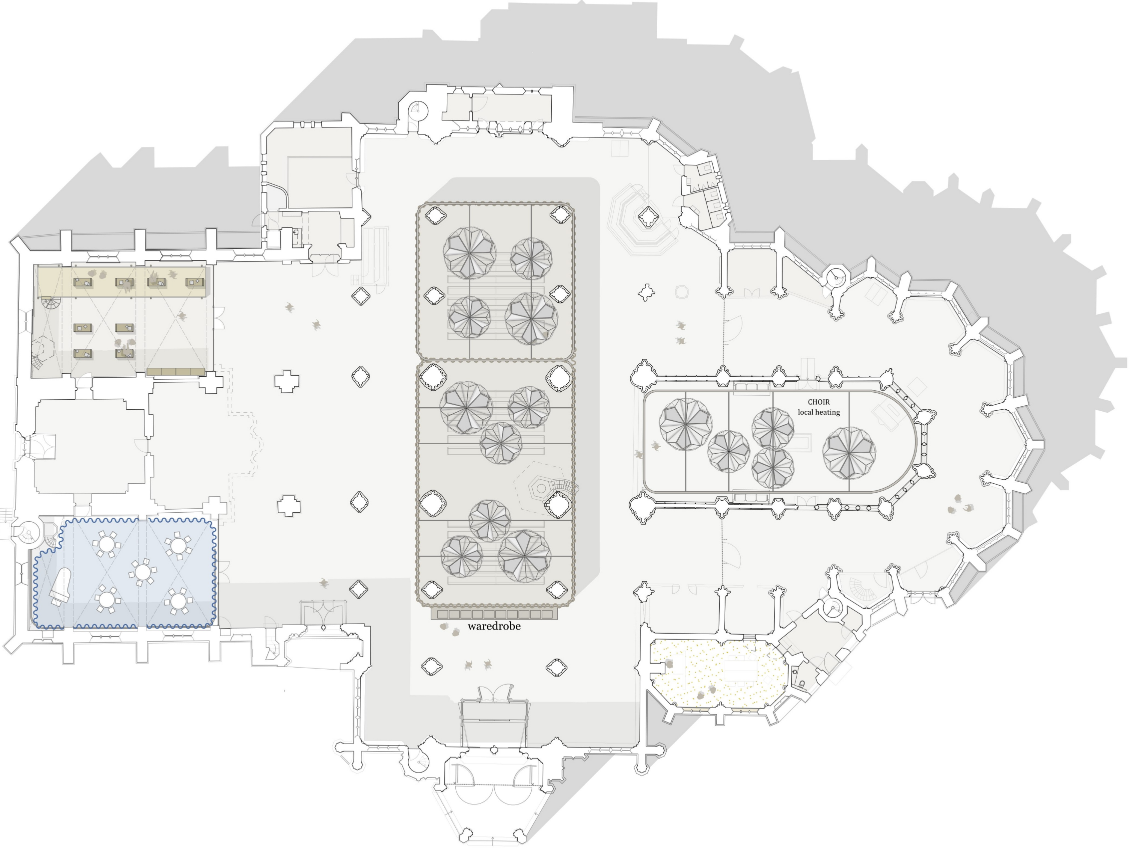


Figure 9.19: Floorplan Stevenskerk renovation proposal - Step 2

- Large church space - Wooden vaults: Insulation
- Large church space - Choir: Local heating

Selection and evaluation combined renovation strategies (figure 9.20)

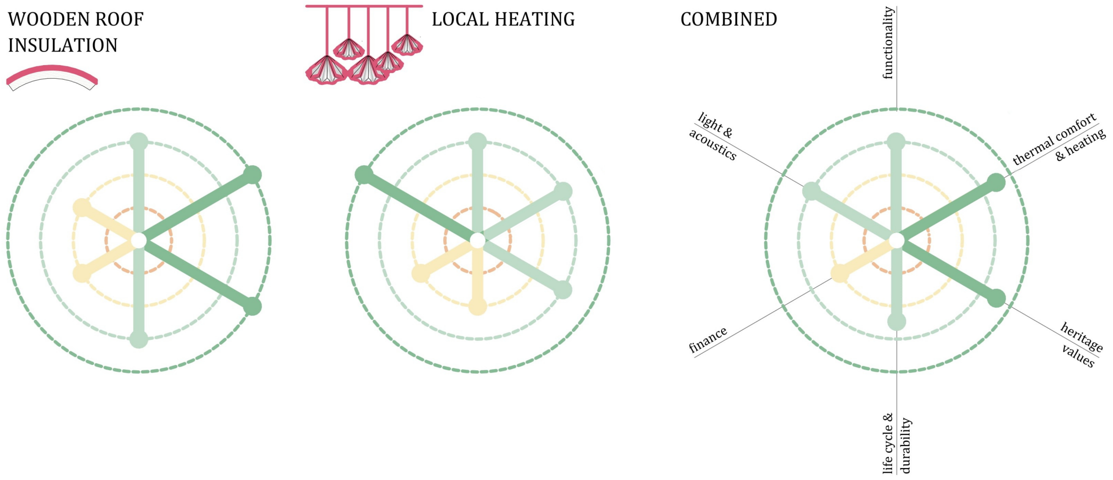


Figure 9.20: Large church space: Selection and evaluation renovation strategies

By insulating the wooden vault of the main nave and the transept in the Stevenskerk it will be more feasible to keep the large church space at a constant mid-range temperature (ca. 12-15 °C). This would be beneficial for the irregular and multi-functional use, the *thermal comfort* and the conservation of *heritage values*. However, this renovation strategy requires additional investigation and therefore it is suggested to be implemented in a second step.

After the introduction of an internal space in the transept (step 1), the addition of a second internal space in the choir is suggested. After increasing the multi functional use and the number of visitors of the Stevenskerk during the next years, more space will be required for the simultaneous use of the church for different functions (figure 9.19).

From the existing floorplan of the church the choir can already be identified as a smaller space within the larger building. It could be referred to as the heart of the church and accomodates a number of significant monuments: several gravestones, the stone tomb of Catharina van Bourbon, the choir organ and the canon pews.

After testing the local heating modules in the transept for some time, their influence on the monumental inventory can be assessed and refined. Afterwards their application in the choir is suggested. Small concerts or talks about the significant monumental values in this space could then be realised providing very good thermal conditions for the visitors (figure 9.21 to 9.23).

Figure 9.21: Indoor perspective choir now - Thermal discomfort during winter

Figure 9.22: Indoor perspective choir new with local heating modules for thermal comfort

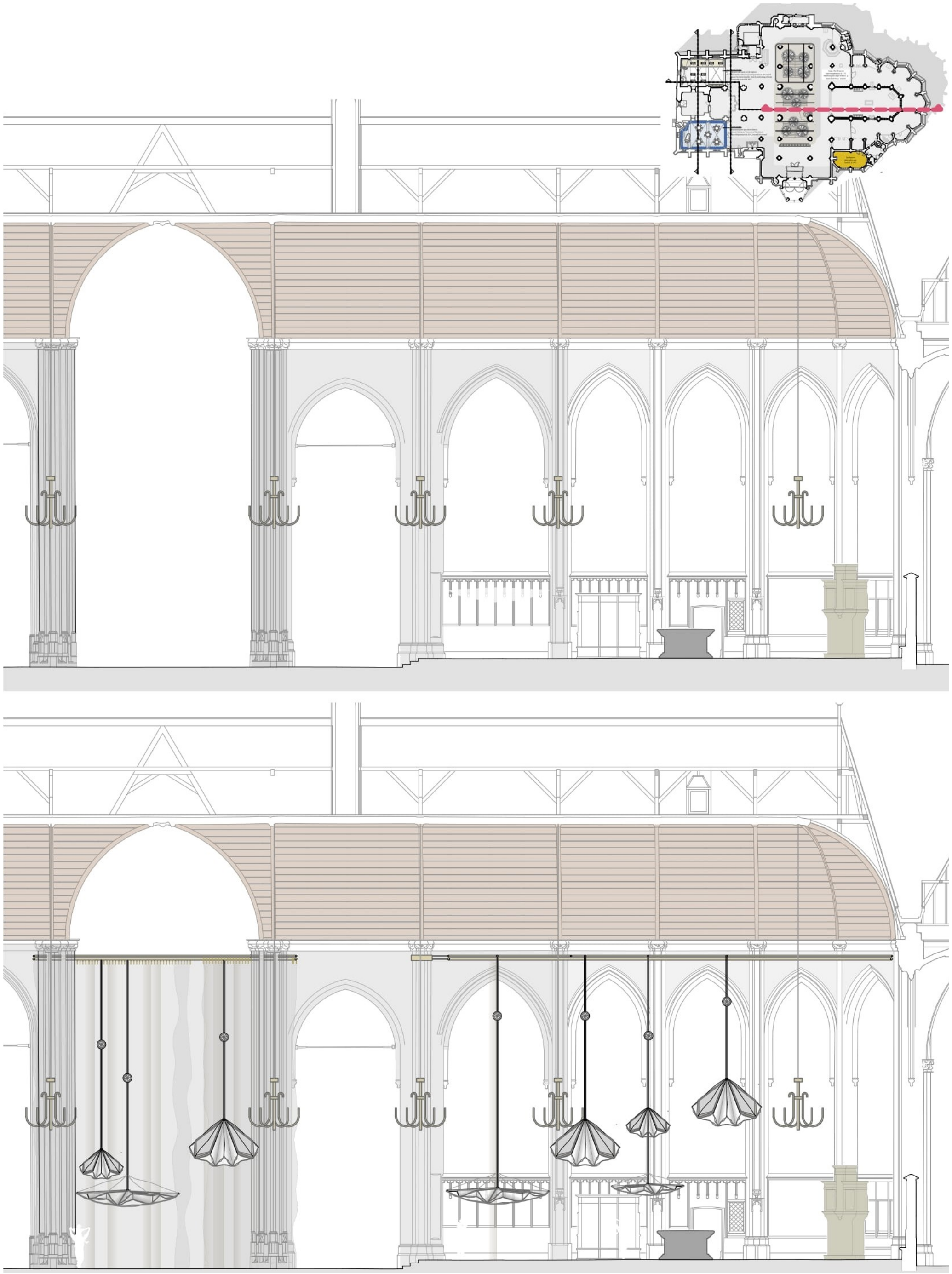


Figure 9.23: Section choir Stevenskerk - before and after

9.4.1 Wooden vault insulation

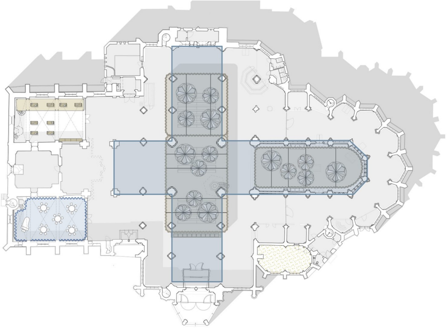


Figure 9.24: Stone vaults Stevenskerk

The vaults of the main nave and the transept in the Stevenskerk are constructed in wood (figure 9.24). The oak wood planking significantly contributes to the indoor space appearance of the church.

For the second step of the renovation their insulation is suggested to improve the thermal comfort without intervening in the visual appearance of the indoor space.

In contrast to the stone vaults the space in the roof is limited (Appendix B figure B.10 and figure 9.25). There is a narrow walkway integrated in the central part of the roof space, however it is difficult to access the sides of the vault.

The wooden vaults could be insulated by applying horizontal insulation blankets in the central part using a similar principle as proposed for the stone vault insulation (chapter 9.2.2 and figure 9.25). For the sides of the vault the application of flexible insulation blankets is suggested. As they are placed on top of the curved wooden beams ventilation in the roof structure can be ensured. Sufficient ventilation is crucial for the wooden vault to avoid the appearance of humidity leading to material damage. Therefore, the insulation material should be moisture permeable.

Figure 9.25 illustrates a first approach towards the wooden vault insulation in the Stevenskerk. Nevertheless, the impact of roof insulation on the air-permeability with regard to indoor space ventilation and conservation risks as well as the feasibility are to be considered in future research.

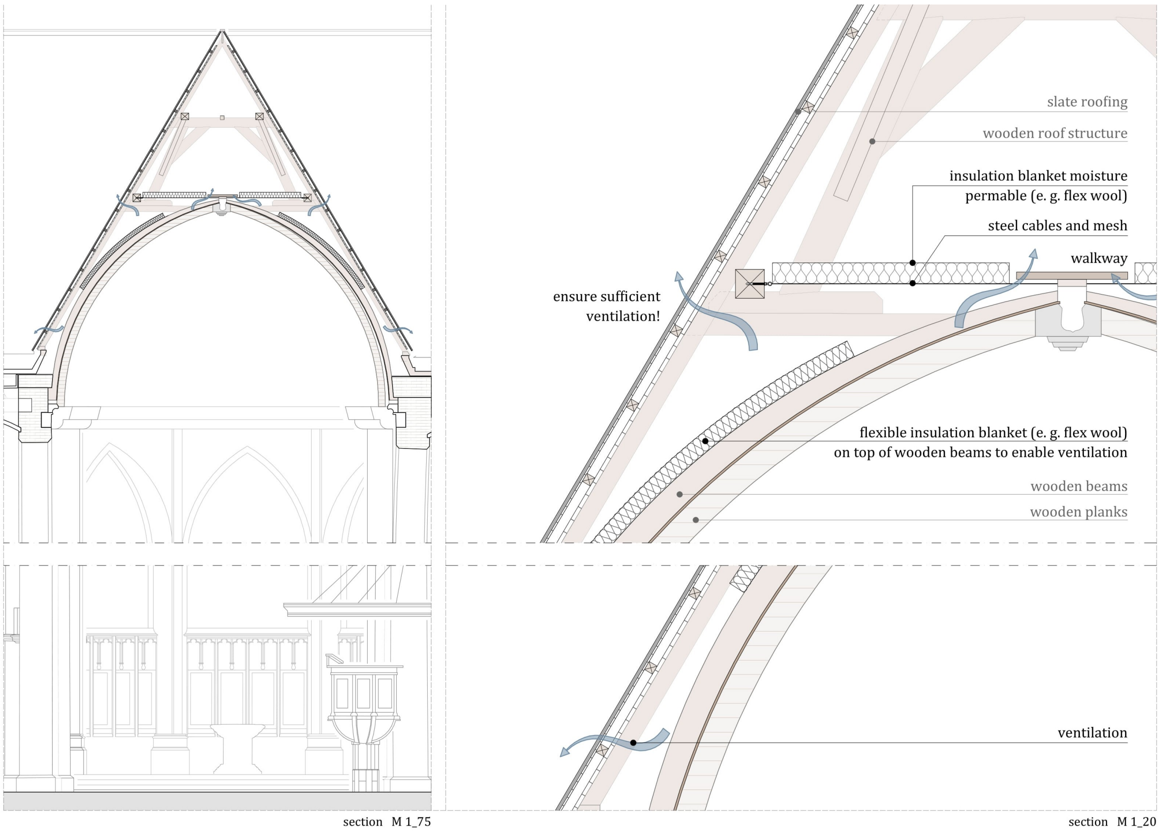


Figure 9.25: Conceptual detail wooden roof insulation

9.4.2 Ventilation concept

Hypocaust air heating system

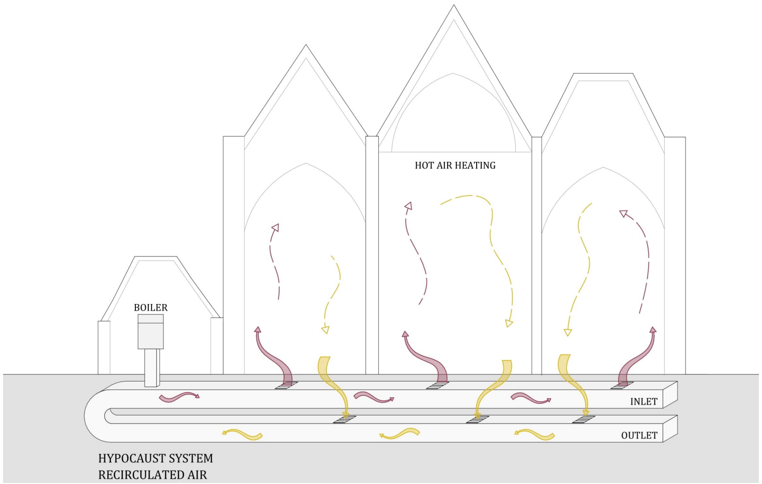


Figure 9.26: Concept diagram Hypocaust system now

The Stevenskerk was equipped with a Hypocaust floor heating system during its reconstruction (1953-1969) (figure Appendix B.11 and B.12). Air is heated by boilers and distributed to the indoor space through hardly insulated air channels in the floor construction (figure 9.26). Previous research has stated that this system is inefficient and proposed the adaptation to a water-based heating integrated into the flooring (Aarle, 2007; Nusselder & Zandijk, 2015). As the Hypocaust channel system is very uncommon, from a heritage perspective, it contains *high rarity-value* (heritage matrix Appendix B figure B.2) speaking in favour of its conservation as part of the monumental Stevenskerk. Additionally, the integration of a mechanical ventilation system will be required when improving the air-tightness of the Stevenskerk as it was suggested in the renovation proposal. The infiltration with outside air will be significantly reduced and the present Hypocaust air heating is a closed system which does not provide fresh air for the indoor space. Therefore, this chapter introduces two different conceptual ideas for re-using the channel system by integrating a mechanical ventilation for the supply of fresh air in the Stevenskerk.

