REFURBISHMENT OF THE CITG FACULTY'S FAÇADE

A research on a new façade for the Civil Engineering and Geosciences faculty building, which will provide high indoor comfort combined with higher energy efficiency.

H. L. Roodvoets

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A research on a new façade for the CiTG faculty building, which will provide high indoor comfort combined with higher energy efficiency.

Master thesis of Hilde Liesbeth Roodvoets

This graduation project is initially formulated by Dipl. Ing T. Ebbert and Ir. H.R. Schipper of the Delft University of Technology. The project is part of the Building Technology department in which the chair of Design of Construction, under guidance of Prof.dr.ing. U. Knaack, functions as the main chair.

Delft, November 2, 2009

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Preface

In February of 2009, I started this master thesis within the chair of Construction and Design. The initial assessment was formulated by Roel Schipper and Thiemo Ebbert which both are familiar with the problems that can occur with old facades. Along the whole process of research and writing, they helped me to understand problems, finding solutions and pointing out new interesting aspects within the refurbishment project of the Civil Engineering and Geosciences faculty building. Tillmann Klein, who fulfilled the role of main tutor, supported me during the design and writing process in which I learned about many aspects that make refurbishment both complicated and appealing at the same time.

One could imagine, that in a refurbishment project a team of architects and advisors work together as a sort of tailor to create a coat that suits the building perfectly, and provide it with a comfortable indoor climate. It should respect the characteristics of the initial building, and on the other hand it should compete with new buildings. Refurbishment should revitalize a building, so that old and new can be found in the same object, like the image that is shown beneath. I think that within the time limits of this master thesis, some interesting ideas are developed, and tested. The results can be used within the further process of the CiTG faculty's façade refurbishment. Hopefully, in 2015, I can return to the Delft University of Technology campus with some of the students that I studied with during the master track, and admire the new façade of the CiTG faculty building. Maybe I'll find some similarities between the final design and the façade principles that are developed within this master thesis.

Concluding, my gratitude goes out to my parents who have supported me all along my study and to all of the previously mentions tutors along with Regina Bokel, without whom I could not have made the computer simulations.

Young lady or old woman?

Delft, November 2, 2009

Hilde Roodvoets

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1. Introduction

On August 24th 2009, all employees of the Civil Engineering and Geosciences faculty (CiTG) received an email of the facility management. The subject was: what to do about the extreme temperatures in the building? Many employees and students working in the CiTG faculty building complain about the extreme temperatures. Not only in the summertime, when the solar gain in the offices is very high, but also in the wintertime when cold downdraft along the façade causes thermally uncomfortable situations. The conclusion of the email; the continuity and quality of the service desks should not be affected by the temperature and individual workers should plan meetings in the morning and possibly work at home in the afternoon to escape from the extreme heat. A blower could be requested if necessary. The complete email can be found in Appendix 1

Figure 1.1 Faculty building of Civil engineering and Geosciences

Of course, these measures are not sufficient in the long run. The extreme heat that is previously described will cause discomfort, and the extreme cold that will occur in winter time will also cause an enormous energy use because of the large heating demand. Many buildings from the 1960's or 1970's are not well insulated. Many cold bridges, which might cause condensation problems, can be found in these buildings. The differences in standard between current standards and those from previous decades are noticeable. The heating was often realized by a radiator and cooling is summertime was only realized by natural ventilation. Summarized, there is a lot to improve on mid-century buildings, both in comfort and energy terms. On the other hand, the structure of the building is, most of the time, still in good condition. Destruction of an old building, and designing and realizing a new building, is not always the answer to these issues regarding comfort and energy. Moneywise, and from a sustainable point of view, the reuse of the initial building-structure is very tempting. In these cases, refurbishment is an option. When a building is refurbished, the façade can be adjusted so that the quality of the façade is Upgraded. It is also possible to replace the façade as a whole. Numerous possibilities can be thought of. However, not all the possibilities are capable of meeting the project specific requirements. Therefore, a selection of various suitable façade principles has been made. Eventually, the decision for a final design should be made.

To review the façade principles that are suggested for a refurbishment project, a new tool has been developed by T. Ebbert, during his PhD research on refurbishment processes, at the Delft University of Technology (DUT). The so called 'Wheel of potentials', that is shown in Figure 1.2, gives a graphic overview of the qualities that a façade principle has. The weaknesses can be pointed out easily as well. Aspects that are of influence on refurbishment are placed in a excel sheet. This sheet contains questions that result in a score for each aspect. The aspects are categorized in four important goals of refurbishment:

- Economic
- Architecture and function
- Material and energy
- Comfort

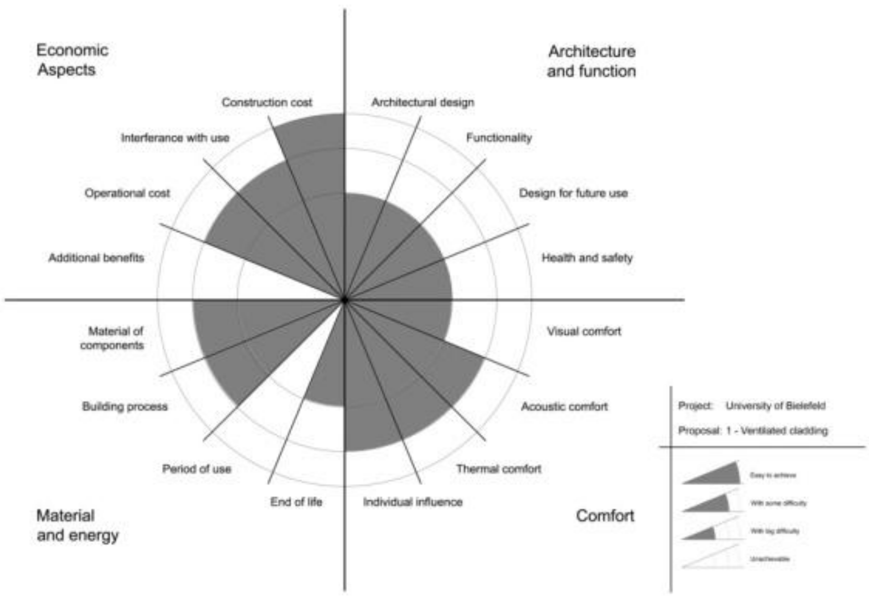


Figure 1.2. schematic evaluation of facades by Thiemo Ebbert

With the use of these graphics, relations between the different aspects of refurbishment can be made clear and the façade proposals are made comparable.

To find out if this tool is useful for refurbishment projects, a case study is done. As previously mentioned the CiTG faculty building has a lot of comfort problems and uses an enormous amount of energy. Because higher energy efficiency and a higher comfort standard are admired within this building by Delft University of technology (DUT), the refurbishment of the CiTG faculty building will function as a case study for this graduation project.

By increasing the comfort level in an office, employees are able to concentrate more on their work and work more efficiently. Imagine working in a very cold room; the low temperature will disturb the concentration over and over again. In an uncomfortable situation, a human being will try to make himself comfortable by adding or removing cloths and regulating the heater or cooling device constantly. On the other hand every uncomfortable situation can be solved with cooling and heating devices. However, these installations consume a lot of energy. So, when many installations are placed to control the indoor climate, more energy is used. Therefore, coherence between comfort on the one hand and energy use on the other is one of the keynotes within this project.

A research is done into comfort aspects, such as the standard temperature that people prefer in offices. Background information and legislation are consulted and applied into requirements for this particular refurbishment project. Furthermore, technical drawings of the building and future plans of DUT are consulted and onsite visits are executed to understand the present shortcomings in the building. Computer simulations are run to check the thermal comfort and energy use in the offices in the initial situation as compared to the simulation models of the new façade. The findings are then used to evaluate and compare the comfort and energy performance of the façade principles more specifically.

To secure the uniformity between the different façade principles, a standard section of the building is used. After the evaluation with the Wheel of potentials, a final design is made for the façade of the CiTG faculty building. To come to this final design, many questions are answered. The main question of this research can be formulated as:

Which façade is the most suitable for the refurbishment of the CiTG faculty building, if the focus is on indoor comfort aspects and energy consumption?

However, to be able to answer this question properly, some key questions have to be answered first:

- What are the (essential) aspects that determine inside comfort?
- What are the comfort requirements for the CiTG building?
- What are the shortcomings in comfort within the CiTG building?
- With what interventions can the comfort requirements be fulfilled?
- How is the CiTG building constructed and what does that mean for possible façade solutions?
- What are possible solutions for a new façade for the CiTG building?
- What are the comfort and energy performances of these solutions?
- How do the solutions perform in terms of other refurbishment aspects like execution, building technology, and architecture?
- How does the Wheel of potentials work, and can the refurbishment solutions be evaluated properly with this tool?
- What is the best overall solution?

After this introduction, the theoretical framework will be formulated. In the first paragraph, the comfort aspects: temperature, air, acoustics, daylight, and fire are discussed and translated into a list of requirements. In the second paragraph, the energy consumption and future energy reduction plans of the DUT are explained. Chapter two will give insight into the case study method, by analyzing the CiTG faculty building in the first and a brief overview of the standard section that is used, can be found in the second paragraph. In the third paragraph an explanation of the standard computer models is given. Furthermore four façade principles for the refurbishment of the CiTG faculty building are introduced as well as the computer models that are used per façade principle and the wheel of potentials is discussed in the last paragraph. The calculations that are done with the use of the earlier introduced computer models result in graphics and numeric output, which are given in chapter four per façade principle. The wheels of potential for each façade principle can be found in this chapter as well. Chapter five will interpret and evaluate the results per façade principle and discuss the wheels of potentials. A discussion of the wheel of potential as an evaluation tool can be found in the second paragraph of chapter five and different scenarios that give insight in different future perspectives and the influence on the aspects are set out in the last paragraph. In chapter six, conclusions will be drawn from the discussion in chapter five. The report will be concluded by chapter seven, where a façade proposal for the refurbishment of the CITG faculty building can be found. The buildup of the report and process is shown in Figure 1.3.