Concept 1 - Passive pre-heating and -cooling of fresh air

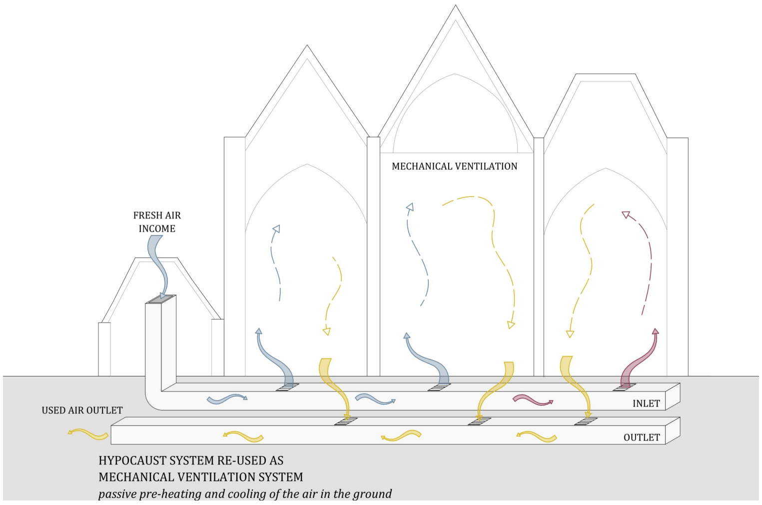


Figure 9.27: Concept diagram ventilation concept 01

It is proposed to use the Hypocaust channels as ducts for the ventilation while heating the space heating with an independent water-based system. During the winter fresh and cold outside air enters the hardly insulated channels and will be pre-heated by the higher enclosing ground temperature (figure 9.27). During the summer, the cooler ground will decrease the temperature level of the hot outside air. Thereby, the Stevenskerk is supplied with fresh and passively pre-tempered air. The used air is sucked through the existing outlet channel. An electric ventilation fan enables the ventilation rate control. However, the temperature of the supply air cannot be regulated and depends on the outside and the ground temperature as well as the duct length. The contamination of the existing ducts with finedust or asbestos could be an issue (Nusselder & Zandijk, 2015)

Concept 2 - Pre-heating and -cooling of fresh air with heat exchanger

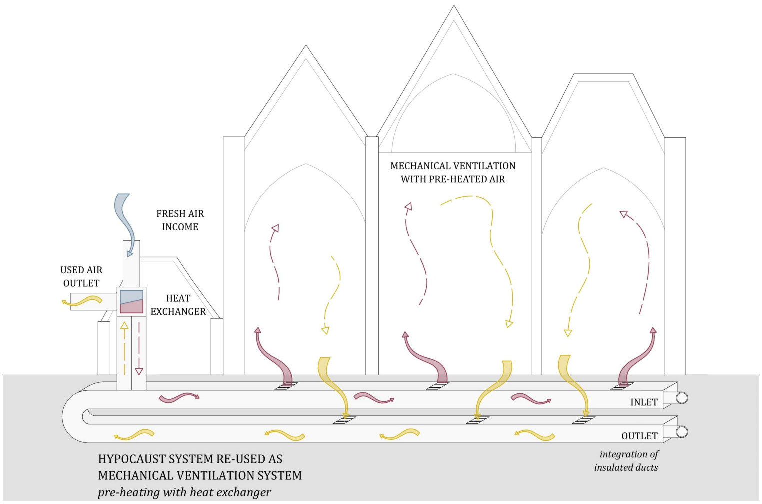


Figure 9.28: Concept diagram ventilation concept 02

In order to enable a better regulation of the temperature levels of the supply air from the mechanical ventilation, the integration of a heat exchanger and well insulated ventilation ducts is proposed (figure 9.28). At the location of the boiler (Appendix B figure B.12), a heat exchanger can be integrated into the system in order to pre-heat or pre-cool the incoming fresh outside air. This air is then transported to the indoor space through insulated ducts which are built into the existing channel system.
This enables the distribution of fresh air for the indoor space at different locations at a uniform temperature level. The used air is moved through well insulated ducts which are integrated into the outlet channels back to the heat exchanger and then leaves the building.

Conclusion and outlook
The introduced concepts are first ideas for integrating a mechanical ventilation system into the existing Hypocaust channels in the Stevenskerk. This shows potential for re-using and conserving building elements with heritage value on the one hand and introducing a mechanical ventilation for a comfortable indoor environment at adequate comfort levels on the other hand within an monumental building.
Nevertheless, the application of a ventilation system in the Stevenskerk requires additional investigation, development and design and should therefore be subject of future research.

9.5 Conclusion renovation proposal

To conclude, the selection of different strategies was chosen according to the separate assessment regarding the functional requirements for the different zones. The interventions in the large church space are focused on providing an adaptive space with flexibility for different functions. The proposed design for the South chapel leads to a quiet, introverted space for reflection and private or smaller events. The North chapel will be open for all visitors to experience and observe the space. In the Gerfkamer, comfortable thermal conditions for the current office use was the main objective.
Overall, the renovation measures were selected because they improve the accessibility and the perception of the monumental values by supporting multi functional usability of the Stevenskerk.

9.6 Use-case scenarios

In order to demonstrate how the renovation enhances the multi functional and adaptive usability of the Stevenskerk, this chapter illustrates three different use-case scenarios by means of floorplan and section drawings. According to the spatial and user requirements of the current functionality, the zones in the Stevenskerk can be adapted. The Gerfkamer is constantly used as an office space.

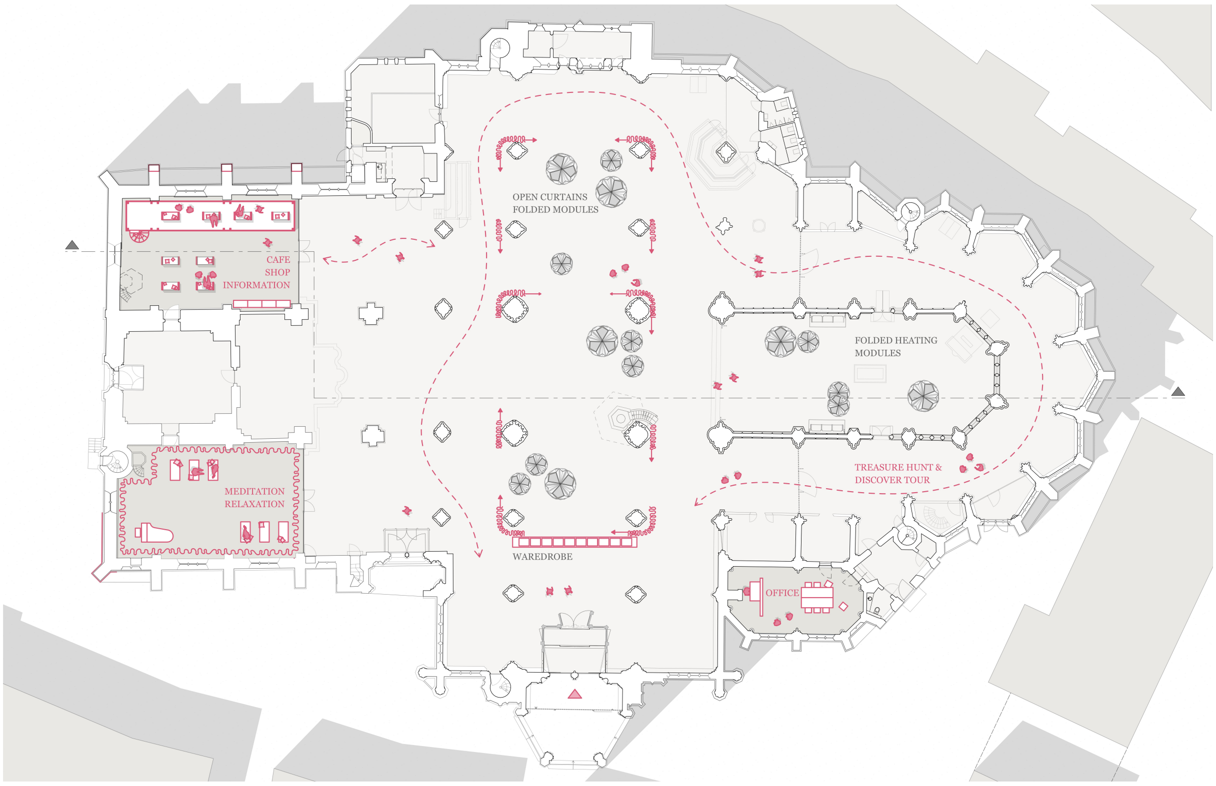


Figure 9.29: Scenario 1 - Floorplan - No event and open church for visitors

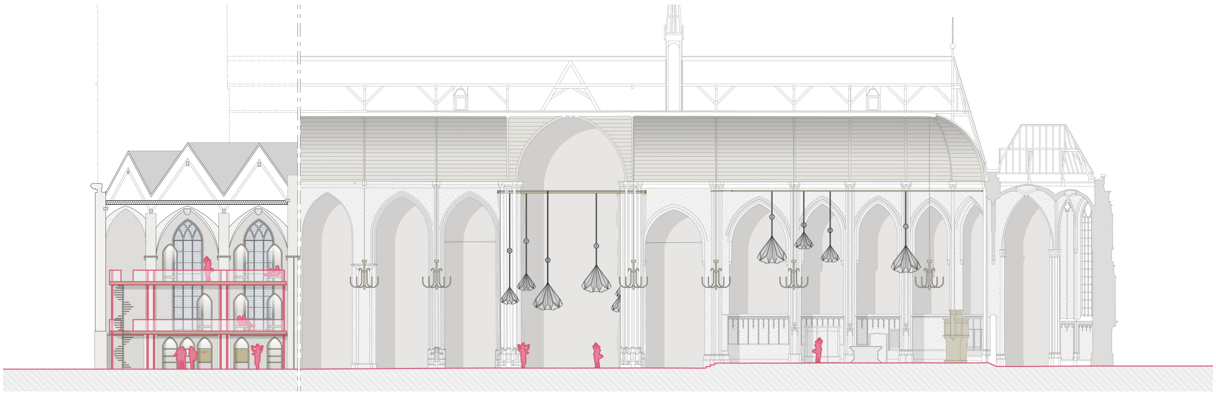


Figure 9.30: Scenario 1 - Section

Scenario 1 - No event in the Stevenskerk, open for visitors

In the first scenario the Stevenskerk is open for visitors to walk around and experience the monument (figure 9.29). They can get a coffee and information about upcoming events in the North chapel (figure 9.30). As the visitors are moving and can keep their outside clothing on the thermal requirements are limited. The curtains and the heating modules are collapsed to enable the full spatial experience. In the South chapel the visitors find a calm space for relaxation.

Scenario 2 - Simultaneous events in the Stevenskerk

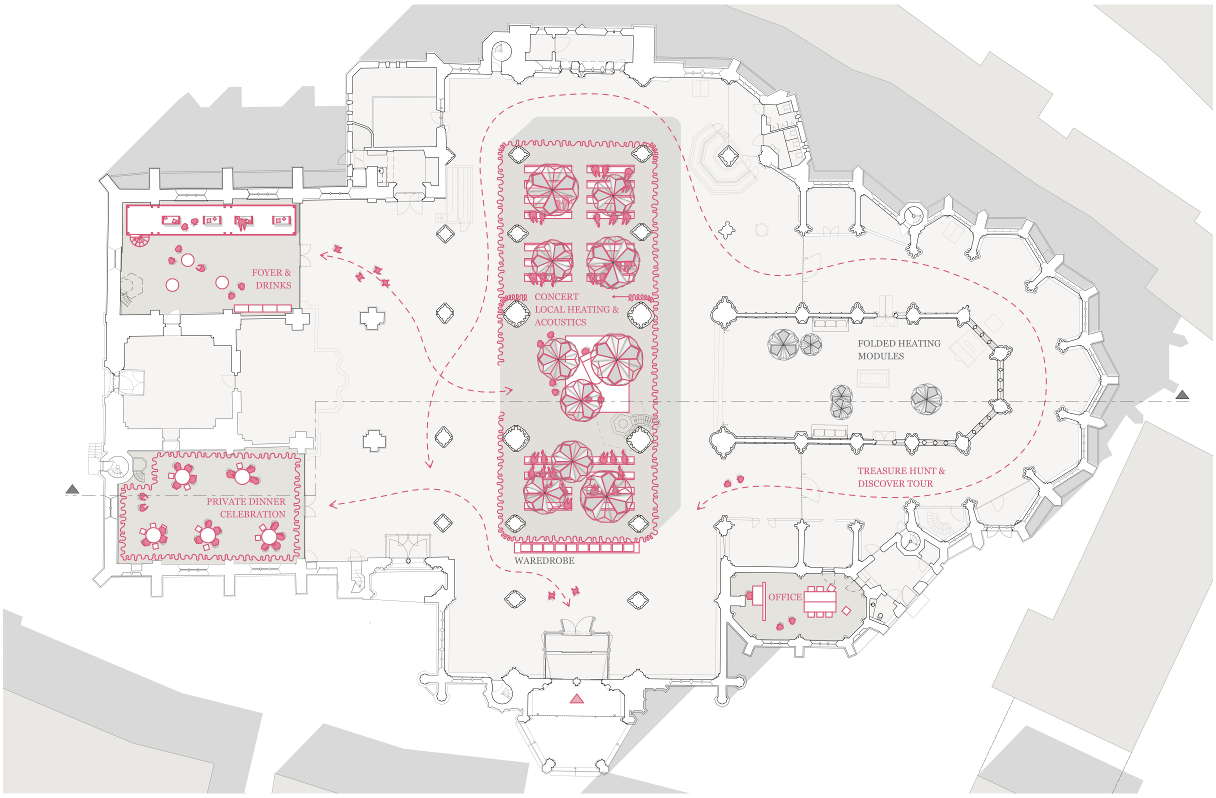


Figure 9.31: Scenario 2 - Simultaneous events

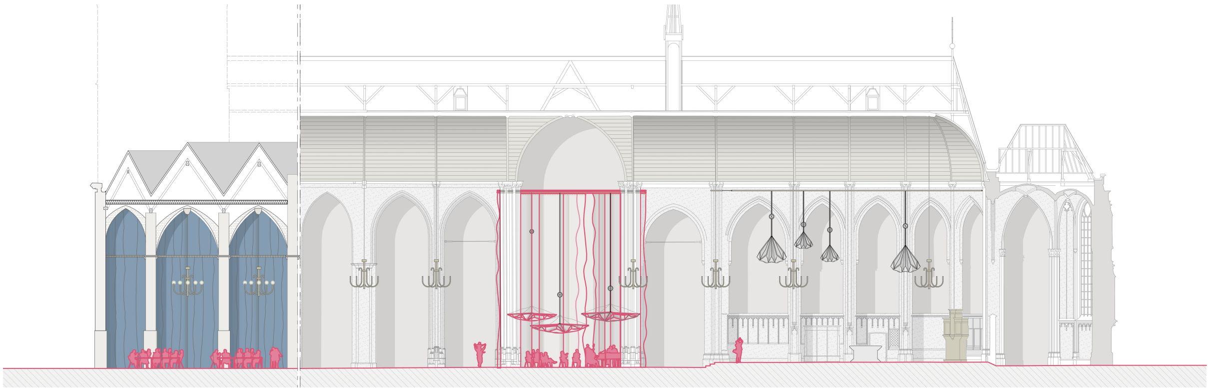


Figure 9.32: Scenario 2 - Section

During the second scenario different events are happening simultaneously. The curtains create a separate space in the transept (figure 9.31) which is appropriate for a concert due to improved acoustic and thermal conditions (heating modules and acoustic performing fabric). During the break, the audience can get a drink at the bar in the North chapel while experiencing the church space. A private dinner event is happening in the South chapel which is visually separated by the curtains (figure 9.32). At the same time, other visitors can experience the large church space (choir, ambulatory) by walking around. Moreover, a treasure hunt for children can be integrated in the large indoor space.

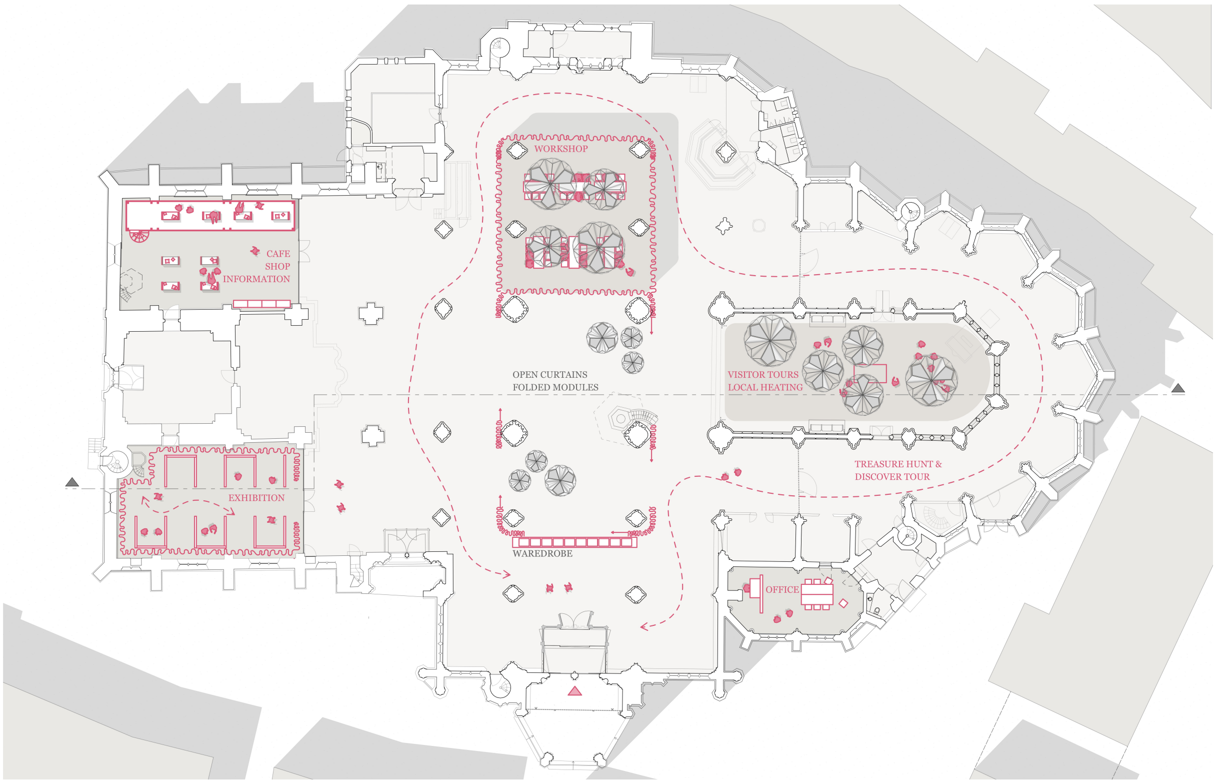


Figure 9.33: Scenario 3 - Floorplan - Cultural events

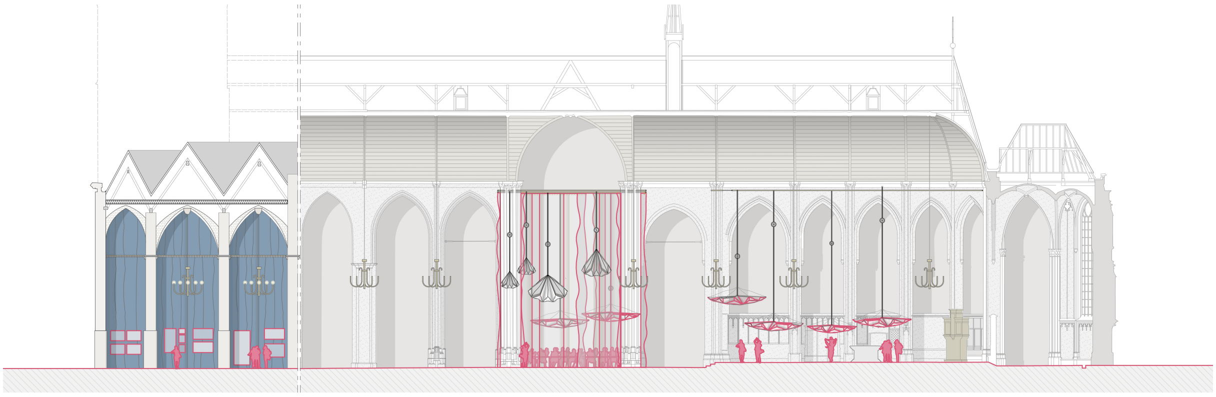


Figure 9.34: Scenario 3 - Section

Scenario 3 - Cultural events in the Stevenskerk

The third use-case illustrates how the smaller compartmentalized space in the transept with a good thermal and acoustic comfort level can be used for a workshop, a literature event or small presentation (figure 9.33). At the same time the main nave and the remaining large church space with its heritage values is open to be discovered by the visitors. In the choir the local heating modules provide thermal comfort during a guided tour about the Stevenskerk. Simultaneously, the South chapel accommodates an exhibition (figure 9.34). The shop and the cafe in the North chapel are accessible for all visitors of the different events.

10 Conclusion

10.1 Summary

The main goal of this research was to identify suitable renovation strategies for the improvement of the thermal comfort in the Stevenskerk in order to enhance the accessibility of the monument for different user groups and multi functional use.

The main research question was:
« How can the renovation of the stained glass windows in combination with indoor space adaptations increase the thermal comfort in the multi-functional Stevenskerk in order to improve the accessibility of the monument all year around? »

First, it was important to understand the current conditions in the case study building. Therefore, its thermal comfort challenges (chapter 4.2) as well as its heritage values (chapter 3.3) were assessed. Afterwards, the requirements for the thermal comfort and heritage conservation were compared (chapter 4.4). To understand possible approaches for solving the thermal comfort problem, an overview of renovation strategies for the stained glass windows was made and the thermal behaviour of the windows in the Stevenskerk was assessed by means of measurements and modelling (chapter 5). Moreover, different indoor spatial adaptation strategies were summarized (chapter 6).
The impact on thermal comfort improvement by promising renovation strategies was assessed by means of thermal comfort simulations (chapter 7).
Afterwards, the findings from the previous work were used as an input for evaluating the different renovation strategies according to an evaluation framework based on the research objectives (chapter 8).
The final outcome of the thesis is a comparative overview of different window renovation and spatial adaptation strategies applicable for multi-functional and monumental churches as well as a derived renovation proposal for the Stevenskerk (chapter 9).
Thus, this report provides a selection of several renovation measures with a potential for thermal comfort improvement and demonstrates its application on the Stevenskerk. Thereby, the research question could be answered. Nevertheless, it became clear that not one single solution can be identified as the best option but that the most suitable renovation strategies largely depend on the weighting of previously defined renovation objectives. Those result from the building specific future vision and can be related to heritage conservation, spatial functionality, durability, proportionate financial investment or indoor environmental quality.
Furthermore, this project shows that the combination of design, calculation models, measurements and computer simulations can serve as a suitable strategy for identifying and evaluating renovation strategies for a building.

10.2 Final conclusion

The Stevenskerk has been identified as an important heritage building. This refers to its status as a national monument but also to its significance for the city of Nijmegen and its inhabitants as an iconic landmark and a building for communal use. Even though the Gothic church dates from different construction and renovation periods it contains numerous monumental attributes with very high age, historic, use, rarity and relative art value which are to be preserved.

However, the current thermal situation in combination with an immense heating demand lead to an underused church which is closed during winter. Thus, this project has introduced different strategies for thermal comfort improvement to make the monument and its heritage attributes more accessible for different user groups.

By the selection of specific renovation strategies the current usage requirements on the one hand can be combined with the preservation of the monument on the other hand, according to the principle *«I have to change in order to stay the same»*.

In order to intensify the multi functional use of the Stevenskerk, the availability of zones with different functional and spatial characteristics is required. Therefore, the different spaces in the church and their distinctive condition and potentials were assessed. Taking into consideration that one renovation solution for the whole building cannot fulfill all requirements, specific and individual strategies were identified for each space. Accordingly, the final design proposal suggests distinctive designs for the different zones in the Stevenskerk which enable a flexible and adaptive use according to the needs of the user in a long-term perspective.

To conclude, this project provides one potential solution for a sustainable transformation of the Stevenskerk in accordance with its monumental values and its social function as a community building.

Figure 10.1: Kunstacademie Rotterdam, quote by Willem de Kooning

10.3 Limitations

This research has several limitations, of which a few are described below:

Renovation strategies:
This project was focused on the renovation of the stained glass windows and indoor spatial adaptations as two strategies with potential for thermal comfort improvement. Alternative renovation strategies such as the adaptation of the heating system, the vault insulation or heat recovery were mentioned and partially explained but they were not the focus of this project.

Renovation proposal:
The detailed application of the introduced renovation strategies including connections, materiality etc. was not the focus of this project. Instead, a comparative overview of different solutions is provided. The planning and the development of the detailed application of the renovation proposal on the Stevenskerk will require more time.

Simulations:
The comfort simulations in *DesignBuilder* are very time consuming which makes it challenging to quickly compare different strategies or adapt the simulation model according to a simulation outcome. Therefore, the number of thermal simulations was limited.

Measurement equipment:
The equipment for measuring the temperature and RH in the Stevenskerk was only available for a limited time period which defined the measurement period. Further assessment of the condensation risk in the closed cavity construction with internal PG would require measurements over a longer time period.

10.4 Recommendations for further research

Extension and application evaluation matrix:
The evaluation matrix for renovation strategies is limited to window renovation and spatial adaptation strategies. In order to make this matrix better applicable for other churches it should be extended with other renovation strategies. Furthermore, the performance criteria are based on the requirements for the Stevenskerk which could vary for another building.
The application of the matrix on different case-studies would be a suitable step for developing and extending the evaluation framework further towards universal validity for multi-functional and monumental church buildings in a heating dominated climate. Finally, the matrix could serve as a design and decision-making guideline for architects and building owners.

Physical aspects secondary glazing constructions:
This project focused on the effects of window renovation on thermal comfort. When considering the physical change of the window construction due to the application of secondary glazing, the following questions could be of interest:
To what extent does the application of secondary glazing change the reverberation time of a historical stained glass window?
To what extent are high RH levels a conservation risk for clear lead glass?
To what extent does humidity enter the natural stone wall or window frame when the moisture transport through the permeable stained glass is prevented by the application of secondary glazing? Does this lead to degradation risks for the stone?
Furthermore, the observation of the test windows with internal PG in the Side chapels and the Gerfkamer of the Stevenskerk is recommended for assessing the condensation risk over a longer time period.

Vault insulation:
Based on previous investigations on energy saving measures for the Stevenskerk this project included the vault insulation as a potential renovation strategy in the thermal simulations and provided an approach for integrating insulation in the roof space. However, this research only focused on the impact of the vault insulation on the thermal indoor comfort. Further research on the insulation material regarding moisture control (especially for the wooden vault) and the constructive placement of the insulation layer on the curved vault structure is required in order to apply this measure.

Ventilation and heat recovery:
The introduced renovation measures aim at reducing heating losses and natural infiltration in the Stevenskerk for thermal comfort improvement. However, a certain amount of natural infiltration is required to provide the church with fresh outdoor air. Therefore, before applying renovation measures, a careful consideration of the ventilation system is recommended. Chapter 9.4.2 provides a possible approach for re-using the Hypocaust floor channels for the integration of a mechanical ventilation. Nevertheless, this topic requires further and more extensive research.

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A Reflection

A.1 Graduation process and methodology

Overall, the project has shown that the selected methodologies of literature research, simulation and calculation modelling in combination with design can support each other enable the comparison of existing and the development of alternative renovation ideas.

The literature review was a suitable starting point for the project as it provided an overview of existing renovation strategies, their challenges and methods for their assessment. Furthermore, the research available about the Stevenskerk helped to identify and understand the problem.

The integration of the calculation model for the secondary glazing system including the experimental measurements taken was helpful to understand the physical functionality and the thermal problems resulting from the stained glass windows in the Stevenskerk. Furthermore, the calculation model could be used as a comparative tool. However, it has also become clear that the model in its current state is only an approximation to reality. Therefore, the results cannot serve as a definite decision making tool and further observation of the test windows is required which raises the question if the amount of time spent on developing and understanding the calculation model was unreasonable.