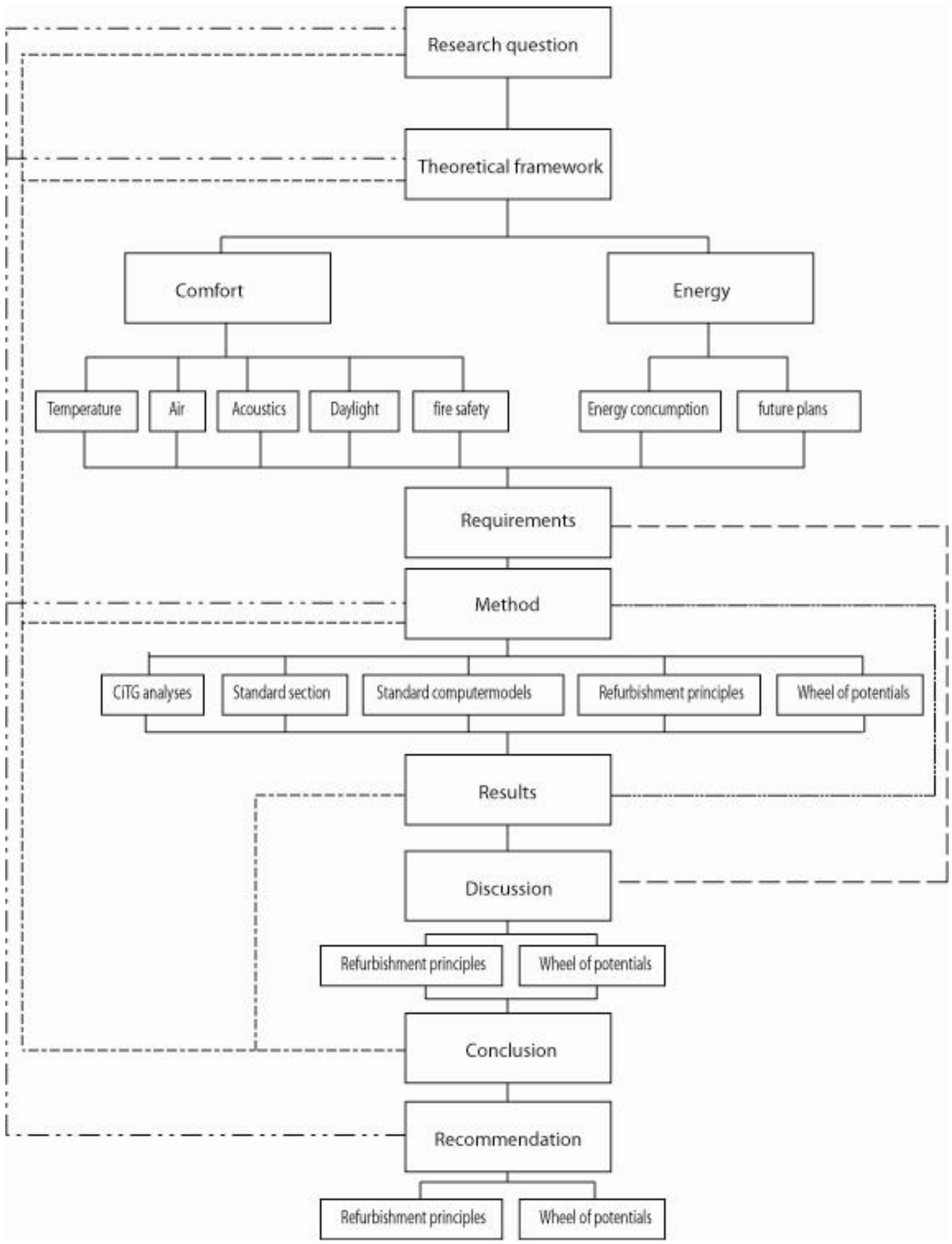


Figure 1.3 Schematic overview of research and report structure

2. Theoretical Framework

There are three main topics that can be defined within this research: refurbishment, indoor comfort, and energy consumption. These are all interrelated. Refurbishment functions as a frame work for this research and so it can be found through the whole report. Within paragraph 2.1, comfort aspects in general as well as those for the refurbishment of the CiTG faculty building are discussed and in the end, translated into a list requirements. In paragraph 2.2 energy aspects, like energy consumption and energy efficiency, are discussed, and a brief conclusion concerning the energy aspects of the CiTG refurbishment project.

2.1. Comfort

Comfort is a broad expression. It is used, for example, in 'user comfort' and 'comfortable'. To accomplish user comfort, any object, for instance a coffee-maker or a wheelchair has to be easy to use and well adjusted to a human being. Different factors define whether a situation is indicated as comfortable, like the atmosphere, temperature, acoustics and etcetera. In this report, the term comfort will be used to indicate the indoor climate. The aspects that affect indoor climate are explained in this paragraph. Temperature, ventilation, acoustics, daylight and fire protection are introduced and a reference is made to the concerning Dutch legislation. Buildings are not only refurbished from a maintenance point of view, but also to meet now-a-days' standards. A summary of the most important comfort standards that are applicable to this project can be found at the end of this paragraph.

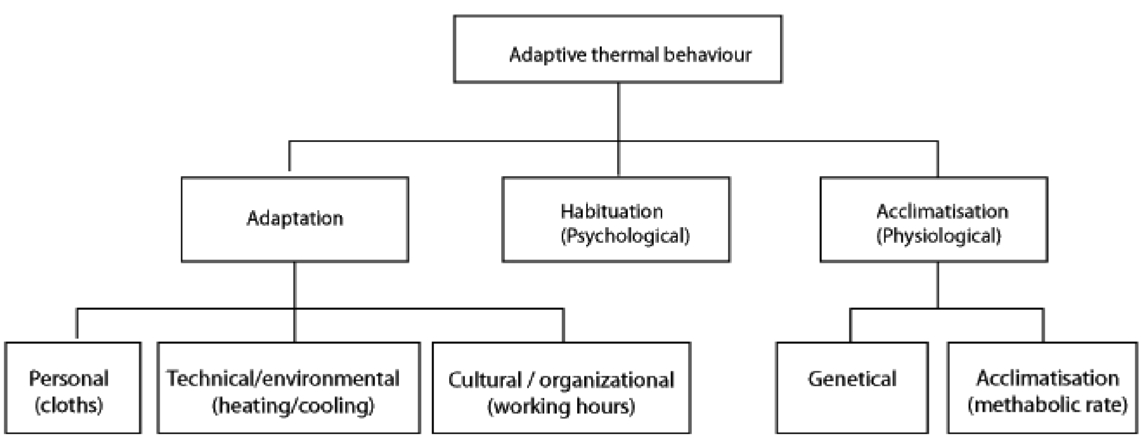
Temperature

Thermal comfort can be defined as: 'The condition wherein a human being is satisfied with its thermal environment and does not feel the need for a warmer or colder environment' [1]

It is influenced by the physical surroundings of a user, which consider the following aspects;

- air & radiation temperature,
- air velocity & turbulence intensity
- humidity.

The personal sensation of the user, such as activity level (metabolic rate) and clothing level (insulation) also play part in the experience of the thermal situation. A human being can adapt himself in three different ways to the environment, which are shown in Figure 2.1.[2] These adaptations are caused by several factors which are schematically shown in Figure 2.2.



[1] *ISSO publication 74*

[2] A.C van der Linden et al, "Adaptieve temperatuurgrenswaarden (ATG)", 2004

Figure 2.1 Categories of adaptation of the inside climate

The Adaptation, acclimatisation and habituation are caused by several factors which are schematically shown in Figure 2.2.

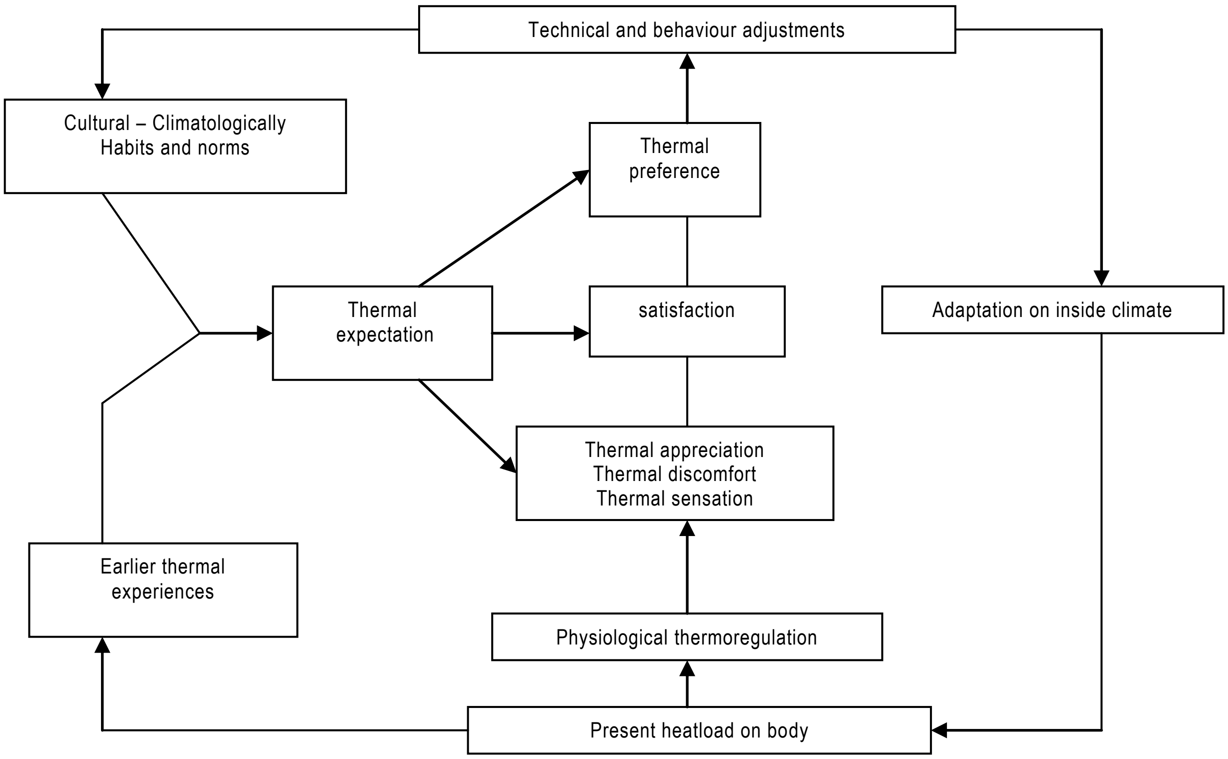


Figure 2.2. Adaptive model for thermal comfort according to Auliciems (De Dear, 1994)

Temperature requirements that have been used in the Netherlands have been changed over time, first the '*Temperature Exceeding hours-criterion: 100 TO-hours*' were set as a standard around the 1970's. Then, the '*Predicted mean vote /predicted percentage dissatisfied (PMV/PPD)-criterion (NEN-EN-ISO 7730): -0,5<PMV<+0,5 and PPD<10 %*' and the '*Measured temperature exceeding hours (GTO)-criterion: 150 GTO-hours (requirement of Government Building Agency)*' replaced this rule in the eighties. Eventually the '*Criterion of De Dear & Brager:* $\vartheta_{in\ 90\ \%\ acc} = 18{,}9 + 0{,}255 \cdot \vartheta_{eff\ mean\ out} \pm 2{,}5$ *°C*' was accepted as the standard for temperature inside a building in the nineties.

Nowadays, an Adaptive Temperature Boundary value (ATG-indicator) is used in the Netherlands as the standard, which is based on the previously mentioned De Dear and Brager criterion. The ATG is visualized in a graphic, see Figure 2.3 and Figure 2.4, where the maximum inside temperature is plot against the outside temperature. These graphics can also be found in Figure 2.5 and Figure 2.6.
Figure 2.6. The percentages that are shown, 80% and 90%, are related to indoor comfort classes which will be explained later in this paragraph. This indicator is a tool which is used to easily test buildings and communicate with the users of the building. It replaces the GTO criterion. However, the PMV method, which was introduced together with the GTO criterion, can still be used. This is because the PMV method indicates the acceptation of the user, and does not give a maximum boundary to the temperature, as will be explained later on in this paragraph in more detail.

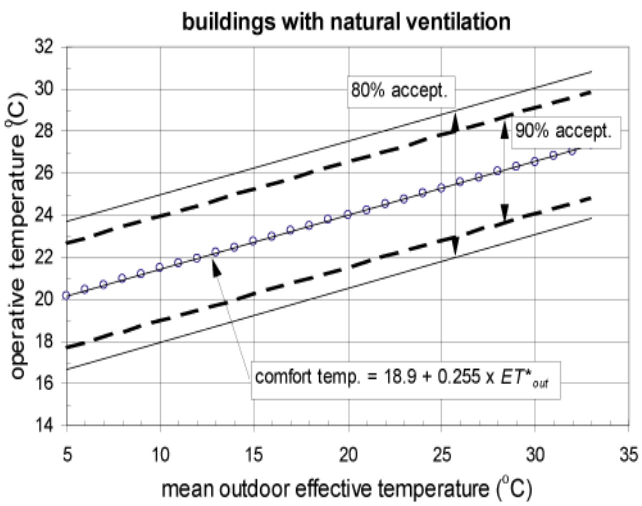


Figure 2.3. Adaptive PMV method to predict optimum comfort temperature and acceptable temperature areas (80%-90%) in natural ventilated buildings. [2]

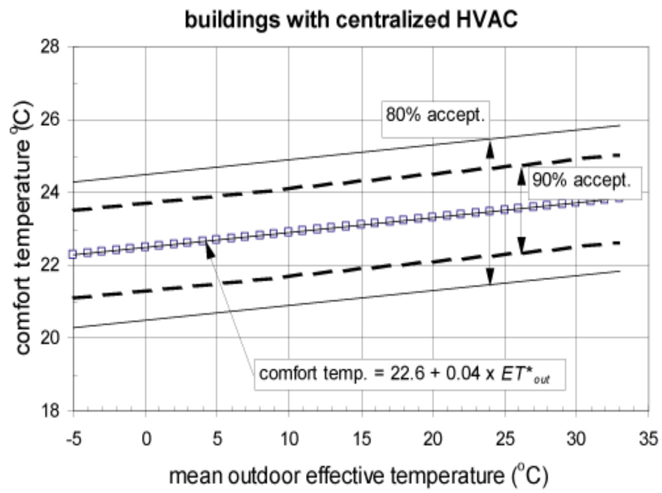


Figure 2.4. Adaptive PMV method to predict optimum comfort temperature and acceptable temperature areas (80%-90%) in centralized conditioned buildings.[3]

The Predicted mean vote (PMV) is a standard which is used to express the opinion of users. The PMV is zero when a user does not require a lower or higher temperature. When the PMV is 0; 5% of the people still feel uncomfortable, either being too hot or too cold, 40% of the people find it is quite warm or quite cold and 55% find the inside temperature neutral (PMV = 0). Therefore a PMV of -0,5 to 0,5 is acceptable. This is comparable with an office situation with a temperature range of 4°C. In the summertime (during working hours), a rise of 5% of the PMV on top of the 0,5 is accepted. Furthermore, a PMV of 0,8 is accepted for 1% of the whole year. This is also in agreement with the 150 GTO (Measured Temperature Exceeding hours) that are set by the Government Building Agency, which was previously the standard for inside climate. In the summertime people wear fewer cloths, and therefore, the same PMV value is achieved although the temperature is higher. So, for example, there is no need to cool to 21°C all the time to reach a correct PMV-value. When the user is able to control the climate himself, a higher comfort level can be reached if the action, with which the climate is controlled, is quickly changing the thermal situation. This increase in comfort level is experienced by the user when the difference in climate is noticeable on short term (raw 1994), therefore a perfect air treatment system might work contra productive, for example, because it is not changeable by the user[4]. Within the regulations that are used today, buildings have been divided into two groups. An Alpha building (natural ventilation) has other standards than a Beta building (mechanical ventilation). A higher maximum temperature in an Alpha building is allowed for example, because of the positive impact of controlling the climate by the user himself. The CiTG faculty building is categorized as an Alpha building, according to Appendix 2 where the blue answers are related to the CiTG faculty building.

[3] De Dear, R., Brager, G., Cooper, D, "Developing an Adaptive Model of Thermal Comfort and Preference", Final report ASHRAE RP-884, 1997.

[4] Vroon 1994

Now that the distinction between Alpha and Beta buildings are clear, the quality of the indoor climate needs to be classified. To judge the quality of the inside climate, buildings are divided into Classes A, B and C. they are, together with the formulas that are used to calculate the temperatures, shown in Table 1. In Figure 2.5 and
Figure 2.6 the ATG is showed for these classes. The classification is based on the difference in acceptation of the inside climate by the users of the building. Class C is only used for temporary buildings and for measurements in an existing building. If at least 90% of the users accept the inner climate, the building is marked as Class A; 'very good inner climate'. From 80% to 90% acceptation, the building will be categorized as Class B; 'good inner climate', which is used for standard buildings. Class B means that the PMV index does not exceed 0,5. In the summertime, this leads to operative temperatures of 23 to 26 °C, as the activity level is 1,2 and the insulation value of the clothes is 0,7 clo.

Class	Acceptation	**Building/ Climate type Alpha** (upper boundary only with $T_{e,ref}$ > 10-12 °C)	**Building / Climate type Beta** (and upper boundary Alpha with $T_{e,ref}$ < 10-12 °C)
	Maximum	$T_{oper} = 17,8 + 0,31\ T_{e,ref}$	$T_{oper} = 21,45 + 0,11\ T_{e,ref}$
A	90%	Upper boundary : $T_{oper} < 20,30 + 0,31\ T_{e,ref}$ Lower boundary: $T_{oper} > 20,20 + 0,11\ T_{e,ref}$	Upper boundary : $T_{oper} < 22,70 + 0,11\ T_{e,ref}$ Lower boundary: $T_{oper} > 20,20 + 0,11\ T_{e,ref}$
B	80%	Upper boundary : $T_{oper} < 21,30 + 0,31\ T_{e,ref}$ Lower boundary: $T_{oper} > 19,45 + 0,11\ T_{e,ref}$	Upper boundary : $T_{oper} < 23,45 + 0,11\ T_{e,ref}$ Lower boundary: $T_{oper} > 19,45 + 0,11\ T_{e,ref}$
C	65%	Upper boundary : $T_{oper} < 22,00 + 0,31\ T_{e,ref}$ Lower boundary: $T_{oper} > 18,95 + 0,11\ T_{e,ref}$	Upper boundary : $T_{oper} < 24,15 + 0,11\ T_{e,ref}$ Lower boundary: $T_{oper} > 18,95 + 0,11\ T_{e,ref}$
	Special situations High metabolism, High cloth insulation	Correction boundary value with: $\Delta T = -6\ (I_{cl} - 0,7) - 8\ (M-1,4)$ Valid at 1,4 <with < 4,0 and 0,7 < clo < 2,0	Correction border value with: $\Delta T = -6\ (I_{cl} - 0,7) - 8\ (M-1,4)$ Valid at 1,4 < with < 4,0 and 0,7 < clo < 2,0

Table 1 Classes for the quality of the inside climate.

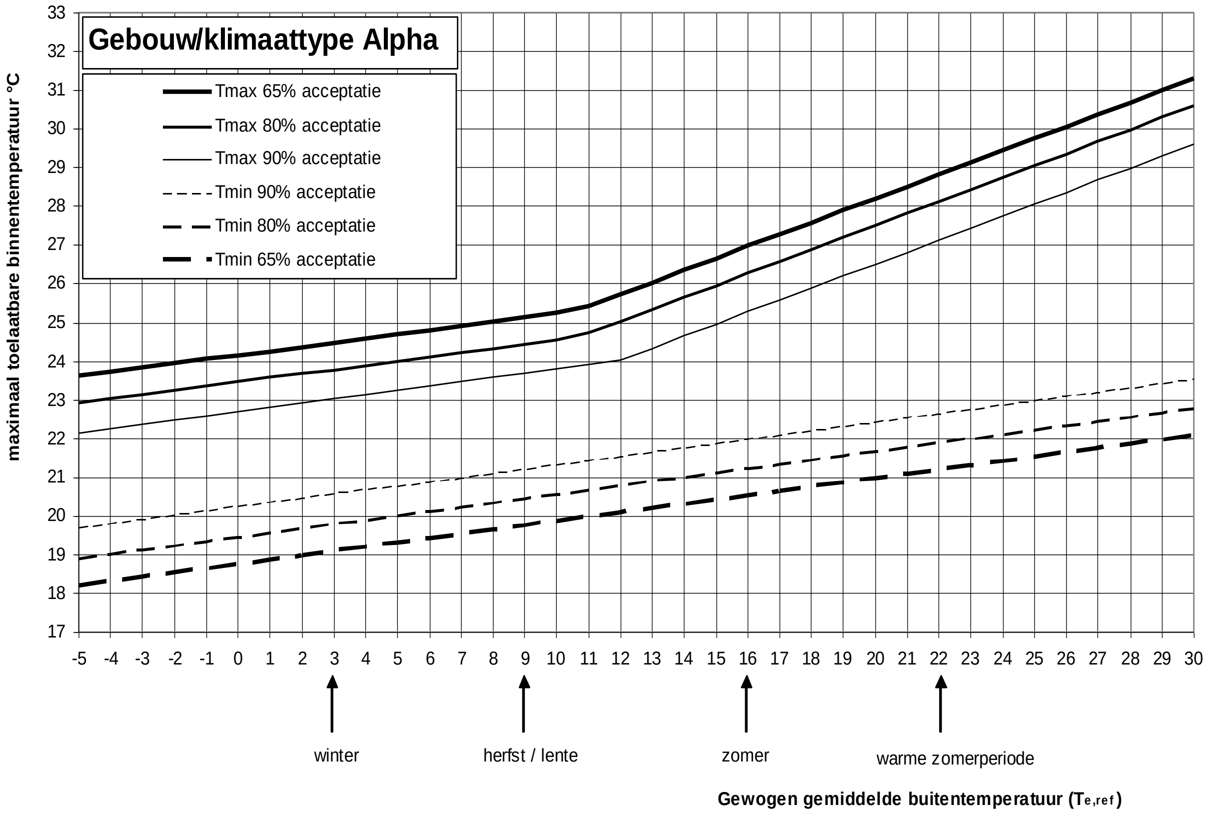


Figure 2.5 Maximum operative temperatures for the inside of an Alpha building

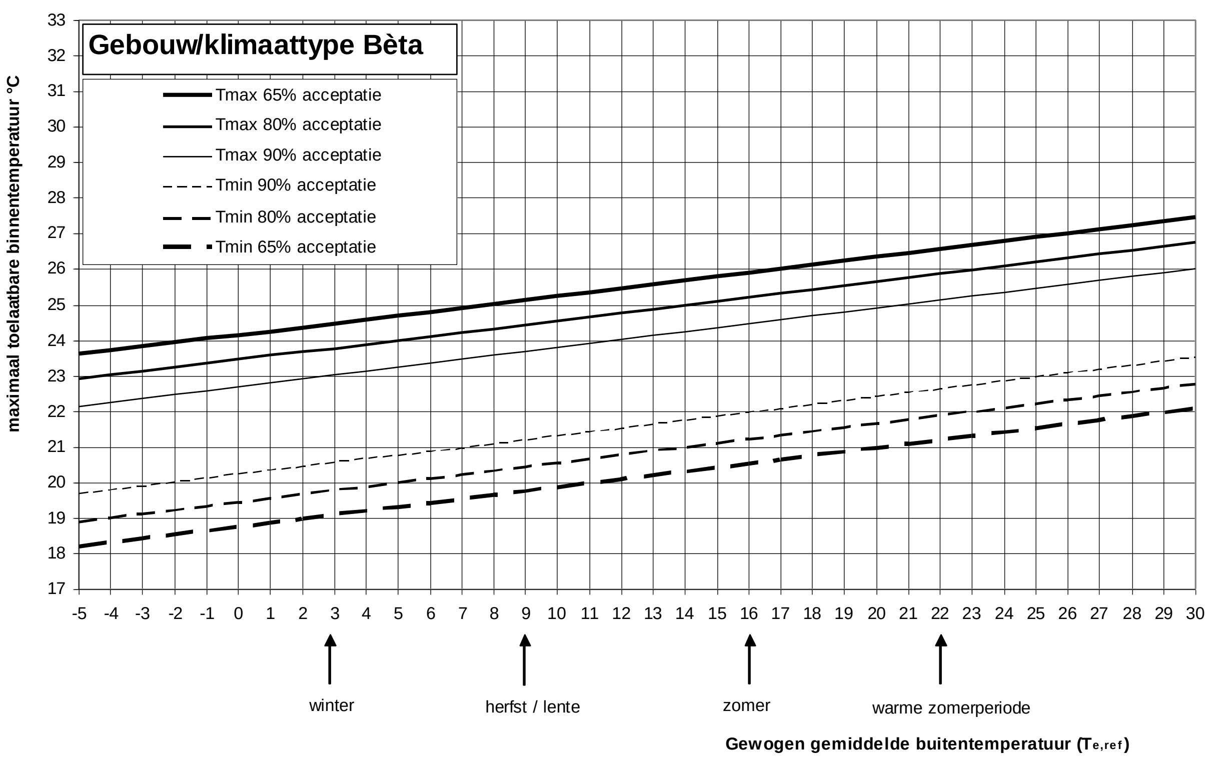


Figure 2.6 Maximum operative temperatures for the inside of a Beta building

Air

As previously mentioned, ventilation is also one of the factors that will influence the indoor comfort.
The right amount of ventilation can increase the comfort level, if the air is clean. When ventilation air is polluted, the comfort level will decrease because a large amount of polluted ventilation air will raise the pollution in the ventilated space. Cooled air is mostly unpleasant, because the cooling system is often polluted and cold air flows will quickly create a feeling of draft.

According to the Building decree, the ventilation in a residential area should be at least 1.3 dm^3/s per m^2 and in a common room it should be at least 1.0 dm^3/s per m^2 (article 3.48, table 3.46.1). The wind speed should not exceed 0,2 m/s. A comfortable humidity of the ventilation air is between 30 and 70 percent.
The inlet component should be adjustable by the user. In the area of 0 to 25% of the capacity; there should not be more than 10% inlet when the component is closed. (see article 3.50)
The previously mentioned ventilation quantities are minimum requirements; NEN 8087 shows the calculation method for the amount of air for the ventilation of a room.