Similarly, the thermal computer simulations represent an approximation to reality, however, they are very suitable for visualizing the comparative analysis of different strategies. Nevertheless, the time required for thermal simulations using *DesignBuilder* was a challenge.

A.2 Relation research and design

The literature research provided the basis for the identification of the problem regarding the thermal comfort in the Stevenskerk as well as the conservation requirements of the monumental values and the stained glass windows. Accordingly, the designs provide solutions for the identified challenges.

Furthermore, the research on case study projects provides inspiration for the design of renovation strategies and demonstrates recommendations and guidelines for the application of renovation methods.

This thesis introduced an evaluation framework for the objective an analytical assessment and selection of the renovation strategies which resulted in a comparative overview. However, the expectation that this objective analysis strategy could lead to the selection of the most suitable measures could not be proved because there will always be advantages and disadvantages for the different strategies and the development of new combinations or adaptations could lead to a better solution.

Therefore, design and the influence of qualitative parameters which cannot be measured such as the spatial impression of a space or aesthetics have to be part when developing renovation strategies for a building. Thus, this project shows the necessity of combining research as the analytical approach together with design as a creative and subjective influence in order to find an appropriate solution.

A.3 Relation of the project to sustainability

Due to a replacement rate of only 1 to 3 % per year new built constructions are the minority of the buildings that will exist in 2050 (Ma et al., 2012). Thus, when targeting the European climate goals for 2050 in order to fight the ongoing climate crisis, the significance of extending the lifespan of existing non-residential buildings in order to make use of their embodied energy while decreasing their greenhouse gas emissions by reducing their energy demand becomes clear.

Referring to the described significance of the sustainable built environment transformation, this thesis provides and compares ideas how to improve the energy performance of a monumental building while enabling usability, thereby making use of its embodied energy and extending its lifespan as well as preserving its heritage values. The proposed interventions for the Stevenskerk are an example for the sustainable transformation of the built environment in a challenging case.

Furthermore, the results of this project may not only be relevant for the foundation Stevenskerk, but also for the owners of other multi-functional monuments aiming for a sustainable improvement of its climate performance while corresponding to thermal comfort requirements of the user.

A.4 Socio-cultural impact of the project

The improvement of the thermal comfort conditions in monumental buildings such as the Stevenskerk enables and promotes their accessibility all year around for an increased number of different user groups which is a central aspect in developing a sustainable future perspective for a building.

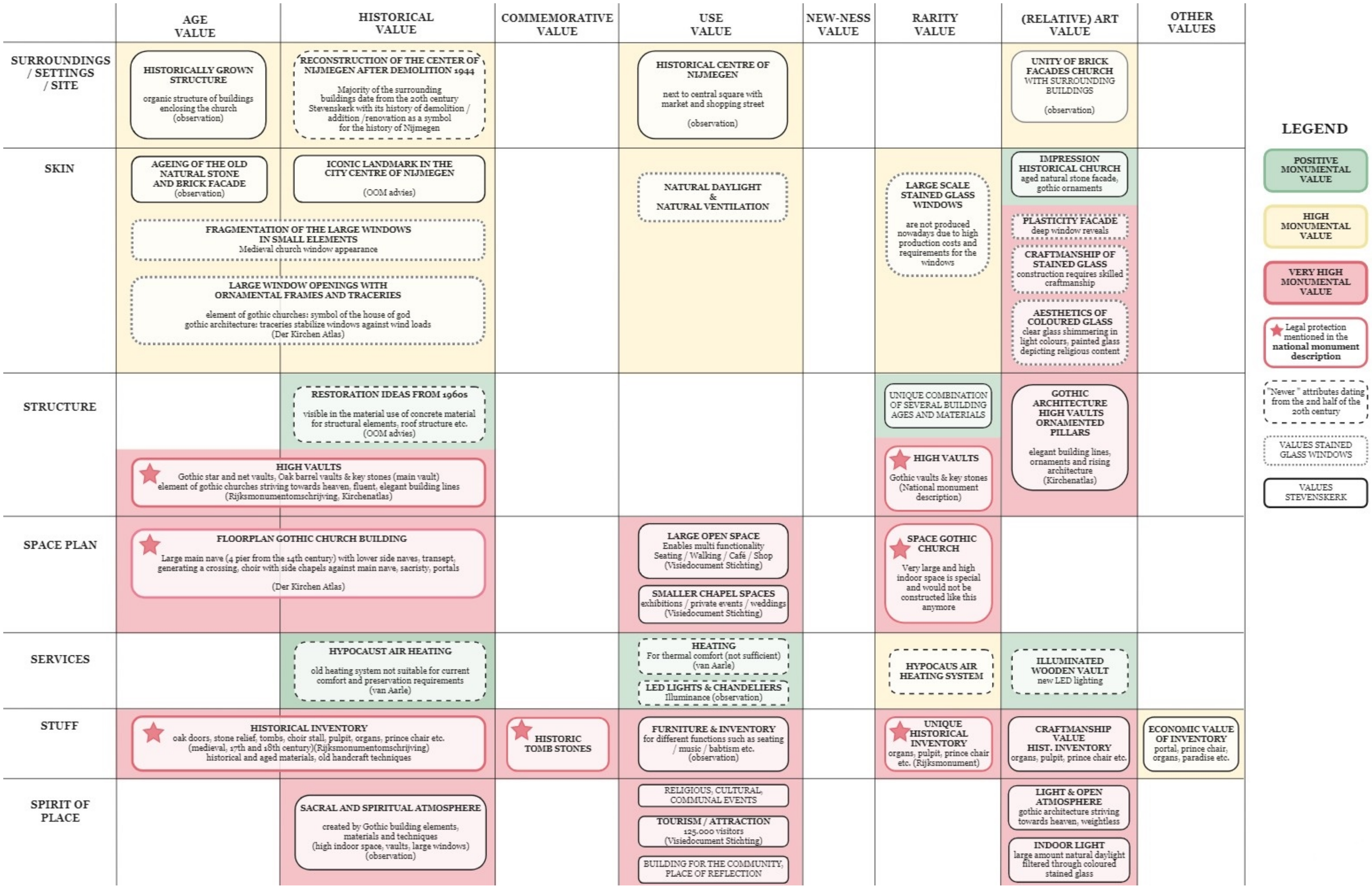
Although the preservation of monumental buildings is protected by law as they contain significant cultural-historical values, the usability and the accessibility are crucial arguments for the existence of a building. The objective for protecting those heritage values is because they are are relevant for the future generations. However, those values can only be experienced by future generations if they are accessible.

Therefore, the improved accessibility of a monument such as the Stevenskerk should not only be the objective from an economic perspective but also from a societal point of view.

B Tables and figures

TIME	BUILDING TRANSFORMATION
1254 – 1273	Gothic cross basilica (today four pillars have been preserved)
1343 – 1361	Extension east side: transept, large main choir with two side choirs
1375 – 1425	Conversion basilica to a three-aisled nave
end of the 14th century	Extension main nave with side aisles Sculpted portal south aisle
1420s	reconstruction: new Gothic choir with ambulatory and two-sided chapels sacristy (today the Gerfkamer) (south)
1431	reparation of the tower, which had burned down
1456	Completion net vaults above the ambulatory
1500 – 1565	Major renovation, Stevenskerk elevated to collegiate church: new transept with three naves completion large South portal chapel of the Holy Sepulchre against the north transept vaults of the side aisles
1591	Iconoclasm - Permanent reformation of the Stevenskerk Disappearance of the Catholic inventory including altars
beginning of the 17th century	New wooden structure for the tower in Mannerist style
1773 – 1776	Assembly organ by Christian Ludwig König
1870s	Renovation roofs
19th – beginning of the 20th century	Building fell into disrepair
22.02.1944	Bombardment Nijmegen Demolition of the tower, south chapel, south aisle and the western vault of the North chapel
1953 – 1969	Reconstruction of the church: Tower in reinforced concrete Use of concrete on the wall crowns and in the roof areas in the church Renewal of almost all caps (concrete) Vaults main aisle: higher and more pointed arch-shaped wooden barrel Reconstruction of the gables of the transepts (demolished in 1870s) Reparation small bell tower of the choir Closure of the western parts of the church Installation new heating system New crypt below the choir Renewal stained glass windows
2001	Installation painted stained glass windows by Marc Mulders

Figure B.1: Timeline building transformations Stevenskerk



	AGE VALUE	HISTORICAL VALUE	COMMEMORATIVE VALUE	USE VALUE	NEW-NESS VALUE	RARITY VALUE	(RELATIVE) ART VALUE	OTHER VALUES
SURROUNDINGS / SETTINGS / SITE	**HISTORICALLY GROWN STRUCTURE** organic structure of buildings enclosing the church (observation)	**RECONSTRUCTION OF THE CENTER OF NIJMEGEN AFTER DEMOLITION 1944** Majority of the surrounding buildings date from the 20th century Stevenskerk with its history of demolition / addition /renovation as a symbol for the history of Nijmegen		**HISTORICAL CENTRE OF NIJMEGEN** next to central square with market and shopping street (observation)			**UNITY OF BRICK FACADES CHURCH** WITH SURROUNDING BUILDINGS (observation)	
SKIN	**AGEING OF THE OLD NATURAL STONE AND BRICK FACADE** (observation) **FRAGMENTATION OF THE LARGE WINDOWS IN SMALL ELEMENTS** Medieval church window appearance **LARGE WINDOW OPENINGS WITH ORNAMENTAL FRAMES AND TRACERIES** element of gothic churches: symbol of the house of god gothic architecture: traceries stabilize windows against wind loads (Der Kirchen Atlas)	**ICONIC LANDMARK IN THE CITY CENTRE OF NIJMEGEN** (OOM advies)		**NATURAL DAYLIGHT & NATURAL VENTILATION**		**LARGE SCALE STAINED GLASS WINDOWS** are not produced nowadays due to high production costs and requirements for the windows	**IMPRESSION HISTORICAL CHURCH** aged natural stone facade, gothic ornaments **PLASTICITY FACADE** deep window reveals **CRAFTMANSHIP OF STAINED GLASS** construction requires skilled craftmanship **AESTHETICS OF COLOURED GLASS** clear glass shimmering in light colours, painted glass depicting religious content	
STRUCTURE	★ **HIGH VAULTS** Gothic star and net vaults, Oak barrel vaults & key stones (main vault) element of gothic churches striving towards heaven, fluent, elegant building lines (Rijksmonumentomschrijving, Kirchenatlas)	**RESTORATION IDEAS FROM 1960s** visible in the material use of concrete material for structural elements, roof structure etc. (OOM advies)				UNIQUE COMBINATION OF SEVERAL BUILDING AGES AND MATERIALS ★ **HIGH VAULTS** Gothic vaults & key stones (National monument description)	**GOTHIC ARCHITECTURE HIGH VAULTS ORNAMENTED PILLARS** elegant building lines, ornaments and rising architecture (Kirchenatlas)	
SPACE PLAN	★ **FLOORPLAN GOTHIC CHURCH BUILDING** Large main nave (4 pier from the 14th century) with lower side naves, transept, generating a crossing, choir with side chapels against main nave, sacristy, portals (Der Kirchen Atlas)			**LARGE OPEN SPACE** Enables multi functionality Seating / Walking / Café / Shop (Visiedocument Stichting) **SMALLER CHAPEL SPACES** exhibitions / private events / weddings (Visiedocument Stichting)		★ **SPACE GOTHIC CHURCH** Very large and high indoor space is special and would not be constructed like this anymore		
SERVICES		**HYPOCAUST AIR HEATING** old heating system not suitable for current comfort and preservation requirements (van Aarle)		**HEATING** For thermal comfort (not sufficient) (van Aarle) **LED LIGHTS & CHANDELIERS** Illuminance (observation)		**HYPOCAUS AIR HEATING SYSTEM**	**ILLUMINATED WOODEN VAULT** new LED lighting	
STUFF	★ **HISTORICAL INVENTORY** oak doors, stone relief, tombs, choir stall, pulpit, organs, prince chair etc. (medieval, 17th and 18th century)(Rijksmonumentomschrijving) historical and aged materials, old handcraft techniques		★ **HISTORIC TOMB STONES**	**FURNITURE & INVENTORY** for different functions such as seating / music / babtism etc. (observation)		★ **UNIQUE HISTORICAL INVENTORY** organs, pulpit, prince chair etc. (Rijksmonument)	**CRAFTMANSHIP VALUE HIST. INVENTORY** organs, pulpit, prince chair etc.	**ECONOMIC VALUE OF INVENTORY** portal, prince chair, organs, paradise etc.
SPIRIT OF PLACE		**SACRAL AND SPIRITUAL ATMOSPHERE** created by Gothic building elements, materials and techniques (high indoor space, vaults, large windows) (observation)		RELIGIOUS, CULTURAL, COMMUNAL EVENTS **TOURISM / ATTRACTION** 125.000 visitors (Visiedocument Stichting) BUILDING FOR THE COMMUNITY, PLACE OF REFLECTION			**LIGHT & OPEN ATMOSPHERE** gothic architecture striving towards heaven, weightless **INDOOR LIGHT** large amount natural daylight filtered through coloured stained glass	

LEGEND

- 🟩 POSITIVE MONUMENTAL VALUE
- 🟨 HIGH MONUMENTAL VALUE
- 🟥 VERY HIGH MONUMENTAL VALUE
- ★ Legal protection mentioned in the **national monument description**
- "Newer " attributes dating from the 2nd half of the 20th century
- VALUES STAINED GLASS WINDOWS
- VALUES STEVENSKERK

Figure B.2: Heritage value matrix Stevenskerk

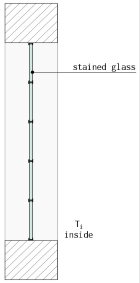
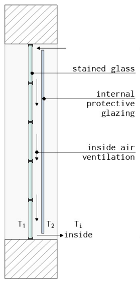
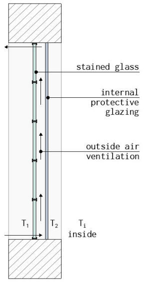
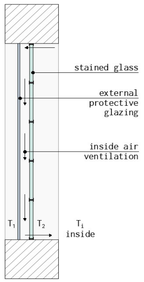
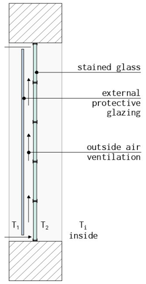
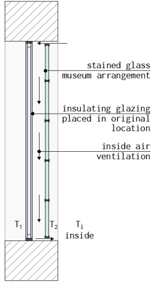
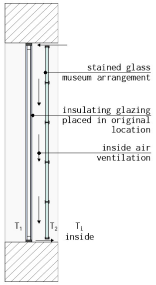
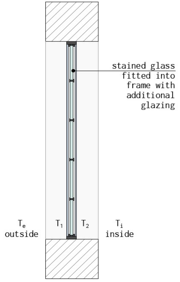
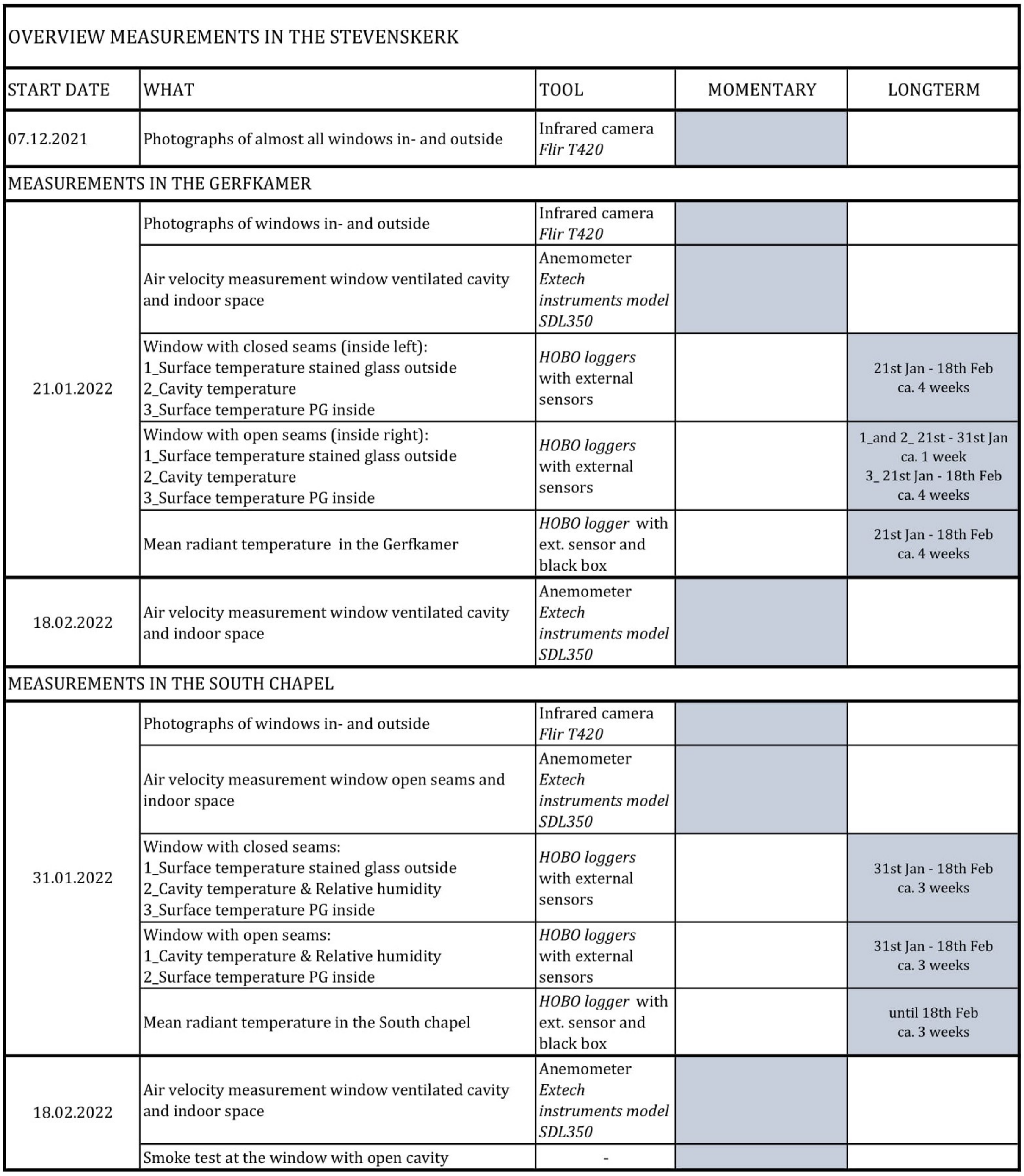
OVERVIEW COMMONLY USED PROTECTIVE GLAZING TYPES FOR STAINED GLASS WINDOWS (LITERATURE RESEARCH)	**1** 	**02** **INTERNAL PROTECTIVE SINGLE GLAZING**  	**03** **EXTERNAL PROTECTIVE SINGLE GLAZING**  	**04** **EXTERNAL DOUBLE GLAZING** 	**05** **MUSEUM ARRANGE-MENT** 	**06** **BONDED GLAZING** 
DESCRIPTION (outside to inside)	Single stained glass window	Stained glass window Protective glazing (Possibly with infrared coating on the inner surface reflecting heat back to the inside)	Glazing fitted in a metal or wooden frame to the window reveal, not connected to stained glass cavity depending on window's reveal, rarely perfectly airtight Stained glass window	Double glazing Cavity --- usually min 15mm for ventilation (toolkit, OOM) Stained glass window	New insulating glazing is placed at the locatin of the stained glass Bridging bars; space min 15mm, max60mm, ventilated with indoor air (toolkit, OOM) Stained glass is placed in a special frame	Protective glazing unventilated cavity (<40 mm) Stained glass Together fitted into a frame into double glazing Total construction min 19mm (toolkit, OOM)
TYPES OF PROTECTIVE GLAZING		UNINSULATED GLASS may cause condensation, limited effect on thermal improvement (toolkit, OOM) INSULATED GLASS Recommended for thermal improvement (toolkit, OOM)	LAMINATED GLASS outside air ventilation is advisable; accepting lower insulation effect (toolkit, OOM) GLASS WITH HEAT-REFLECTIVE FILM ventilation with inside air can cause severe condensation (toolkit, OOM) PLASTIC PRODUCTS (PLEXIGLAS) unsightly character with remaining high risk of condensation only allowed by monumental authorities in places without monumental values (toolkit, OOM)		If single glazing is used: Risk of condensation on the protective glazing; Therefore recommended to use glazing with a better insulation value	
ADVANTAGES	High amount of daylight income Aesthetics	Outside skin remains unchanged --- preserving the aesthetic monumental value Energy savings around 25% (DuMo, 2018) Stained glass remains in ist original position	Protection against external degradation (dirt / rain etc.) Energy savings of 6% (van Aarle, 2007) Reduction of transmission and infiltration losses (van Aarle, 2007) Comfort improvement (higher average radiation temperature, air velocity due to cold fall along the high windows is lower) (van Aarle, 2007) U-value stained glass improved from 5.7 to 3.6 W/m2K (van Aarle, 2007) Stained glass remains in ist original position	Improves thermal conductivity by approximately factor 3 (Wolf et al., 2013) Considerably imroves insulation value (toolkit, OOM)		Protection of the stained glass against all external degradation (dirt/rain/condensation etc.) No condensation when no humidity can enter the cavity
DISADVANTAGES	THERMAL COMFORT Windows are large thermal bridges Local discomfort due to radiation assymetry DEGRADATION STAINED GLASS Stained glass unprotected against weathering from in- and outside Risk of condensation when warm inside air passes the cold surface of the window	Internal glazing increases the risk of condensation on the stained glass (OOM, 2018) Stained glass remains unprotected against weathering from the outside	Smooth surface of the new glazing often reflecting the surroundings (Oidtmann, 1994) ---changing the aesthetic value	Condensation on frames and adjacent wall surfaces with cold surface temperatures, may lead to detrimental conditions for the interior (Wolf et al., 2013) Stained glass remains in ist original position	Aesthetic value Change of appearance from the inside and from the outside Removal of the stained glass = Risk for damage	Aesthetic value Change of the external skin, spatial effect, visibility of the stained glass Reflection of double glazing make stained glass less visible (from in- and outside) New lead solder will shine strongly (option for patinating) Not suitable for Large stained glass surfaces due to differences in thermal expansion; Not suitable for bridge rods (toolkit, OOM) Windows with a high monumental value (changes need to made to stained glass) Risk of thermal breakage as temperatures between glass panes, particularly with dark colours may rise
		VENTILATED WITH INDOOR AIR Condensation can form on the exterior of the stained glass due to the warm and humid air cooling down along the cold surface; sufficient ventilation in the cavity required to avoid condensation or only form on the PG (Oidtmann 1994) Chapel Stevenskerk: Cold trap seems to have intensified (Vis, 2020)	VENTILATED WITH INDOOR AIR Condensation can form on the interior of the protective glazing due to the warm and humid air cooling down along the cold surface The stained glass on the inside remains warm and is therefore not in risk of condensation (Oidtmann 1994) Good climatic and conservation conditions due to limited external ventilation	VENTILATED WITH INDOOR AIR Due to the higher insulation value of the construction condensation risk on the glazing is much lower		
		VENTILATED WITH OUTDOOR AIR Stained glass window should be seamlessly connected to the frame so that no air can enter between the stained glass and the PG; Otherwise there is a risk of condensation (toolkit, OOM) Cavity should be lightly ventilated with outside air (toolkit, OOM) Entrance of rain, dirt or insects from the outside	VENTILATED WITH OUTDOOR AIR Condensation can form on the inner surface of the interior stained glass due to the cold outside air cooling down the stained glass pane (Oidtmann 1994) Limited insulating effect (toolkit, OOM)			
INTERVENTIONS ON THE BUILDING'S VALUES	---		Placement of a new window frame into old reveal --- changing the historical value? New aethetics of the external skin, plasticity, visibility of the stained glass --- changing the aesthetic value?	Placement of a new window frame into old reveal --- changing the historical value? New aethetics of the external skin, plasticity, visibility of the stained glass --- changing the aesthetic value?	Placement of a new window frame into old reveal --- changing the historical value? visibility of the stained glass --- changing the aesthetic value?	Structural changes to the stained glass (trimming, remove armouring etc.) --- changing the value of craftmanship? Placement of a new window frame into old reveal --- changing the historical value? visibility of the stained glass --- changing the aesthetic value?
COSTS	---	270 EUR / qm (DuMo, 2018)		Low durability of double glazing (20-30 years), add. Costs (Wolf et al., 2013)	relatively expensive (toolkit, OOM)	more expensive than placement of external or internal PG (toolkit, OOM)

Figure B.3: Comparison protective glazing types



OVERVIEW MEASUREMENTS IN THE STEVENSKERK

START DATE	WHAT	TOOL	MOMENTARY	LONGTERM
07.12.2021	Photographs of almost all windows in- and outside	Infrared camera *Flir T420*	▨	
MEASUREMENTS IN THE GERFKAMER				
21.01.2022	Photographs of windows in- and outside	Infrared camera *Flir T420*	▨	
	Air velocity measurement window ventilated cavity and indoor space	Anemometer *Extech instruments model SDL350*	▨	
	Window with closed seams (inside left): 1_Surface temperature stained glass outside 2_Cavity temperature 3_Surface temperature PG inside	*HOBO loggers* with external sensors		21st Jan - 18th Feb ca. 4 weeks
	Window with open seams (inside right): 1_Surface temperature stained glass outside 2_Cavity temperature 3_Surface temperature PG inside	*HOBO loggers* with external sensors		1_and 2_ 21st - 31st Jan ca. 1 week 3_ 21st Jan - 18th Feb ca. 4 weeks
	Mean radiant temperature in the Gerfkamer	*HOBO logger* with ext. sensor and black box		21st Jan - 18th Feb ca. 4 weeks
18.02.2022	Air velocity measurement window ventilated cavity and indoor space	Anemometer *Extech instruments model SDL350*	▨	
MEASUREMENTS IN THE SOUTH CHAPEL				
31.01.2022	Photographs of windows in- and outside	Infrared camera *Flir T420*	▨	
	Air velocity measurement window open seams and indoor space	Anemometer *Extech instruments model SDL350*	▨	
	Window with closed seams: 1_Surface temperature stained glass outside 2_Cavity temperature & Relative humidity 3_Surface temperature PG inside	*HOBO loggers* with external sensors		31st Jan - 18th Feb ca. 3 weeks
	Window with open seams: 1_Cavity temperature & Relative humidity 2_Surface temperature PG inside	*HOBO loggers* with external sensors		31st Jan - 18th Feb ca. 3 weeks
	Mean radiant temperature in the South chapel	*HOBO logger* with ext. sensor and black box		until 18th Feb ca. 3 weeks
18.02.2022	Air velocity measurement window ventilated cavity and indoor space	Anemometer *Extech instruments model SDL350*	▨	
	Smoke test at the window with open cavity	-	▨	