$q\mathrm{v} = C \times \Delta p^n$

in which:
$q\mathrm{v}$ = air volume flow, in dm^3/s;
C= air permeability coefficient, in $dm^3/(s*Pa\,n)$;
n =flow exponent;
Δp= pressure difference, in Pa.
For terms and conditions of this calculation reference is made to NEN 8087.

Apart from thermal comfort, a healthy environment is important for the indoor comfort as well. The factors that cause pollution are:

- Cooling of ventilation air
- Humidification of ventilation air
- Recirculation of ventilation air
- Polluted filters in the ventilation system

Furthermore, heat exchangers, interior finishes with a high emission, the Total Volatile Organic Compound (TVOC) and office machines with a high emission need to be reduced in order to increase a healthy environment. In offices it is wise to place large machines in separate spaces. The decrease of glass surfaces and the use of sunscreens will reduce the external heat load. Reduction of internal heat load by energy efficient equipment, armatures and software will also improve the environment.

Acoustics

Sound insulation and room acoustics are, similar to for example indoor temperature, typical comfort requirements. The acoustic comfort is based on the use, the users and the expectations that the users have. It is hard to formulate requirements for acoustic comfort because it is quite subjective. The requirements that do exist are expressing the minimum standards, to prevent serious failures in the building process.

The following relevant acoustic requirements are selected from NEN 1070 and NEN 5077.
For airborne transmission of sound an average of 65dB(A) is used which matches loud speech, with a dynamic of 12 dB(A) and a tolerance of 0 dB(A) between two offices.
Impact transmission and noise from installations are not influenced by the façade and therefore they will not be discussed in this study. Noise from outside is in first place specified as noises from the surrounding, which matches the environment of the building. Some examples of airborne transmission sources are given in Appendix 3.
The indoor reference level is normally defined by the buildings' environment and the function of the building. For the CiTG faculty building, the indoor reference level will be between 30 and 35 dB (A) according to table B2 of NEN 1070, which can be found in Appendix 2.
It is wise to apply enough acoustic material in a meeting room or office, so that the acoustic absorption A is minimal 1/8 of the rooms' volume for the octave band of 250, 500, 1000 and 2000Hz. Furthermore, a reverberation time in a meeting room of ≥ 0,7 and ≤0,9 seconds is preferred. In other residential areas than meeting rooms a reverberation time of 0,5 to 0,8 seconds is preferred. Longer reverberation will cause a lower experienced comfort.

When the term acoustic comfort is used, the reference is not to these minimum standards, but to higher requirements than these standards prescribes. The quality of the acoustic performance in a room is expressed in five levels shown in Table 2 (from table B3 NEN 1070).

Source of sound	**Performance quantity**	**Quality grade** K=1	K=2	K=3	K=4	K=5
Outside	$D_{g;atr}$, $D_{g;a}$≥	B_g-L_{ref} +3≥28	B_g-L_{ref} -2≥23	B_g-L_{ref} -7≥18	B_g-L_{ref} -12≥18	B_g-L_{ref} -17≥18

Table 2 Acoustic quality grades for residential areas wherein B_g= outside noise and L_{ref}= inside reference level

Different factors are of influence on acoustic comfort. Noise can have a different impact on people depending on its origin and content, it is often classified as 'annoying' when[5]:

- It is not traceable
- It is not predictable
- It is repetitive
- It is tonal
- It is not necessary
- It cannot be influenced
- It has an informative load, like speech

[5].Leijten, J.L, Kurvers, S.R., Binnenklimaat kantoorgebouwen, 2007

Daylight

To have a comfortable and safe working environment inside an office, it is important to have enough daylight or artificial light. There are no standards wherein the amount of lux is prescribed for an office; however there are some guidelines which show the essential amount of lux per activity. The terms that are related to light and the most important guidelines from NEN-EN 12464 and NEN 3075 are mentioned below.

NEN 3075 prescribes strength of 10 lux for safety reasons, so people can see where they walk. When people have to work in the room, an amount of 200 to 500 lux is prescribed. The amount of lux that is required for different tasks in an office rooms are showed in Figure 2.8.

An office has a certain equivalent daylight surface defined by NEN 2057 on which will not be elaborated further within this research. According to the building decree, this equivalent daylight surface should not be less than 2,5% of the offices' surface and for common spaces not less than 0,5 m^2. A daylight factor of 1% is the standard nowadays. Although the ARBO regulations, that prescribed 1/20 of the floor surface as area where daylight can enter, are no official standards anymore, it could be kept in mind as a rule of thumb while designing. For psychological reasons, not only the daylight surface, but also the possibility to see the outside environment was appreciated in the ARBO regulations. Visual contact with the outside world is important for human wellbeing, especially if ones work is bound to one and the same location for a longer period of the day.

3	**Offices**				
Ref. no.	**Type of interior, task or activity**	**$\bar{E}_m$** lx	**UGR_L** -	**R_a** -	**Remarks**
3.1	Filing, copying, etc.	300	19	80	
3.2	Writing, typing, reading, data processing	500	19	80	DSE-work: see 4.11.
3.3	Technical drawing	750	16	80	
3.4	CAD work stations	500	19	80	DSE-work: see 4.11.
3.5	Conference and meeting rooms	500	19	80	Lighting should be controllable.
3.6	Reception desk	300	22	80	
3.7	Archives	200	25	80	

Figure 2.7 Amount of lux required for a specific action from NEN EN 12464

Fire safety

Fire safety is very important for the CiTG faculty building; a fire can start unexpectedly and be very destructive, like in the faculty of Architecture in 2008. Because all employees and students need to be able to escape safely when the building is on fire, the building needs to be fire resistant for a certain amount of time. These requirements are formulated in the building decree.

For fire safety, there are no specific refurbishment standards. The façade will have to be designed conform the standards for newly built buildings, wherein a fire resistance of 60 minutes is obligatory between floors, through the connection between floor and façade and 30 minutes through the façade. It is important to know that the façade will bend as a consequence of the heat from the fire, a gap will appear between the façade and the floor, through which the fire will get to the next floor and the needed 60 minutes of fire resistance cannot be realized.

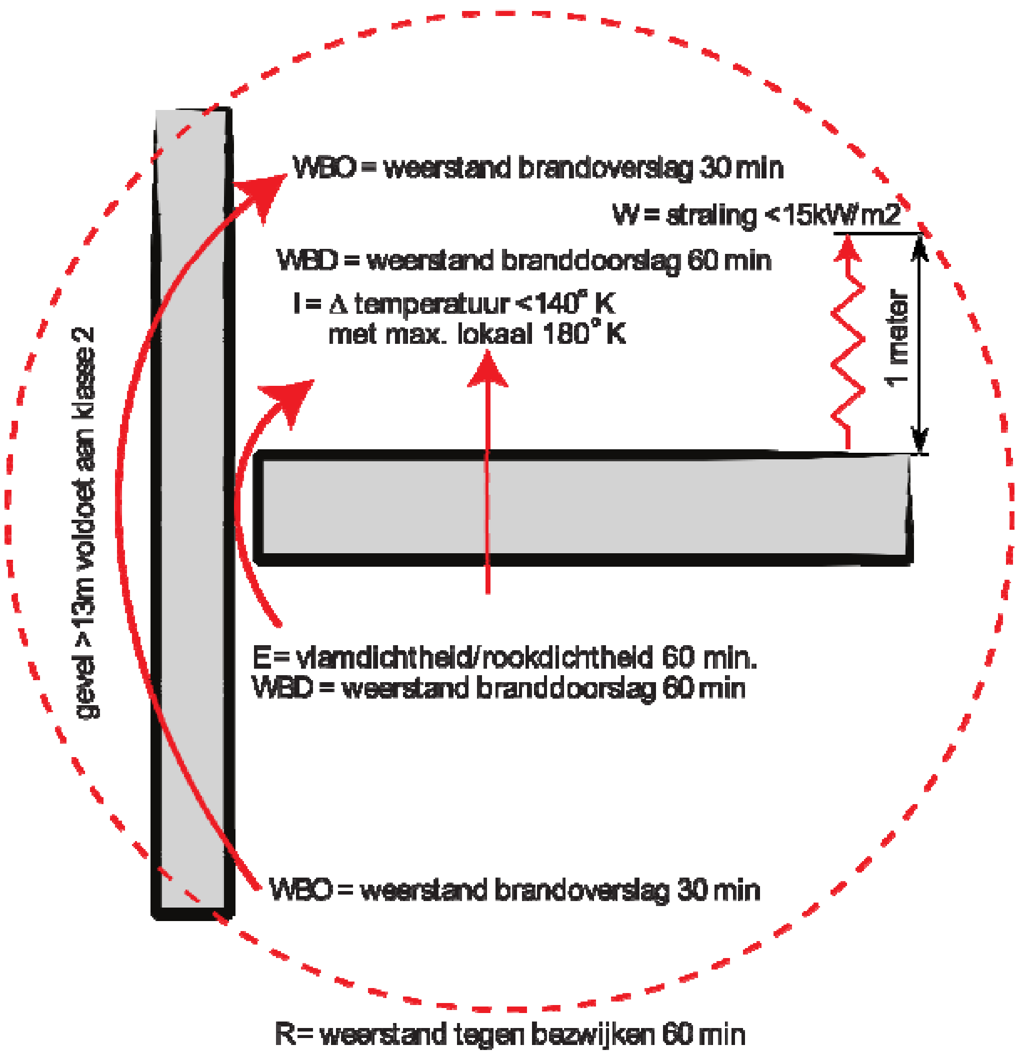


Figure 2.8 Fire resistance requirements[6]

[6] From Brandveiligheid gevel/vloeraansluitingen by Kevin Truijens

Measures

If the indoor climate, in a whole building or single room, is indicated as uncomfortable, there are many ways to tailor to the requirements of the user. Not only does a good indoor climate stimulate concentration and therefore more productivity of the user, it can cause a change in energy consumption of the building.

A well know way of controlling the temperature is mechanical ventilation with cooling and heating devices. These installations will increase the energy consumption. While improved insulation to reduce a cold indoor climate can cause a decrease in energy use. Therefore, all the pros and cons of possible measures should be balanced well before making a decision.

Furthermore, the disturbance of the users should be kept as minimal as possible. Normally a façade is stripped from top to bottom and build up from bottom to top again. Within the CiTG faculty building there is a division in 5 parts, section A, B, C, D and E as is shown in Figure 2.9. These sections will be refurbished one by one, so in this way the employees are moved per section for a relative short period and students can still work at their own faculty.

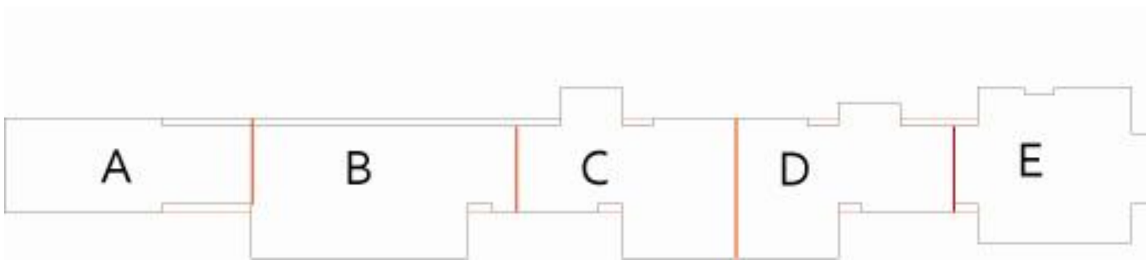


Figure 2.9 Sections within the CiTG faculty building

Conclusion

A good indoor climate depends mainly on temperature, ventilation, acoustics, daylight and fire protection. To reach a high comfort standard, an office in the refurbished CiTG- faculty building should comply with:

- The Adaptive Temperature Boundary value (ATG) with an acceptation of 90%
  (or: there should be less than 100 hours where the temperature exceeds $26^{o}C$)
- There should be at least 1.3 dm^3/s ventilation per m^2 floor space
- 200 to 500 lux and a daylight factor of 1% should be present
- The indoor reference level should be 30 to 35 dB(A)
- The façade connection point should be fire resistant for at least 60 minutes

2.2. Energy

Energy is a quantity that indicates a power. The terms radiation, conduction and convection indicate a way of energy transport. When, for example, a window has a lower temperature than the human body, the body heat is radiated to the glass surface and therefore the window feels cold when one is sitting beside it. This way of energy transfer is called radiation. A metal teaspoon in a cup of tea feels hot because the warmth of the tea is transferred through the material of the spoon, so called conduction. A radiator in a room does not only radiate heat to the surrounding surfaces, it also transfers the heat through the air that flows along the radiator. This phenomenon is called convection.
All these forms of transport are important for the energy consumption of a building because they often cause energy loss. In this paragraph the present energy consumption, future energy consumption and influence of the CiTG façade refurbishment on the energy consumption will be discussed.

Current energy, gas and water consumption

The CiTG faculty building has quite a low water and gas consumption; however it has high energy consumption. These consumptions are monitored by the facility management and real-estate department of DUT, the data from 2007 and 2008 is made available for this research and can be found in Appendix 10. The amount of water used in 2007 was 46.399 m^3 and in 2008 it was 20.711 m^3. This reduction of 55% is caused by the replacement of a cooling system which used large amounts of drinking water. The gas consumption was 20.929 m^3 in 2007 and 5.034 m^3 in 2008, this reduction of 75% is caused by the limited use of the only laboratory in the CiTG faculty building which uses gas. The energy consumption is split into heat and electricity consumptions. In 2007 the electricity consumption was 7.214.004 kWh and in 2008 it was 5.750.227 kWh, which is a reduction of almost 25%. The heat use is centrally monitored at the cogeneration system which provides the whole DUT campus of hot water for the heating systems. In 2007 the heat use was 6,947 MWh, in 2008 it increased to 8,233 MWh. This raise can be partly explained by the weather. In 2007 the average temperature of April was 20.5°C, while 13.8°C was the average temperature for April in 2008; these changes in temperature can be corrected by so called 'degree days'. The method counts the amount of days in a year when the average temperature is less than 18°C. These 'degree days' are then compared to the amount of the degree days the year before; finally the energy consumption is corrected. Table 3 shows this calculation for the CiTG faculty building for the heat consumption of 2007 and 2008.

Calculation of corrected use of heat			
	2006	**2007**	**2008**
Heat use in MWh		6.947	8.233
Degree days	2.671	2.484	2.767
Correction factor, in comparison with last year		93%	111%
Corrected heat use in MWh		**7.433**	**7.327**

Table 3Calculation of correction on heat use by using 'degree days' [7]

With the corrected data, the decrease of heat consumption is almost 1,5%.
The lack of data from previous years makes an accurate final conclusion, about increasing or decreasing energy consumption, not possible. However, the data that is given in this paragraph can be used to compare now a day's energy consumption to assumed energy consumptions of the future.

[7] Graad dagen, KWA bedrijfsadviseurs, www.kwa.nl

Energy efficiency plan

Refurbishment is, besides making the inside climate more comfortable, used to reduce the energy consumption of the building. This reduction can lead to a financial profit and is more sustainable. Sustainability is nowadays a hot subject because of the climate changes in the world. A lot of good initiatives are raised to reduce the energy consumption. DUT has joined such an initiative, of which the content will be discussed next.

DUT has committed itself to the SenterNovem Multi Year Agreement 3 (MYA3) this multiyear agreement between government, universities and companies, expects an effort of all parties to improve the energy efficiency as well as a reduction in fossil fuel use and efficient distribution of energy and heat.

From 2005 to 2020 the energy efficiency should increase with 2% each year, so a total increase of 30% should be realized. An energy efficiency plan is set up for the period up to 2012 which includes methods to reduce the energy use. Of these, the refurbishment of the CiTG faculty building is one of the most important ones, because it is one of the main energy consumers of DUT, as can be seen in Figure 2.10.

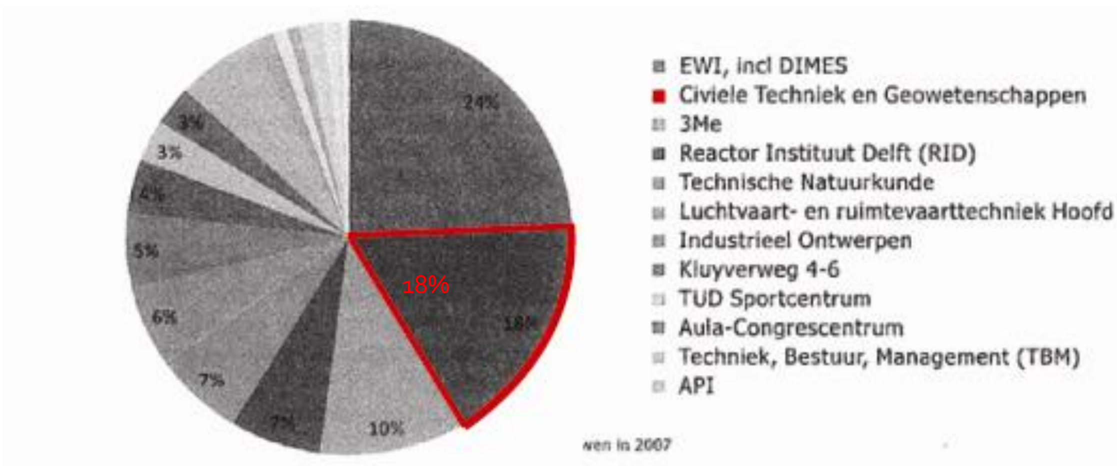


Figure 2.10 Energy use of DUT divided in energy use per faculty[1]

Not only the Energy efficiency plan is part of the MYA3, but an energy care system and a line route map are also included. This map will probably be ready in 2010 and shows the steps that will be made in the future. The care system is a combination of technical, management and behavior measurements; it will reduce the use of energy by making people more aware of the energy they use. The slogan for the MYA3 is 'Energy reduction on natural moments', which implicates that the energy reduction measurements are taken when other maintenance needs to be preformed. The refurbishment of the CiTG faculty building, for example, need to be done in arrear maintenance, but is also very useful for the energy reduction if the right adjustments are done.

The heat consumption could be reduced a lot by the refurbishment of the façade. Now 71% of the used heat is lost through conduction, of which again 88% is caused by the façade [6]. When, for example, the single glazing in the façade would be replaced by HR++ glass (U=1,1), the reduction will be:

Replacement glass	**MWh th**	**GJ primarily**	**Ton CO_2**	**Percentage**	**Year**
Reduction	2.598	11.595	658,6	21,2%	2010

Table 4 The reduction by an increased heat resistance after refurbishment[8]

As previously mentioned, there are some interventions taken or planned for the near future to realize the 30% higher energy efficiency. One of these interventions is the replacement of the cogeneration system that the DUT uses now, with an aquifer or heating system which uses heat of the earth. The choice of heating system will influence the installations that can be used inside the building. To stimulate the

[8] *Energy efficiency plan 2009-2012, A.Winkels, 2009, Deltahage*

reduction in fossil fuel, Co_2 emission is legally set on a maximum by the government, which is based on the use in previous years. If the maximum is exceeded, DUT has to pay for the extras.

In the Energy efficiency plan (A. Winkels, 2009) the CiTG's façade is assumed to be refurbished in 2010. This date is not permanently set, but the fact that the refurbishment is mentioned in this approved plan means that the building will be refurbished within the next 10 years. The financial crisis has its impact on the DUT. The investment space in budgets is very small and a big project like the refurbishment of the CiTG faculty's façade of is very costly, so a cheap façade will have the preference above the more costly version. The estimated investment will be 25 million euro. Off course, the financial profit of reduction in energy, heat, water and gas will decrease the user's costs.

Conclusion

With 18% of the total energy consumption, the CiTG faculty building is one of the largest energy consumers of DUT. A multiyear agreement with SenterNovem (MYA3) that DUT signed in 2005 prescribes that the energy efficiency has to be improved with 30% in 2020. A step by step plan is set up for the next years to make sure the requirements of the MYA3 are met. In this 'Energy efficiency plan' (A. Winkels 2009), the refurbishment of the CiTG faculty building is indicated as one of the main interventions that have to be done in order to increase the energy efficiency of the whole DUT with 2% per year. Now, a lot of energy is lost through the façade of the CiTG faculty building because of poor thermal insulation.

3. Method

Now that the energy use and comfort requirements are known, the next matter is to understand the CiTG faculty building and to trace the aspects that can be improved. A standard section of the building is detailed, which represents the building in the rest of the research.
To investigate the coherence of comfort and energy consumption, different façade principles are compared. After simulating the different variations of the façade principles, they are evaluated and compared, so that a façade proposal for the CiTG faculty building can be made.

In the first paragraph, the CiTG faculty building is discussed. The standard section that is chosen for the simulations, is presented in the second paragraph. Furthermore, in paragraph four, the computer models are explained. Eventually in the fifth paragraph, the façade principles are introduced together with their simulation input.

3.1. Analyses of the CiTG faculty building

To get insight into the CiTG faculty building, the design and use of the building are discussed within this paragraph. Information about the design and construction, the energy use and the vision of the facility managers is collected. The paragraph is divided into three parts; Architecture, Usage & floor plans and Building physics.

Architecture
The building was designed in 1965 by Van den Broek en Bakema Architects, who became famous for their brutalism, the use of visible concrete and strong geometric gestures. In this building the service balconies along the façade are a typical manifest of such design interventions. The building is designed to resemble a semi-trailer truck. The ground floor is kept free of functions and provides large passages underneath the building. The upper six storeys appear to rest on the prominent lecture halls. The first floor is used as the main hall, in which the entrances to the lecture halls, secretariats and coffee corners are situated.
Six staircases connect the six floors on which offices and student work spaces are located. In the initial plan, the building consisted only of four floors. Because of the increase of student numbers an extra storey was already added during the planning process. During construction phase it was decided to add yet another floor to the building.

Figure 3.1 Faculty of Civil engineering

One corner of the building has recently been refurbished, 2005-2007, by Jeanne Dekkers. This part of the building is now occupied by Geosciences. The rest of the building still remains authentic.

Figure 3.2 Refurbished façade of the faculty of geosciences (photo by T. Ebbert)

Structure

The first five floors of the building are constructed in concrete. Only the top floor has been built as a steel framework in order to reduce structural loads. The load bearing structure consists of a concrete framework cast on site and prefabricated concrete floor plates. The main columns are set back 6.5 meters back from the façade. To make this cantilever possible, a ring beam takes in the loads on the far edges. The ring beams are interconnected by steel columns which function as tension cables. As soon as one floor is maximally loaded, these columns prevent a dangerous deflection by transferring loads to other floors.

Figure 3.3 Lecture halls underneath the building with large underpasses in between

Floor plans and functions

The two main users of the CiTG faculty building are employees and students. Currently there are approximately 1600 students and 570 employees[9]. The building is used about 90 hours during the week (data from 2003) and has a floor area of 70.028 m^2 To give insight in the usage of the building a short overview of floor plans will be given in this paragraph.

Ground floor

The ground floor contains entrances and lecture halls. In the design of the building, the main hall is situated on the first floor. In between the entrances, which are located on the sides of the large lecture halls, large underpasses are created. Structural loads are taken up by columns that seem to pierce through the first floor with, measured from the outside, an offset of respectively 6.2 meters on the north-west and 6.7 meters on the south-east side of the building.

First floor

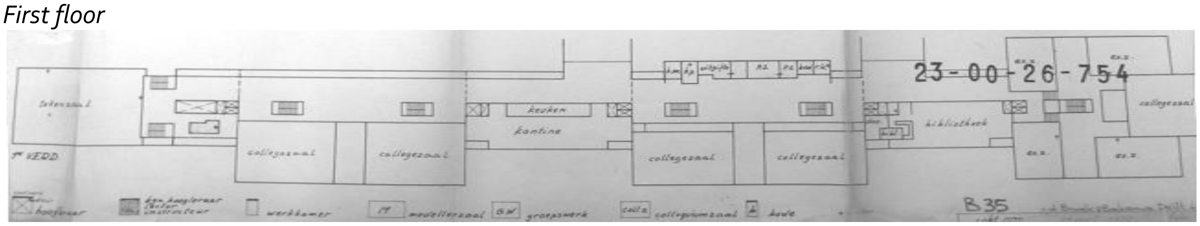


Figure 3.4. Floor plan of the first floor

The main hall is situated on the first floor. Coffee corners, information desks and the entrances to the lecture halls are located near the façade. In the centre of the plan, staircases and elevators are situated. On the far edges of this floor plan the library and examinations rooms can be found.