Figure B.4: Overview measurements in the Stevenskerk

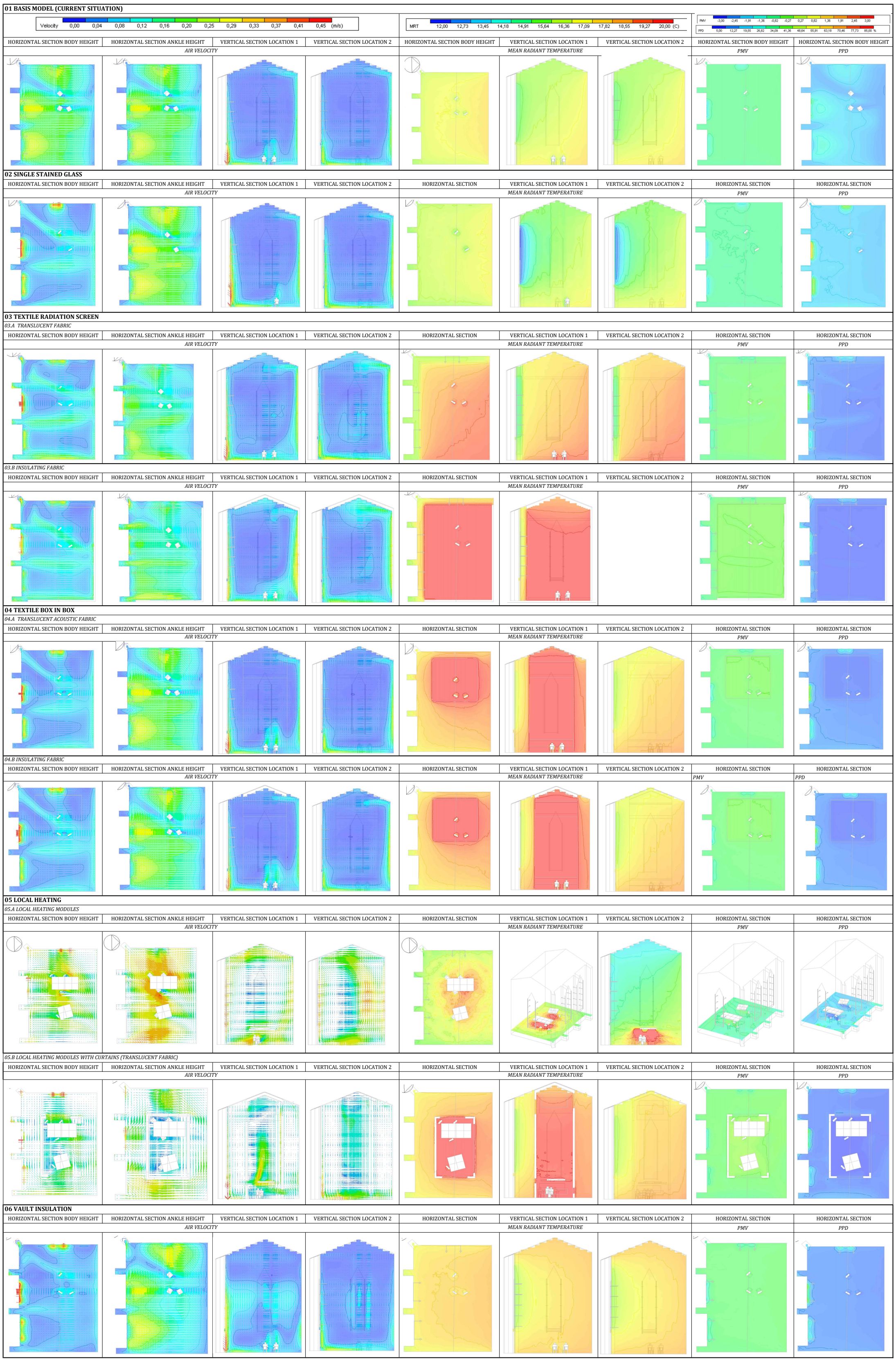
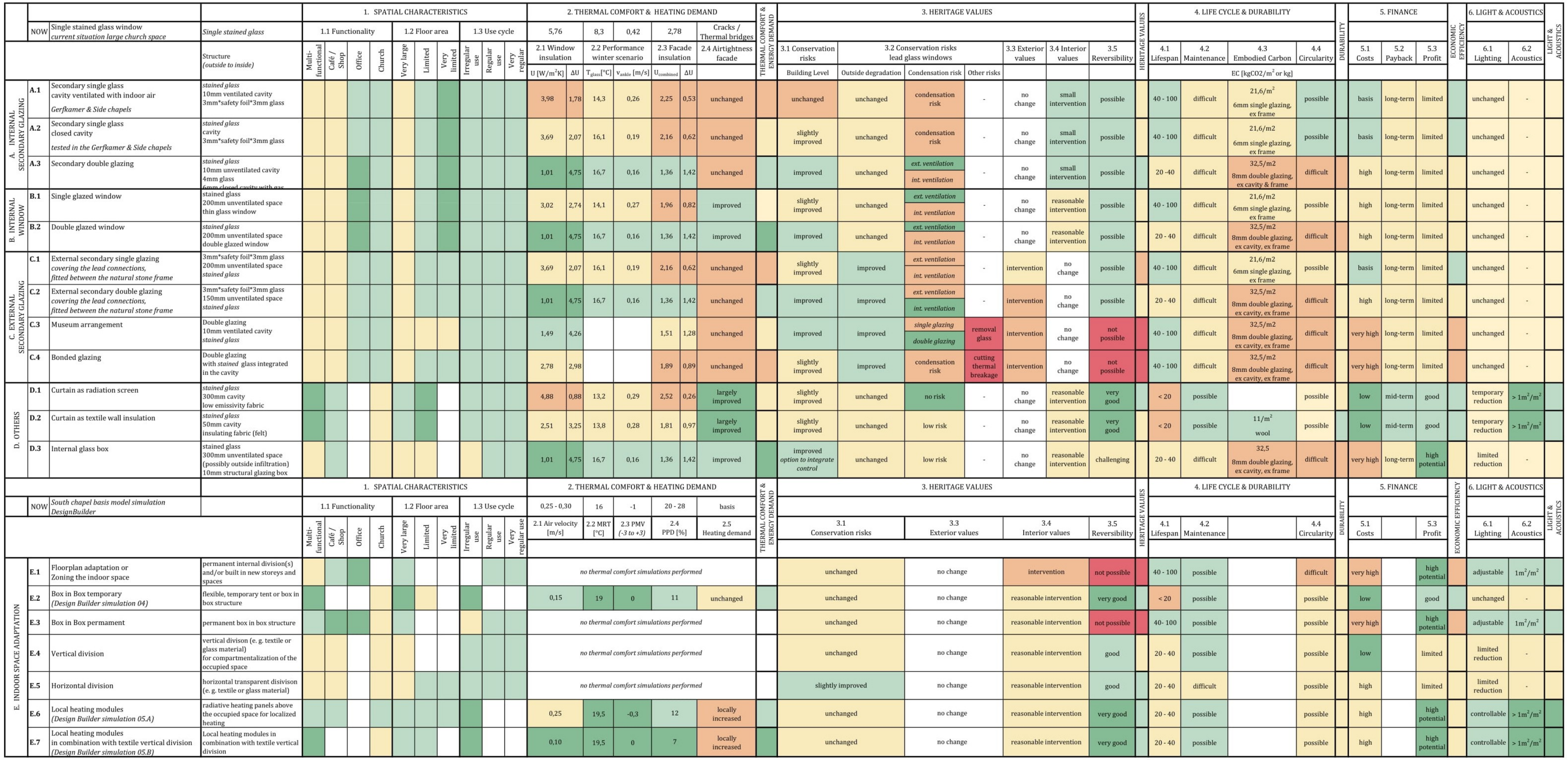


Figure B.5: Overview results thermal simulations South chapel



			Structure (*outside to inside*)	1.1 Functionality: Multi-functional	Café / Shop	Office	Church	1.2 Floor area: Very large	Limited	Very limited	1.3 Use cycle: Irregular use	Regular use	Very regular
	NOW	Single stained glass window *current situation large church space*	*Single stained glass*										
A. INTERNAL SECONDARY GLAZING	A.1	Secondary single glass cavity ventilated with indoor air *Gerfkamer & Side chapels*	*stained glass* 10mm ventilated cavity 3mm*safety foil*3mm glass	🟨	🟨	🟢	🟢	🟨	🟢	🟩	🟢	🟢	🟢
	A.2	Secondary single glass closed cavity *tested in the Gerfkamer & Side chapels*	*stained glass* cavity 3mm*safety foil*3mm glass	🟨	🟨	🟢	🟢	🟨	🟢	🟩	🟢	🟢	🟢
	A.3	Secondary double glazing	*stained glass* 10mm unventilated cavity 4mm glass 6mm closed cavity with gas	🟨	🟨	🟩	🟢	🟨	🟢	🟩	🟢	🟢	🟢
B. INTERNAL WINDOW	B.1	Single glazed window	stained glass 200mm unventilated space thin glass window	🟨	🟨	🟩	🟢	🟨	🟢	🟩	🟢	🟢	🟢
	B.2	Double glazed window	*stained glass* 200mm unventilated space double glazed window	🟨	🟨	🟩	🟢	🟨	🟢	🟩	🟢	🟢	🟢
C. EXTERNAL SECONDARY GLAZING	C.1	External secondary single glazing *covering the lead connections,* *fitted between the natural stone frame*	3mm*safety foil*3mm glass 200mm unventilated space *stained glass*	🟨	🟨	🟢	🟢	🟨	🟢	🟢	🟢	🟢	🟢
	C.2	External secondary double glazing *covering the lead connections,* *fitted between the natural stone frame*	3mm*safety foil*3mm glass 150mm unventilated space *stained glass*	🟨	🟨	🟢	🟢	🟨	🟢	🟢	🟢	🟢	🟢
	C.3	Museum arrangement	Double glazing 10mm ventilated cavity *stained glass*	🟨	🟨	🟢	🟢	🟨	🟨	🟨	🟢	🟢	🟢
	C.4	Bonded glazing	Double glazing with *stained* glass integrated in the cavity	🟨	🟨	🟢	🟢	🟨	🟢	🟢	🟢	🟢	🟢
D. OTHERS	D.1	Curtain as radiation screen	*stained glass* 300mm cavity low emissivity fabric	🟩	🟢		🟨	🟢	🟩		🟢	🟢	🟢
	D.2	Curtain as textile wall insulation	*stained glass* 50mm cavity insulating fabric (felt)	🟩	🟢		🟨	🟢	🟩		🟢	🟢	🟢
	D.3	Internal glass box	stained glass 300mm unventilated space (possibly outside infiltration) 10mm structural glazing box	🟨	🟢		🟨	🟨	🟨		🟨	🟢	🟢

	2. THERMAL COMFORT & HEATING DEMAND: 2.1 Window insulation U [W/m²K]	ΔU	2.2 Performance winter scenario T_{glass}[°C]	v_{ankle} [m/s]	2.3 Facade insulation $U_{combined}$	ΔU	2.4 Airtightness facade	THERMAL COMFORT & ENERGY DEMAND
NOW	5,76		8,3	0,42	2,78		Cracks / Thermal bridges	
A.1	3,98	1,78	14,3	0,26	2,25	0,53	unchanged	🟧
A.2	3,69	2,07	16,1	0,19	2,16	0,62	unchanged	🟨
A.3	1,01	4,75	16,7	0,16	1,36	1,42	unchanged	🟢
B.1	3,02	2,74	14,1	0,27	1,96	0,82	improved	🟨
B.2	1,01	4,75	16,7	0,16	1,36	1,42	improved	🟩
C.1	3,69	2,07	16,1	0,19	2,16	0,62	unchanged	🟧
C.2	1,01	4,75	16,7	0,16	1,36	1,42	unchanged	🟢
C.3	1,49	4,26			1,51	1,28	unchanged	🟨
C.4	2,78	2,98			1,89	0,89	unchanged	🟧
D.1	4,88	0,88	13,2	0,29	2,52	0,26	largely improved	🟨
D.2	2,51	3,25	13,8	0,28	1,81	0,97	largely improved	🟨
D.3	1,01	4,75	16,7	0,16	1,36	1,42	improved	🟩

	3. HERITAGE VALUES: 3.1 Conservation risks Building Level	3.2 Conservation risks lead glass windows: Outside degradation	Condensation risk	Other risks	3.3 Exterior values	3.4 Interior values	3.5 Reversibility	HERITAGE VALUES
A.1	unchanged	unchanged	condensation risk	-	no change	small intervention	possible	🟨
A.2	slightly improved	unchanged	condensation risk	-	no change	small intervention	possible	🟨
A.3	improved	unchanged	*ext. ventilation* *int. ventilation*	-	no change	small intervention	possible	🟢
B.1	slightly improved	unchanged	*ext. ventilation* *int. ventilation*	-	no change	reasonable intervention	possible	🟨
B.2	improved	unchanged	*ext. ventilation* *int. ventilation*	-	no change	reasonable intervention	possible	🟨
C.1	slightly improved	improved	*ext. ventilation* *int. ventilation*	-	intervention	no change	possible	🟧
C.2	improved	improved	*ext. ventilation* *int. ventilation*	-	intervention	no change	possible	🟨
C.3	improved	improved	*single glazing* *double glazing*	removal glass	intervention	no change	not possible	🟥
C.4	slightly improved	improved	condensation risk	cutting thermal breakage	intervention	no change	not possible	🟥
D.1	slightly improved	unchanged	no risk	-	no change	reasonable intervention	very good	🟢
D.2	slightly improved	unchanged	low risk	-	no change	reasonable intervention	very good	🟨
D.3	improved *option to integrate control*	unchanged	low risk	-	no change	reasonable intervention	challenging	🟨

	4. LIFE CYCLE & DURABILITY: 4.1 Lifespan	4.2 Maintenance	4.3 Embodied Carbon EC [kgCO2/m² or kg]	4.4 Circularity	DURABILITY
A.1	40 - 100	difficult	21,6/m² 6mm single glazing, ex frame	possible	🟢
A.2	40 - 100	difficult	21,6/m2 6mm single glazing, ex frame	possible	🟢
A.3	20 -40	difficult	32,5/m2 8mm double glazing, ex cavity & frame	difficult	🟧
B.1	40 - 100	difficult	21,6/m2 6mm single glazing, ex frame	possible	🟨
B.2	20 - 40	difficult	32,5/m2 8mm double glazing, ex cavity, ex frame	difficult	🟧
C.1	40 - 100	difficult	21,6/m2 6mm single glazing, ex frame	possible	🟨
C.2	20 - 40	difficult	32,5/m2 8mm double glazing, ex cavity, ex frame	difficult	🟨
C.3	40 - 100	difficult	32,5/m2 8mm double glazing, ex cavity, ex frame	difficult	🟨
C.4	40 - 100	difficult	32,5/m2 8mm double glazing, ex cavity, ex frame	difficult	🟨
D.1	< 20	possible		possible	🟨
D.2	< 20	possible	11/m² wool	possible	🟢
D.3	20 - 40	difficult	32,5 8mm double glazing, ex cavity, ex frame	difficult	🟧

	5. FINANCE: 5.1 Costs	5.2 Payback	5.3 Profit	ECONOMIC EFFICIENCY	6. LIGHT & ACOUSTICS: 6.1 Lighting	6.2 Acoustics	LIGHT & ACOUSTICS
A.1	basis	long-term	limited	🟢	unchanged	-	🟨
A.2	basis	long-term	limited	🟢	unchanged	-	🟨
A.3	high	long-term	limited	🟨	unchanged	-	🟨
B.1	high	long-term	limited	🟨	unchanged	-	🟨
B.2	high	long-term	limited	🟨	unchanged	-	🟨
C.1	basis	long-term	limited	🟢	unchanged	-	🟨
C.2	high	long-term	limited	🟨	unchanged	-	🟨
C.3	very high	long-term	limited	🟧	unchanged	-	🟨
C.4	very high	long-term	limited	🟧	unchanged	-	🟨
D.1	low	mid-term	good	🟢	temporary reduction	> 1m²/m²	🟢
D.2	low	mid-term	good	🟢	temporary reduction	> 1m²/m²	🟢
D.3	very high	long-term	high potential	🟨	limited reduction	-	🟨

				1.1 Functionality: Multi-functional	Café / Shop	Office	Church	1.2 Floor area: Very large	Limited	Very limited	1.3 Use cycle: Irregular use	Regular use	Very regular use
	NOW	*South chapel basis model simulation DesignBuilder*											
E. INDOOR SPACE ADAPTATION	E.1	Floorplan adaptation or Zoning the indoor space	permanent internal division(s) and/or built in new storeys and spaces	🟨	🟢	🟩		🟢				🟢	🟢
	E.2	Box in Box temporary *(Design Builder simulation 04)*	flexible, temporary tent or box in box structure	🟩			🟨	🟩	🟨		🟩		
	E.3	Box in Box permament	permanent box in box structure	🟢	🟩	🟩	🟨	🟢			🟨	🟢	🟢
	E.4	Vertical division	vertical divison (e. g. textile or glass material) for compartmentalization of the occupied space	🟨	🟨		🟨	🟨			🟢	🟢	🟢
	E.5	Horizontal division	horizontal transparent disivison (e. g. textile or glass material)	🟨	🟨		🟨	🟨	🟢	🟢	🟢	🟢	🟢
	E.6	Local heating modules *(Design Builder simulation 05.A)*	radiative heating panels above the occupied space for localized heating	🟢	🟢		🟢	🟢	🟢	🟢	🟩		
	E.7	Local heating modules in combination with textile vertical division *(Design Builder simulation 05.B)*	Local heating modules in combination with textile vertical division	🟩			🟨	🟢	🟢		🟩		

	2. THERMAL COMFORT & HEATING DEMAND: 2.1 Air velocity [m/s]	2.2 MRT [°C]	2.3 PMV *(-3 to +3)*	2.4 PPD [%]	2.5 Heating demand	THERMAL COMFORT & ENERGY DEMAND
NOW	0,25 - 0,30	16	-1	20 - 28	basis	
E.1	*no thermal comfort simulations performed*					
E.2	0,15	19	0	11	unchanged	🟢
E.3	*no thermal comfort simulations performed*					
E.4	*no thermal comfort simulations performed*					
E.5	*no thermal comfort simulations performed*					
E.6	0,25	19,5	-0,3	12	locally increased	🟢
E.7	0,10	19,5	0	7	locally increased	🟩

	3. HERITAGE VALUES: 3.1 Conservation risks	3.3 Exterior values	3.4 Interior values	3.5 Reversibility	HERITAGE VALUES
E.1	unchanged	no change	intervention	not possible	🟥
E.2	unchanged	no change	reasonable intervention	very good	🟢
E.3	unchanged	no change	reasonable intervention	not possible	🟥
E.4	unchanged	no change	reasonable intervention	good	🟨
E.5	slightly improved	no change	reasonable intervention	good	🟢
E.6	unchanged	no change	reasonable intervention	very good	🟢
E.7	unchanged	no change	reasonable intervention	very good	🟢