Second, third, fourth and fifth floor

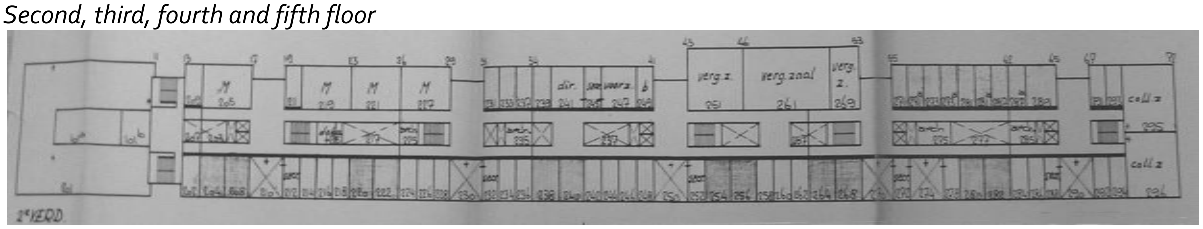


Figure 3.5 Floor plan of the second floor

The second floor is the first regular floor plan where offices, meeting rooms and student work spaces are situated. The offices are placed next to the façade. The toilets, stairs, elevators and copy machines are placed in the middle of the plan along the length axis. Because the lecture rooms do not need a lot of light, yet offices do, the plans are designed very efficiently. By placing the lecture halls on the outside of the floor plan the light is kept outside, because there are no windows placed on the end walls of the building.

Sixth floor

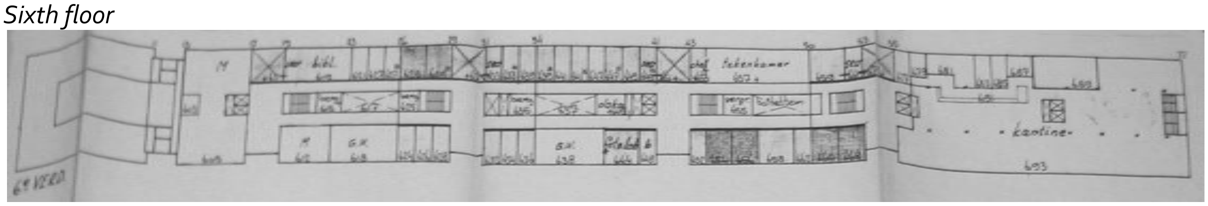


Figure 3.6 Floor plan of the sixth floor

The sixth floor is quite similar to the second, third, fourth and fifth floor. However the difference in this floor plan is the east end of the building. On this upper level of the building, a canteen is situated. In this canteen the employees and students can have lunch and dinner.

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9 http://cms2.tudelft.nl/live/pagina.jsp?id=aed5328b-8cf2-40b7-96aa-e035c009b58f&lang=nl revised in 2009, visited on 5th of march

The space is also used for drinks at special occasions. There are some workspaces for groups on this floor as well. Lately the interior on this floor has been renovated. Now the offices have a different size, therefore the original drawing as shown in Figure 3.6 is not up to date anymore._The floor still has the offices on the side of the façades and the other facilities in between these offices.

Building physics

The building is naturally ventilated by windows that can be opened; small pivot-hung windows in the upper part of the façade can be used for permanent ventilation. Lecture halls and some meeting rooms are mechanically ventilated and air conditioned. The air exhaust is realized mechanically through an exhaust duct that is located near the toilets. On the sixth floor, a new system is applied when the interior of the floor was renovated in 2002. The ventilation and air conditioning is now mechanically regulated, however the windows can still be opened. Because of these openable windows, the mechanical ventilation does not function optimal. Employees are not used to mechanical ventilation and leave their door and windows open, even when the temperature in their office rises.

Most employees like to work with their door open, so that colleagues can walk in easily. In such a situation, the mechanical ventilation is not capable to provide enough air to ventilate and cool not only the room but also a part of the corridor, so the office will heat up and the employees will open their windows. Then, the mechanical ventilation is not useful anymore.

In the rest of the building, employees have to open their window when their office heats up, since this is the only way to ventilate and cool on the first, second, third, fourth and fifth floor.

In wintertime the offices are heated by radiators that are placed in each office underneath the window. These radiators can only be turned on or off and cannot be leveled between hot and cold, which causes discomfort. The external venetian blinds that are used in summertime, cannot always be closed because of strong winds along the façade.

Façade construction

The façade is articulated by the concrete ring beams, which are made visible as service platforms. Prefabricated concrete panels rest on this structure and form the outer cladding. The filling façade structure consists of steel frames. The frame is horizontally separated into four zones. The lower part is filled in with a coated insulated glass panel. The second part contains opening windows which are filled with single layered glass. The third part is filled with a fixed single layered glass pane; and the top zone is formed by small pivot-hung windows. All glass panes are placed into the simple steel framework from the outside and are fixed with lute.

On the bottom, the façade rests on the prefabricated concrete elements. The top edge is attached to the ring beam. Horizontal loads are transferred to steel columns. The façade is equipped with external Venetian blinds, placed on the outer edge of the service platforms. Additionally, small Venetian blinds on the inside of the façade provide individual glare protection.

Figure 3.7 Typical window

Interior

The interior of the offices is designed quite soberly. The gyprock separation walls, which consist of hardboard layers with insulation in between, are painted white. The steel frames of the façade are painted bluish gray. The floors are covered with dark blue linoleum. The wall adjacent to the corridor is filled with large wooden closets that reach two meter high. The area between the top of closet and the suspended ceiling is filled by a window with single layered glass. The suspended ceiling in the office functions as an acoustic ceiling.

Conclusion
The CiTG faculty building is a stretched building in which the first floor functions as a main hall and provides entrance to the lecture halls which are situated on the ground floor. The other four storeys of the building are occupied by student workspaces and offices which are mainly used by two employees each. The mechanical ventilation on the sixth floor replaces, since 2002, the natural ventilation which is still used on the other floors except for the lecture halls and some meeting rooms, where mechanical ventilation was present since the building was built in 1965 by Van den Broek and Bakema. The building will become a city monument and needs to be refurbished because the façade is one large thermal bridge which, in combination with poorly working heating as well as external sunblind, causes uncomfortable situations is summer and wintertime.

3.2. Standard section

Choice of section
A section of the CiTG faculty building is chosen as standard section, which is used as basis to design four refurbishment façade principles. The standard section is chosen in the middle of the building. The exact location and orientation of the offices can be seen in Figure 3.8. The standard section covers two offices, a corridor and two small outside balconies of which a plan and section are shown in Figure 3.9.
and **Fout! Verwijzingsbron niet gevonden.** which can also be found on a larger scale in Appendix 4. It is hosen because of the frequent repetition over the whole building. The schematic version of this section also functions as standard input for computer models so parameters like size and orientation of the offices are fixed for all of the refurbishment façade principles. This way the influence of significant parameters for inside comfort and energy use can be evaluated and compared well between the façade principles.

Figure 3.8 location and orientation of standard office, which has been assessed in this study.

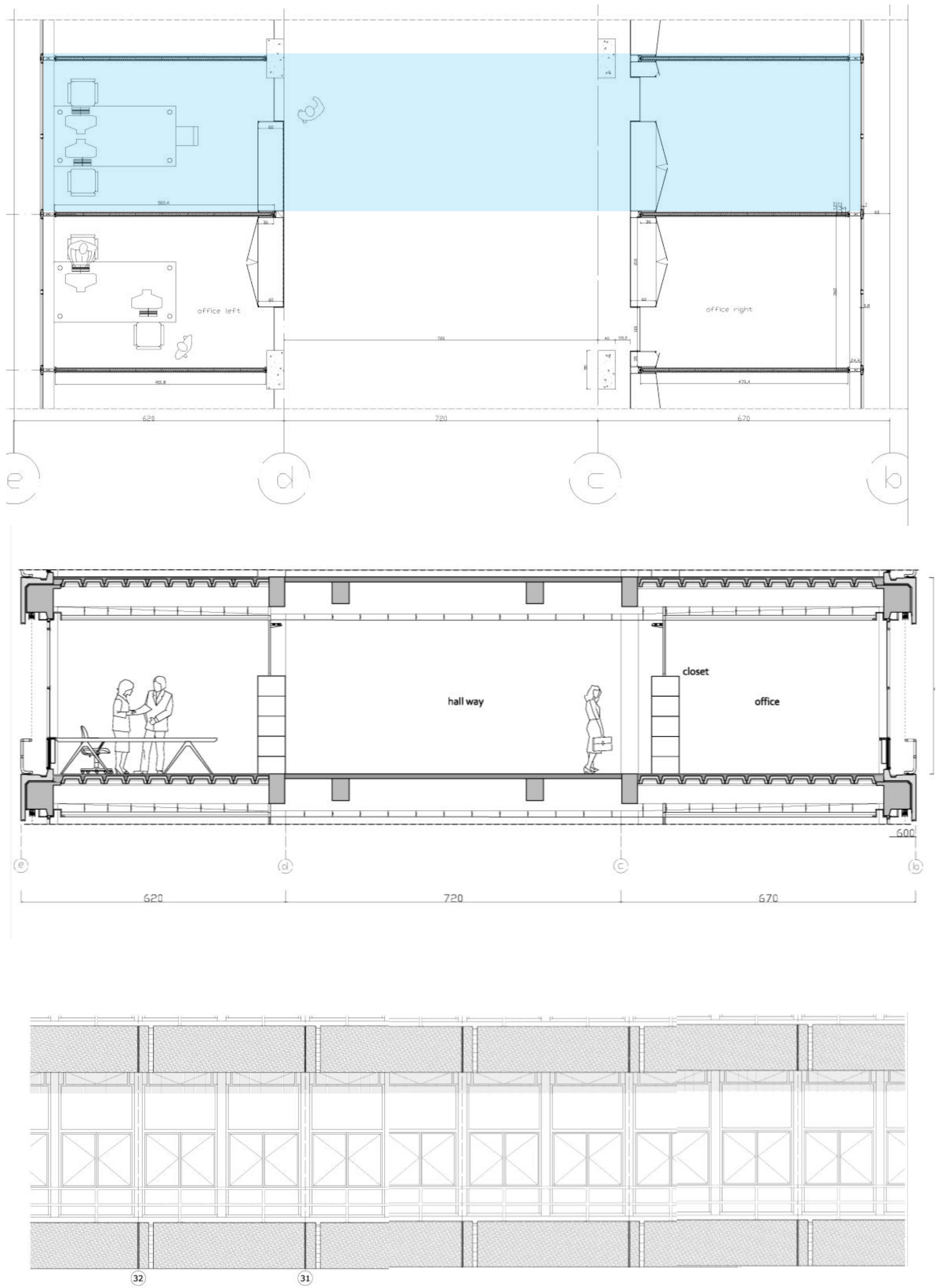


Figure 3.9 Plan, section and elevation of standard section

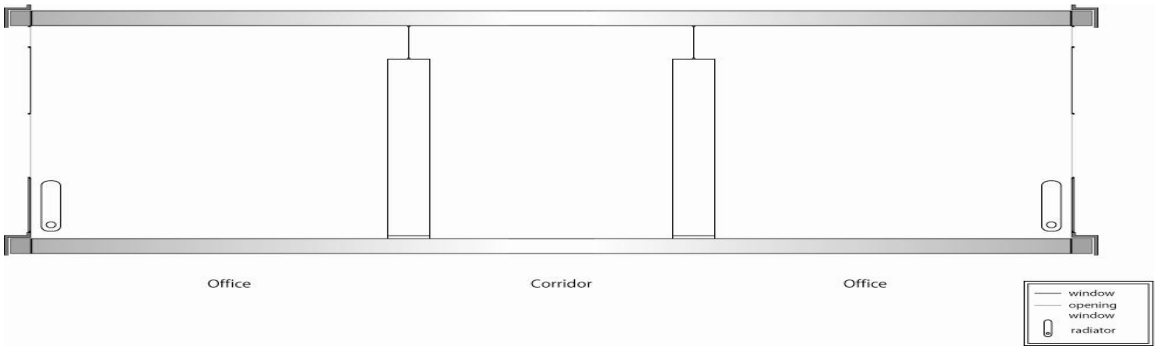
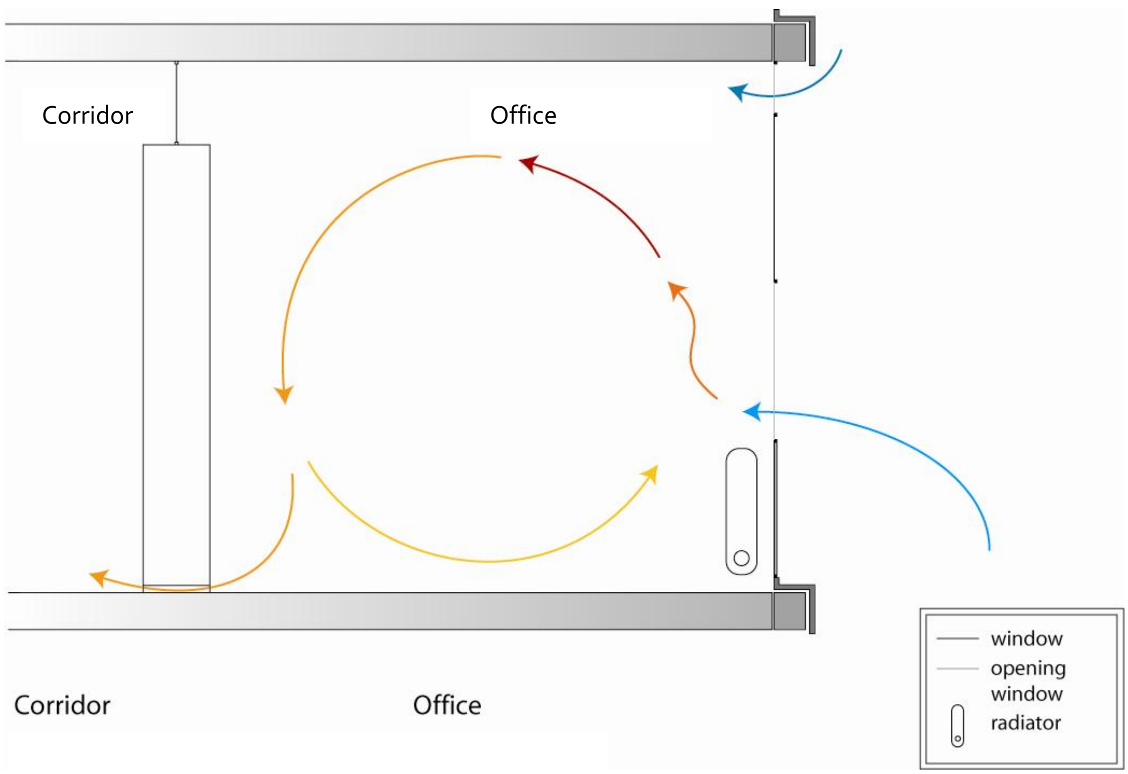


Figure 3.10 Schematic overview of the standard section.

The standard offices are naturally ventilated. Tilting windows in the upper part of the façade are used for continues ventilation. Openable windows are used for extra ventilation and thus for cooling since there is no mechanical cooling system within these offices. The air is heated by a radiator that is positioned adjacent to the insulating panel of the façade. Figure 3.11 shows the air flows in the office schematically.



F ffice

Refurbishment requirements

The CiTG faculty building is currently still in process to become a city monument. This means that the characteristic segments of the building, which, in this case, show many characteristics of the famous brutalism used by Van den Broek and Bakema, will be protected by the city council. Careful treatment of the existing building and preferably the architectural appearance is therefore a necessity.

Currently, the CiTG faculty building has a high energy consumption. According to DUT's energy monitoring, 88% of the current transmission heat loss is owed to the non-insulated glass façade (A. Winkels 2009). Hence, its refurbishment will significantly reduce the energy consumption of CiTG faculty building and thus it will reduce the energy consumption of the Delft University of Technology as a whole. Furthermore a good inner climate is desired in the offices so that employees can focus on their work and stop worrying about the indoor climate.

3.3. Computer models

The input of the initial façade in Capsol and Trisco will be used as neutral situation to compare the performances of the façade principles. Therefore, the input that is described in this paragraph is more detailed compared to the input descriptions of the façade principles. Within this research two computer simulation programs are used, Capsol and Trisco. A brief description of the program and the input data per program is given in this paragraph.

3.3.1. Capsol

Capsol builds up the standard section out of surfaces and zones wherein the building physics plant is simulated. It is able to calculate, amongst others, the temperature in a standard office and the amount of energy that is used by the technical installations.

The input functions which are used to simulate the standard section in Capsol are; wall types, walls, function references, zones, ventilation principles, wall sun obstacles, view factors, controls and points. These functions are briefly explained and a short overview of the input per function is given. In Appendix 5 a more elaborated description is given about the functions and their input.

Wall types

Walls types represent the construction of the walls, ceilings, floors, façades and other surfaces that are used in the standard section. The wall types are created in the 'Wall Editor'. Here, layers of building material are put together to simulate the existing walls of the standard section, as schematically shown in Figure 3.12. The wall types that are used to simulate the standard section are:

1. *Gyproc*: separation walls
2. *Wood_closet:* wooden closet
3. *Glass:* window above wooden closet and façade glazing
4. *Cork:* insulating infill panel in façade
5. *Steel:* steel window frames of façade
6. *Office floor:* office floor
7. *Suspended ceiling:* ceiling in office and corridor
8. *Concrete floor:* floor of corridor

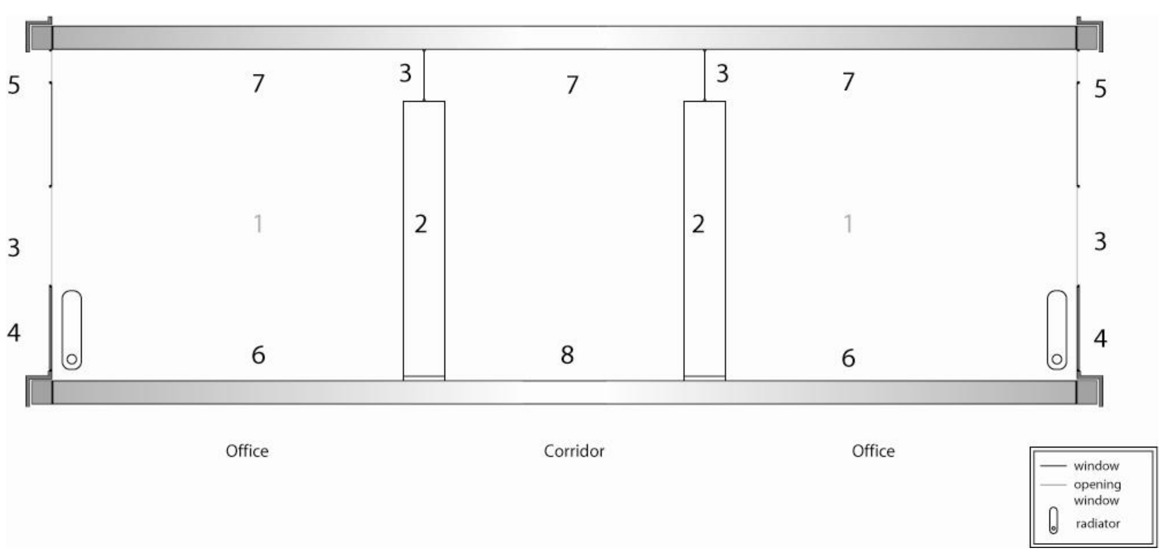


Figure 3.12 Input data walls

Walls

Now that the wall types are created, the walls need to be simulated. Therefore the surface area and boundaries of each wall need to be determined. The measures that are used to calculate the wall surface areas can be found in Appendix 5.
Façade elements are simulated as walls too; however, to involve the impact of the sun on the façades and offices, these walls have bearings. In this case the orientation is south-west (input: 45^{o}) on one side of the standard section and north-east (input: -45^{o}) on the other side.
The walls are always located in between two spaces. So in the simulation the surfaces of a wall borders on an inside, outside or adiabatic boundary. The in- and outside spaces are simulated as zones, which are explained more into detail later in this paragraph.
The adiabatic boundary functions as mirror axis and is used at the margins of the model.
For example; a separation wall between two offices, of which only one office is modeled, is modeled by the input of half a separation wall, with an inside boundary on one side and an adiabatic boundary on the other side. The wall is mirrored at the adiabatic boundary and therefore it will be counted as a whole wall in between two offices.

Zones

As previously mentioned, the zones are divided into inside and outside zones. The zones are defined by their comfort control possibilities. The outside zone, for example, is not controllable while the office spaces are. The following zones are used:

- *Outside:* an *E*xternal space with *S*olar impact, input: ES-zone
- *Office 1:* is an *I*nternal space with *V*iew factors; IV-zone
- *Office 2:*is an *I*nternal space with *V*iew factors; IV-zone
- *Corridor*: is an *I*nternal space without view factors, I-zone

View factors

Walls that are in visual contact with each other will start radiating heat. Capsol automatically calculates so called view factors for the surfaces that are situated in an IV zone, which is previously explained.
If the walls are in the same surface, like the steel frames and glass panes of the façade, the surfaces will not be able to radiate heat to one another, so their view factors are manually set back to 0.

Function references

The function references imitate the environment from outside temperature to the amount of working people inside. There are five different functions, Temperature (T), Ventilation (V) Power (P) diffuse sunlight (D) and direct beam sunlight (B).
The functions that are added for the simulation are:

- *T01:* the temperature measurements of the Bilt in the Netherlands are used to simulate the temperature over a year.
- *T02:* the maximum temperature in the office is 22°C, the minimum 15°C, and there are 9 working hours which start at 8:30 AM
- V01: the air exchange rate, which is the number of volume changes in one hour, is 1.3. This is the minimum for offices according to the building decree. The ventilation starts at 8:30 AM.
- P01: The heat load in the office which is caused by two persons, two computers and some artificial lighting and is present during the 9 working hours.
- B01: the solar beam influence is using the solar beam measurements from the Bilt as reference.
- D01: the measurements from De Bilt are used as reference for the diffuse sunlight impact

The outside zone is linked to the T01 reference, which is explained in previously. Both offices are linked to P01 and T02. The corridor is linked to P0, this standard P reference implicates a heat load of zero

Ventilation

Both offices are ventilated from the outside according to V01. The corridor is ventilated with air that flows from the offices.

Wall sun obstacles
Wall sun obstacles describe objects on the building which blocks the incidence of sunlight. To simulate this object, in this case the balconies on the outside of the façade, a system of coordinates is used as input. The spherical shape of which these coordinates are derived from can be found in Appendix 5.
To give insight in the method, a short example is shown in Figure 3.13.

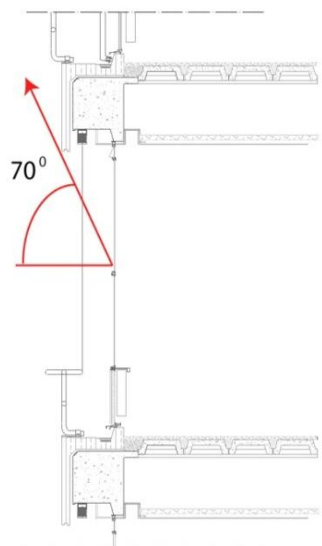


Figure 3.13 Schematic drawing of the derivation from a wall sun obstacle coordinate

The coordinate of the underside of the balcony, measured from the middle of the façade, is 70 degrees as is shown in Figure 3.13 and continues up to 90 degrees. In the model. This wall sun obstacle is of influence on the glass wall of the façade .

Controls
To simulate the radiators that are present in the offices, there is an extra wall type added called '*Water*'. This wall type consists of water and will make the simulation of heating the office through water, comparable to a radiator, possible. A heating control of 4000 Watt is placed in the wall, which is the estimated power of the now present two layer radiator which stretches two meters.
A sensor point is placed in the offices and the target temperature is given by the T02 reference, which is explained earlier. When the temperature in the sensor point becomes higher or lower than the target temperature, the control will automatically switch off or on.
V01 refers to an air exchange rate of 1.3, as earlier explained. By opening the windows, more ventilation will provide a certain amount of cooling in the offices. Therefore a cooling control by ventilation is introduced which is also coupled to the T02 reference.
The outside sun shading is also a control device. The sun shading will be activated by the temperature limits, following the T02 references. By replacing the initial glass wall type in the façade by a glass wall type with a lower g value (light incidence factor) the sun shading is simulated.