	4. LIFE CYCLE & DURABILITY: 4.1 Lifespan	4.2 Maintenance		4.4 Circularity	DURABILITY	5. FINANCE: 5.1 Costs		5.3 Profit	ECONOMIC EFFICIENCY	6. LIGHT & ACOUSTICS: 6.1 Lighting	6.2 Acoustics	LIGHT & ACOUSTICS
E.1	40 - 100	possible		difficult	🟨	very high		high potential	🟧	adjustable	1m²/m²	🟢
E.2	< 20	possible		possible	🟨	low		good	🟢	unchanged	-	🟨
E.3	40- 100	possible		possible	🟨	very high		high potential	🟧	adjustable	1m²/m²	🟢
E.4	20 - 40	possible		possible	🟨	low		limited	🟨	limited reduction	-	🟨
E.5	20 - 40	difficult		possible	🟨	high		limited	🟨	limited reduction	-	🟨
E.6	20 - 40	possible		possible	🟨	high		high potential	🟨	controllable	> 1m²/m²	🟩
E.7	20 - 40	possible		possible	🟨	high		high potential	🟨	controllable	> 1m²/m²	🟩

Figure B.6: Final outcome evaluation matrix

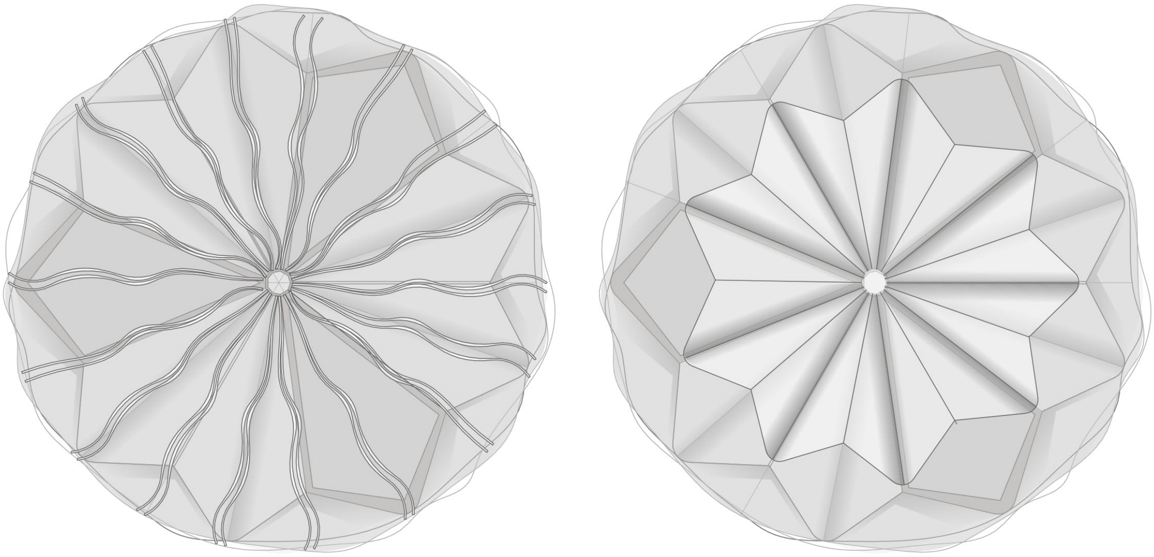


Figure B.7: Two options for the bottom view of the local heating modules with acoustic absorbing fabric

Figure B.8: Section Stevenskerk - South chapel with textile radiation screen, North chapel with walkways

Figure B.9: Walls with concrete ring beam in the roof space of the stone vaults (from Nusselder and Zandijk, 2015)

Figure B.10: Roof space wooden vault with walkway - limited space and roof structure with protective blankets against the entry of rain and snow

Figure B.11: Photograph of the Hypocaust air channels constructed below the floor during the reconstruction of the Stevenskerk (from Nusselder and Zandijk, 2015)

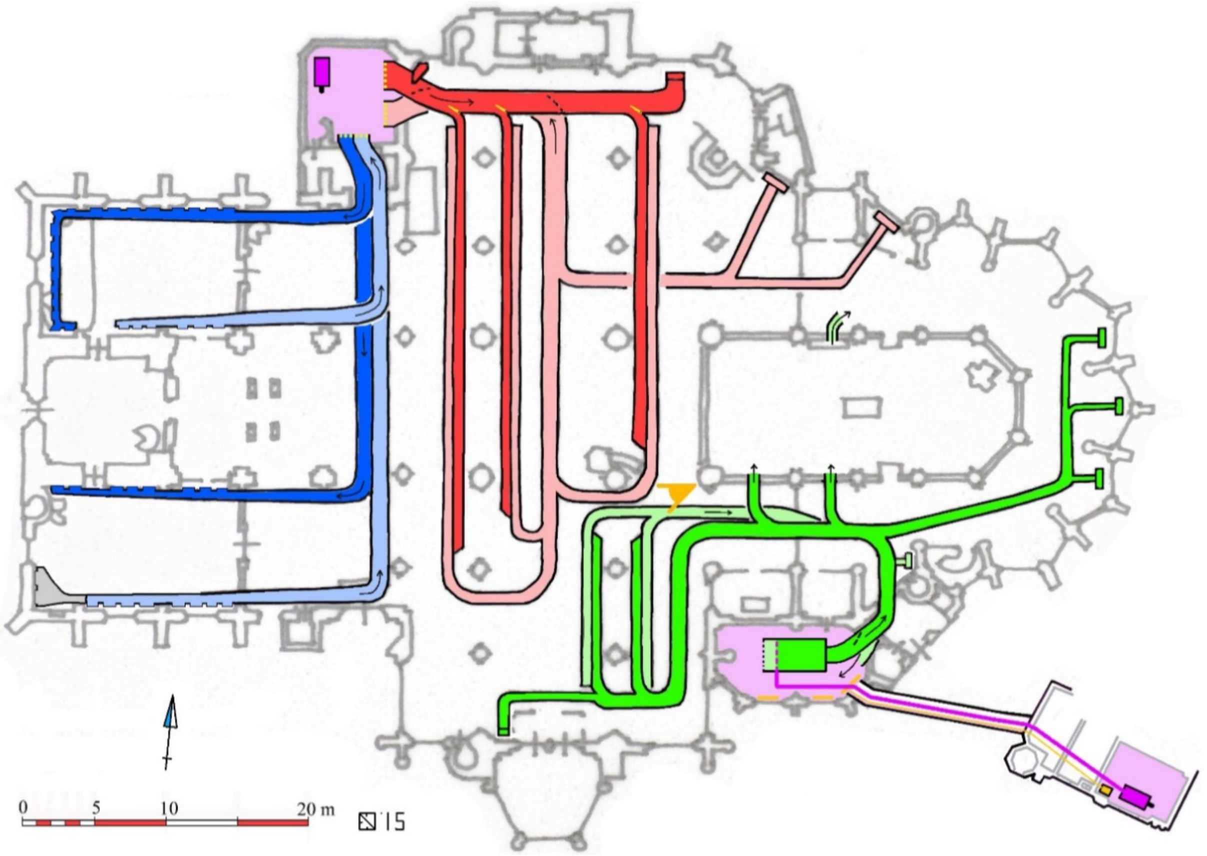


Figure B.12: Plan of the main channels and the boilers (purple) of the Hypocaust air heating system in the Stevenskerk (from Nusselder and Zandijk, 2015)

C Calculation models protective glazing

C.1 Closed cavity calculation model

Basis calculation principle

For the model of the stained glass with internal protective glazing and a closed cavity, a steady state calculation, representing the heat transfer over the cross-section of the window is used. The total heat resistance of the construction is composed of the heat resistance of the different layers. There are standard values for the horizontal heat transfer on the internal and external surface in the Netherlands. The heat resistance of the other construction layers can be calculated using their material thickness and the thermal conductivity of the material. When the total temperature difference between inside and outside is known, the temperature of each layer and accordingly the temperature gradient over the window construction can then be calculated.

$$R_{tot} = r_e + r_{sg} + r_{cav} + r_{pg} + r_i \tag{C.1}$$

where

R_{tot} = total heat resistance closed cavity construction $[m^2K/W]$

r_e = heat resistance external surface = 0.04 for the Netherlands $[m^2K/W]$

r_i = heat resistance internal surface = 0.13 for the Netherlands $[m^2K/W]$

r_{sg} = heat resistance stained glass $[m^2K/W]$

r_{cav} = heat resistance cavity $[m^2K/W]$

r_{pg} = heat resistance protective glazing $[m^2K/W]$

Validation with measurement data

In order to validate the calculation model with the situation in the Stevenskerk, the calculated and the measured temperature gradients were compared for different situations.

No heating

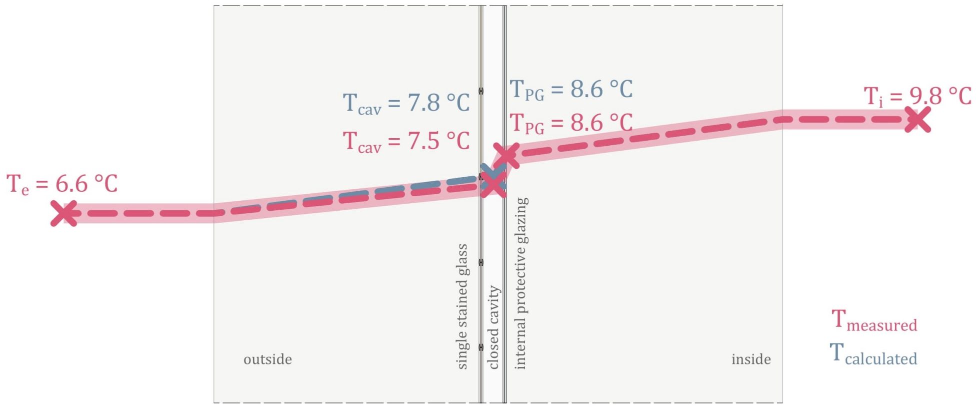


Figure C.1: Temperatures measured and calculated over the closed cavity window construction - No heating

When there is no heating inside, the calculated and the measured temperature gradient over the window construction coincide within a deviance of ± 0,5 °C. Thus, using the calculation model the temperature gradient over the window construction can be represented.

Figure C.1 illustrates the measured and the calculated temperatures (with given T_i and T_e) on the 6th of February 2022 in the South chapel.

During heating

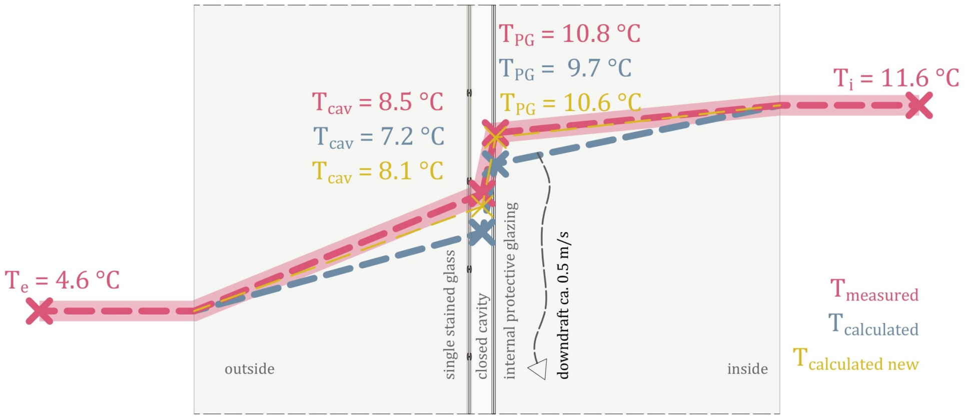


Figure C.2: Temperatures measured and calculated over the closed cavity window construction - During heating

When the heating is turned on, however, there are deviations > 1 °C between the calculated and the measured temperature gradient over the construction. Figure C.2 shows the night from the 17th to the 18th of February in the South chapel as an example when the space had been heated during the previous day.

The measured temperatures of the different window layers in the South chapel were used to calculate the heat resistances of the layers as a comparison to the calculation model based on the standard values. This comparison showed that according to the measurements, the heat resistance of the internal surface was much lower than the value given in the NTA 8800. By using 0.04 m^2K/W as the reduced heat resistance of the internal surface instead of 0.13 m^{2}K/W, the temperature gradient of the calculation model approximates to the measured data with a difference of max. 1.5 °C when there are large temperature differences between inside and outside and to a difference of max. 0.1 °C when the temperature difference is smaller (example figure C.2).

This decrease in the heat resistance of the internal surface can be explained by air movement along the surface. The temperature difference of the window and the indoor air (static pressure difference) and dynamic pressure resulting from the acceleration of air result in a pressure difference of the air layers leading to downdraft (van den Engel, 1993). The velocity of this downdraft can be approximated with formula C.2. The increased air movement does then reduce the insulating performance of the air layer directly adjacent to the internal window surface because it increases the heat transfer by conduction.

Thus, when using the calculation model, a careful consideration of the suitable heat transfer coefficient of the internal surface in relation to the indoor temperature level is required.

$$v_{air} = \sqrt{2 \times \frac{\Delta P}{\rho}} = \sqrt{2 \times g \times h \times \frac{(T_2 - T_1)}{T_2}} \tag{C.2}$$

where

$\Delta P =$ static pressure difference $[P]$

$\rho =$ density of air (at 10°C = 1.25) $[kg/m^3]$

$g =$ acceleration of gravity = 9.81 $[m/s^2]$

$h =$ window height $[m]$

$T_1 = T_{PG} =$ Surface temperature protective glazing $[K]$

$T_2 = T_i =$ Indoor air temperature $[K]$

C.2 Open cavity calculation model

For the ventilated cavity, the calculation model becomes more complex because there is an airflow present in the cavity. Therefore, a nodal model, based on physical models for the calculation of double skin facades (Bokel, 2020) or protective glazing systems (Oidtmann, 1994), available in the literature, was used.

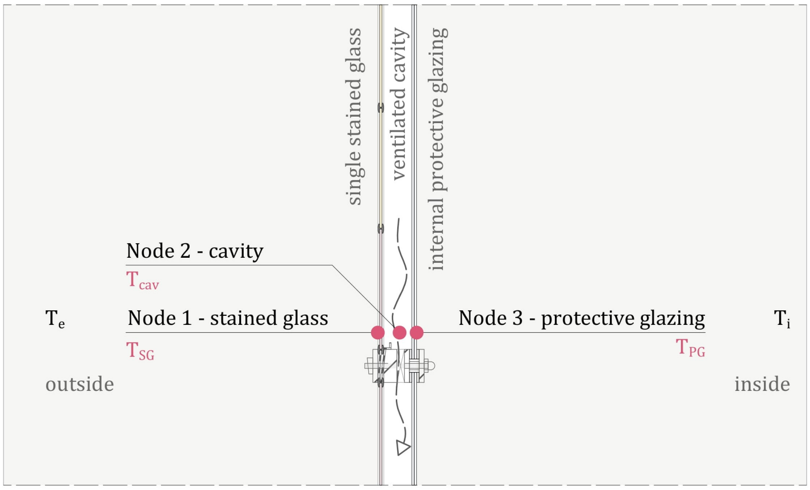


Figure C.3: Illustration nodal model

For the nodal model the window construction is schematized in a stationary situation with a given indoor and outdoor temperature. Horizontally, there are three different nodes in the system for which the heat balance equations are determined (figure C.3).
When the indoor and outdoor temperature are known, by means of the matrix calculation function in *Excel* the three heat balance equations (formulas C.3, C.4, C.6) can be used to determine the following three unknowns: The temperature of the stained glass, of the cavity air and of the protective glazing. The radiative heat transfer coefficient can thereby be calculated as a circular reference to the surface temperatures.

Node 1 - Single stained glass (glass 1)

$$\alpha_e(T_{glass1} - T_e) = \alpha_{c1}(T_{cavity} - T_{glass1}) + \alpha_{rad}(T_{glass2} - T_{glass1}) \tag{C.3}$$

where

α = heat transfer coefficient $[W/m^2K]$

α_e = total heat transfer coefficient to the outside = 25 (DIN4108) $[W/m^2K]$

α_{c1} = convective heat transfer coefficient glass to the cavity $[W/m^2K]$

α_{rad} = radiative heat transfer coefficient glass to the cavity $[W/m^2K]$

Node 2: Ventilated cavity

$$\begin{aligned}&\alpha_{c1}(T_{cavity} - T_{glass1}) \times A_{facade} + v_{air} \times A_{cavity} \times (\rho c)_{air} \times T_{in} \\ &= \alpha_c(T_{glass2-T_{cavity}}) \times A_{facade} + v_{air} \times A_{cavity} \times (\rho c)_{air} \times T_{out}\end{aligned} \tag{C.4}$$

where

α_{c1} = convective heat transfer coefficient to the cavity $[W/m^2K]$

$A_{facade} = b \times h$ = surface area of the cavity glass $[m^2]$

$A_{facade} = t \times h$ = surface area of the cavity cross section $[m^2]$

v_{air} = velocity airflow in the cavity, calculated with formula below $[m/s]$

$\rho \times c$ = specific heat of air = 1000 $[J/kgK]$

The air velocity of the ventilation air flow in the cavity can be calculated by the resulting pressure difference from the air temperature difference between the cavity and the indoor space air. The ventilation openings to the cavity of the windows in the South chapel are very small while the cavity is comparably long. This leads to a resistance against the airflow into the cavity. The usual practice of neglecting this value for simple calculation leads to too high air flow velocity by calculation (formula C.2) compared to the airflow measurements which taken at the ventilation opening exit in the South chapel (values > 1 m/s instead of 0.2 - 0.5 m/s).
Therefore, the pressure resistance which is dependant on the air velocity and the resistance factor was included in this calculation (formula C.5). It is set equal with the pressure difference resulting from the temperature difference and thereby can be solved for the air velocity. The resistance factor was increased up to 2.5 as this resulted in air velocity values matching with the measurements. The air temperature difference is dependent on the matrix calculation results and can be defined as a circular reference in *Excel*.

Refined formula for calculating the air-flow velocity in the ventilated cavity:

$$\xi \times \rho \times \frac{{v_{air}}^2}{2} = \rho \times g \times h \times \frac{\Delta T}{T} \tag{C.5}$$

where

ξ = resistance factor $[-]$

ΔT = air temperature difference cavity air and indoor space $[K]$

Node 3: Internal protective glazing (glass 2)

$$\alpha_e(T_{glass2-T_{cavity}}) + \alpha_{rad}(T_{glass2} - T_{glass1}) = \alpha_i(T_i - T_{glass2}) \tag{C.6}$$

$$\alpha_{rad} = 4 \times \varepsilon_{res} \times \sigma \times (\frac{T_1 + T_2}{2})^3 \tag{C.7}$$

where

α_{rad}	= radiative heat transfer coefficient to the cavity	$[W/m^2K]$
α_i	= total heat transfer coefficient to the inside	$[W/m^2K]$

Vertical segments

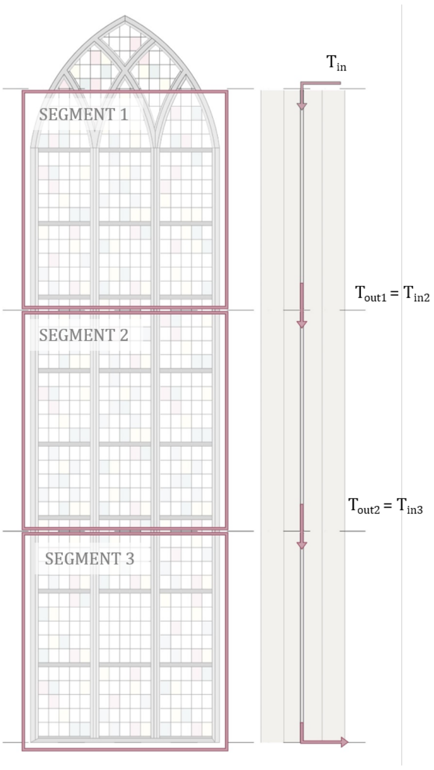


Figure C.4: Illustration vertical segments for the ventilated cavity calculation model

Due to the ventilation air flow in the cavity of the window there is a vertical temperature gradient over the height of the window. During a winter situation, the warm indoor air enters the cavity at the top and cools down along the external glass surface which results in downdraft. Therefore, the air in the cavity is warmer at the top than at the bottom.

In order to represent this gradient in the calculation, the window represented in the model was divided into 3 vertical segments. As described for a winter scenario when $T_i > T_e$, there is a downward air flow in the cavity. Thus, the air temperature which exits the upper segment is the air temperature which enters the segment below (see figure C.4).

Validation with measurement data

First, simple test cases where the outcome was known were used for checking the open cavity calculation model. For example, when the indoor and outdoor temperature are the same, the temperature gradient over the construction shows the equal temperature level and the air velocity in the cavity is zero. Afterwards, in order to validate the calculation model with the situation in the Stevenskerk, the calculated and the measured temperature gradients were compared.

No heating

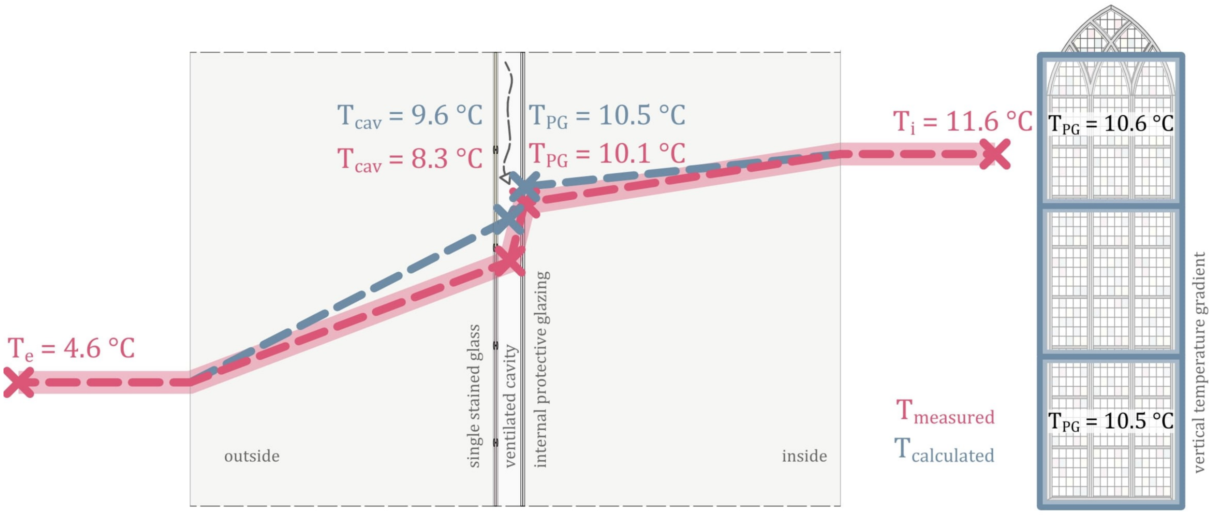


Figure C.5: Temperatures measured and calculated over the ventilated cavity window construction - No heating

When using the open cavity calculation model for a period without heating and without sun incidence, such as from 7pm on the 17th of February until 9am on the 18th of February, the calculated and the measured temperature gradient over the ventilated window construction align quite well (figure C.5). The temperature gradient which had been identified in the thermal imaging (chapter 3.4.2) over the window height is also represented in the calculation model.

Heating during the previous day

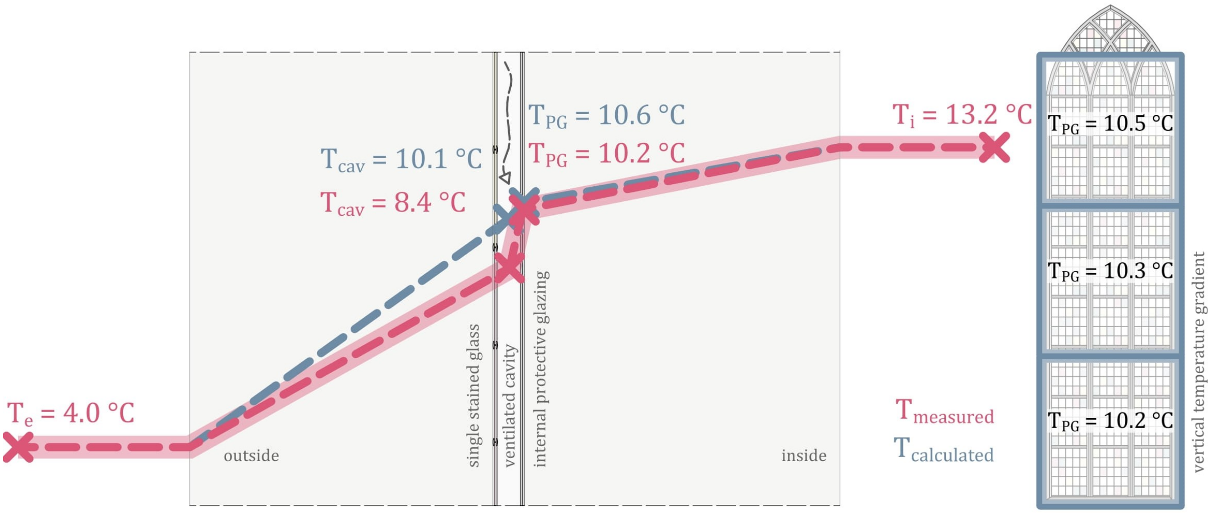


Figure C.6: Temperatures measured and calculated over the ventilated cavity window construction - Previous heating

Figure C.6 shows the temperature gradient from 7pm on the 7th to 9am on the 8th of February. The South chapel had been heated during the previous day which resulted in a higher indoor temperature without «active» heating impact turned on as it was off during the night and there was no sun incidence.

The comparison shows that the calculated and the measured temperature gradient over the ventilated window construction are very similar. The temperature gradient over the window height is also represented in the calculation model.

The comparison has shown that the open cavity model can be used as a representation for the thermal performance during periods without heating and sun incidence.

D Formulas

D.1 Radiation screen

Equation D.1 describes the radiative heat transfer between two surfaces facing each other (figure D.1). From this, an approximation for calculating the emitted radiation between a surface and a person with a radiation screen in between (q_{13}) in relation to the emitted radiation without a radiation screen (q_{12}) can be derived (Verhoeven, 1982).
When calculating the reduction (equation D.2) for a translucent fabric, the resulting emitted radiation is reduced by 50 %. When a high emmissivity fabric is used this reduction can be increased up to 95 %.

$$q_{12} = C_{12} \times ({T_1}^4 - {T_2}^4) \tag{D.1}$$

$$q_{13} = \frac{C_{13} \times C_{32}}{C_{13} + C_{32}} \times \frac{1}{C_{12}} \times q_{12} \tag{D.2}$$

where

T_1 = Surface temperature internal window or wall surface $[K]$
T_2 = Surface temperature occupant $[K]$
q_{13} = Radiation between window or wall surface and occupant with radiation screen $[W/m^2]$
q_{12} = Radiation between window or wall surface and occupant without radiation screen $[W/m^2]$
$C = \frac{1}{\epsilon}$ = Emmissivity material
C_1 = Emmissivity internal window or wall surface $= \frac{1}{0\ 94}$
C_2 = Emmissivity body occupant $= \frac{1}{0\ 95}$
C_3 = Emmissivity curtain, depends on the material
C_{12} = Resulting radiation number from internal window or wall surface towards occupant
C_{13} = Emmissivity from internal window or wall surface towards radiation screen
C_{32} = Emmissivity radiation screen towards occupant

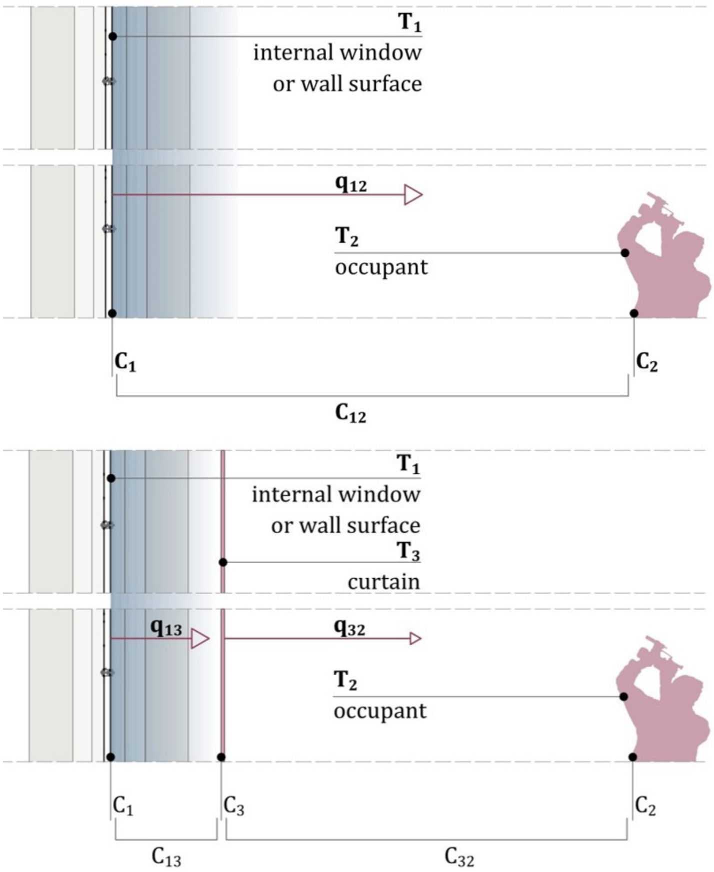


Figure D.1: Principle radiative heat transfer without and with curtain as a radiation screen

D.2 Air-stream velocity at ankle level

Formula D.3 for calculating the air velocity at ankle level is based on previous research (Menchaca-Brandan et al., 2017).
The window size in the South chapel was used as an example for the calculations (7.5m window height + 2.5m sill-height).
The closer the internal surface temperature of the window approximates to the indoor temperature the lower is the resulting discomfort due to downdraft. The lower the air velocity the better for the thermal comfort.

$$v_{ankle} = \frac{0\ 143}{x + 1\ 32} \times \sqrt{H \times (T_{in} - T_{glass})} \tag{D.3}$$

where

x = distance from the facade, 0.4m ≤ x ≤ 2m $[m]$
H = window height + sill height $[m]$
T_{in} = Indoor air temperature $[C]$
T_{glass} = Internal surface temperature glass $[C]$