Points
To get insight in the indoor climate of the offices, thermal sensor points are placed. The points can, besides their function as thermometer also be used to locate controls. In Appendix 5 all used points can be found.

3.3.2. Trisco

Trisco models façade elements with so called blocks, which are placed on a grid. The heat transfer can be calculated and energy losses can be traced. Condensation problems can be predicted, because Trisco is able to calculate temperature flows within the simulated elements.

Blocks

Blocks that are used in Trisco represent elements of the simulated façade or its boundary conditions.
The blocks that are used in the simulation of the standard detail are

- *Outside:* outside temperature of -10°C
- *Inside*: inside temperature of 22°C
- *Ring beam:* concrete ring beam with λ= 2.60 W/mK
- *Prefabricated element:* concrete prefabricated element with λ= 2.60 W/mK
- *Cavity:* cavity between prefabricated element and ring beam, air flow direction Y
- *Steel* window frame: window frames of steel with λ= 50 W/mK
- *Glass:* single layered glass with λ= 0.80 W/mK
- *Insulating panel:* cork panel with λ= 0.043 W/mK

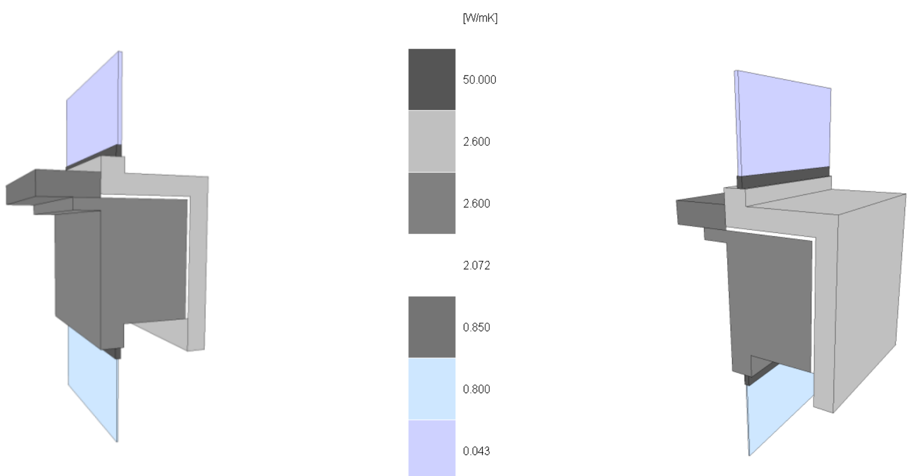


Figure 3.14 Basic input model

Grid

To compose the façade element the blocks have to be placed on the right location. Therefore a grid is used and of the X, Y and Z coordinates of each block is defined. The coordinates of the grid are shown in Figure 3.15 and in Appendix 6.

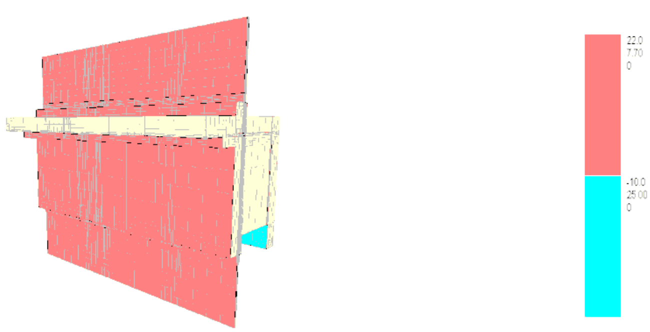


Figure 3.15 Grid and boundary conditions of the basic input model

Node Boundary conditions

To measure the temperature within the façade element, node boundary conditions are placed in this element.

3.4. Façade principles

Because of endless possibilities within façade technology, a sifting of façade types should be made. Some useful keynotes for the CiTG façade refurbishment originate from the theoretical research. These keynotes are; the strong exciting *load bearing structure*, the *intensive use* of the building, the possible future indication as *city monument*, and the need to gain *high comfort* standard and *low energy consumption*.

Four façade principles are worked out which meet all the previously mentioned keynotes in their own way; however they have their unique qualities. The façade principles are:

- Climate façade principle
- Upgrade façade principle
- Retrofit façade principle
- Make over façade principle

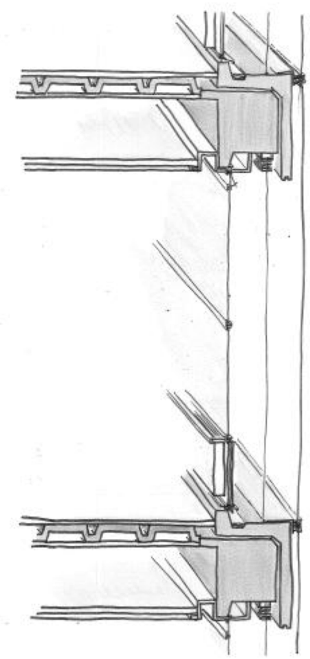
To structure the clarification of the façade principles, they are ordered to the amount of intervention that are done to the interior of the initial situation The drawings can be found on scale 1:10, 1:20 and 1:50 in Appendix 7.

3.4.1. Climate façade principle

The climate façade wraps the old façade in an insulated layer. It aims to provide a new comfort standard without interference with the interior. It uses the balconies to apply an additional insulated glass layer to their outside. In the following, the aspects of this façade are expounded.

Principle and construction

An additional insulated curtain wall is mounted on the outside of the existing balcony structure. Together with the original façade it creates a so called Climate façade, in which the outer shell forms the insulation, and the inner façade functions as a screen between the buffer zone and the inside climate. The glass pane that is situated in front of the prefabricated concrete element is made of opaque glass so that dirt and connection joints are hidden from the outside.



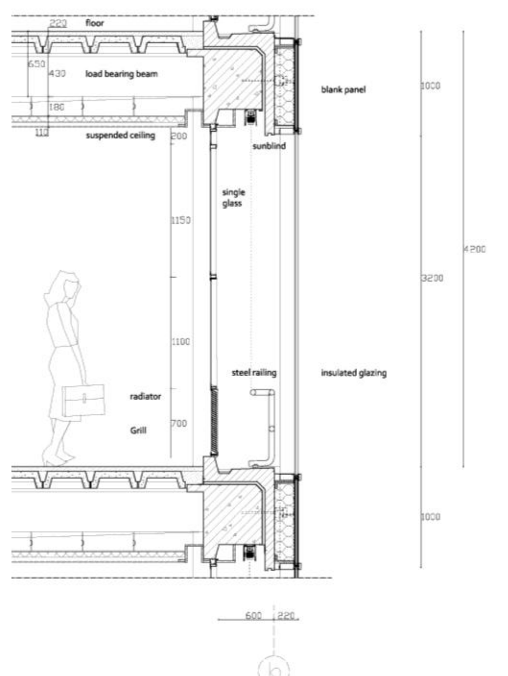


Figure 3.16 concept sketch climate façade

Building physics

The climate control is mechanically regulated. Fresh air is taken in centrally and led past a cross flow heat recovery. The ventilation air is brought into the offices from the ceiling. Used air is extracted from the façade cavity. New openings in the interior façade layer let used air flow from the office to the cavity, where it is mechanically extracted roughly every third office. Thus, excessive solar gains are removed by the ventilation air before reaching the office space. The central exhaust duct is led to the roof again to pass the heat recovery system. The ventilation system can bypass the heat recovery at nighttime to cool down the building. The radiators are replaced and there is a cooling system installed to cool the ventilation air in summertime.

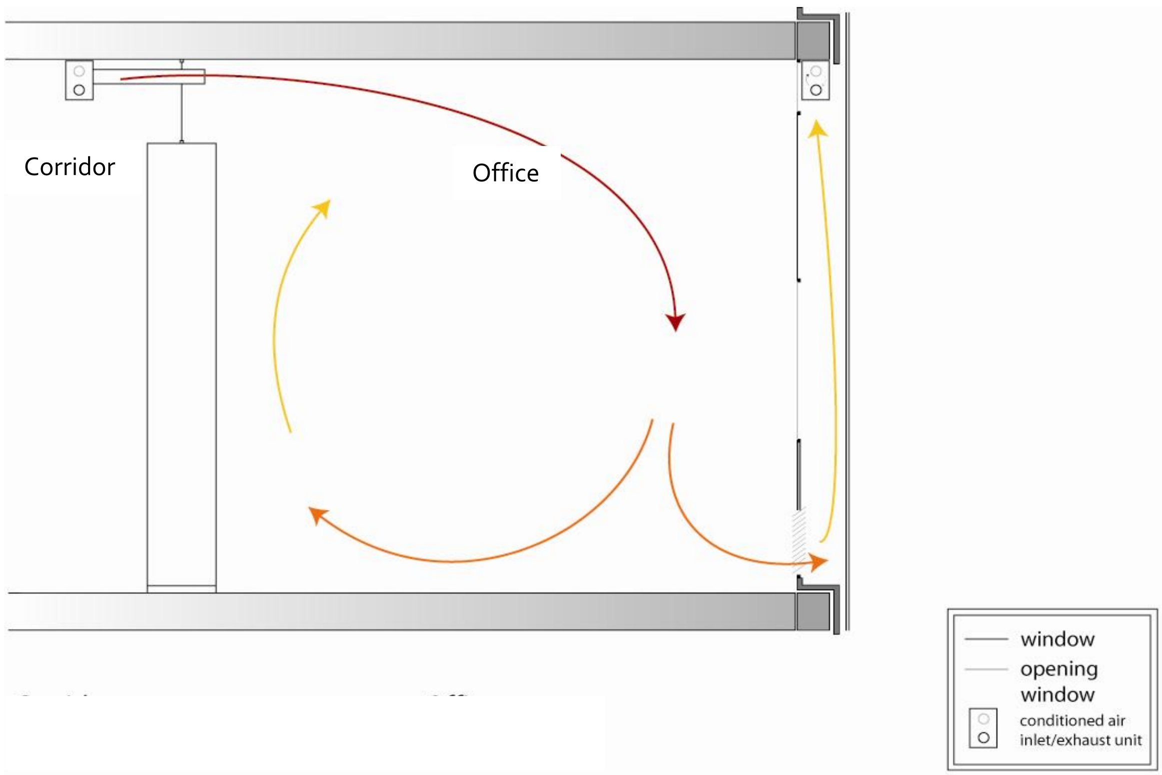


Figure 3.17 air flows in the 'Climate façade'

Potentials and threats

This principle provides a fast and simple solution to reduce energy consumption and raise the indoor comfort. The additional façade improves the insulation of the building without the need to adjust the initial façade construction. The new façade can be mounted from the outside, independently from interior work. Nevertheless, it is necessary to replace the suspended ceiling in the corridor, when new technical climate installations are brought in. Ventilation grilles from the office to the buffer zone need to be placed in the initial façade too.

The zone next to the window will become much more comfortable, because the current downdraft is prevented. Yet, the comfort advantage of natural ventilation will be lost because of the mechanical system that this type of façade requires. The energy efficiency is improved by using a central heat exchanger and by applying a sunblind in the cavity, which can work independent of weather influences like strong winds. However, by cooling the ventilation air, the energy efficiency is reduced again. Using opaque glass in a part of the façade will decrease the heat load in the office, however it will affect the look of the building drastically.

The load bearing connection of the new façade is difficult, as it needs to punctuate the existing concrete panels. Also, the additional weight at the far end of the ring beam causes extra forces on the construction; however the construction is over dimensioned and can carry the extra loads without further measures.

When, in summer time, the buffer zone becomes hot by the solar gain and the ventilation speed in the office reaches a maximum, for a comfortable indoor climate, it is possible to ventilate the buffer zone by making opening elements in the outer layer of the climate façade as can be seen in Figure 3.18. This way, the solar gain in the cavity can be lost quickly and prevent the office from heating up.

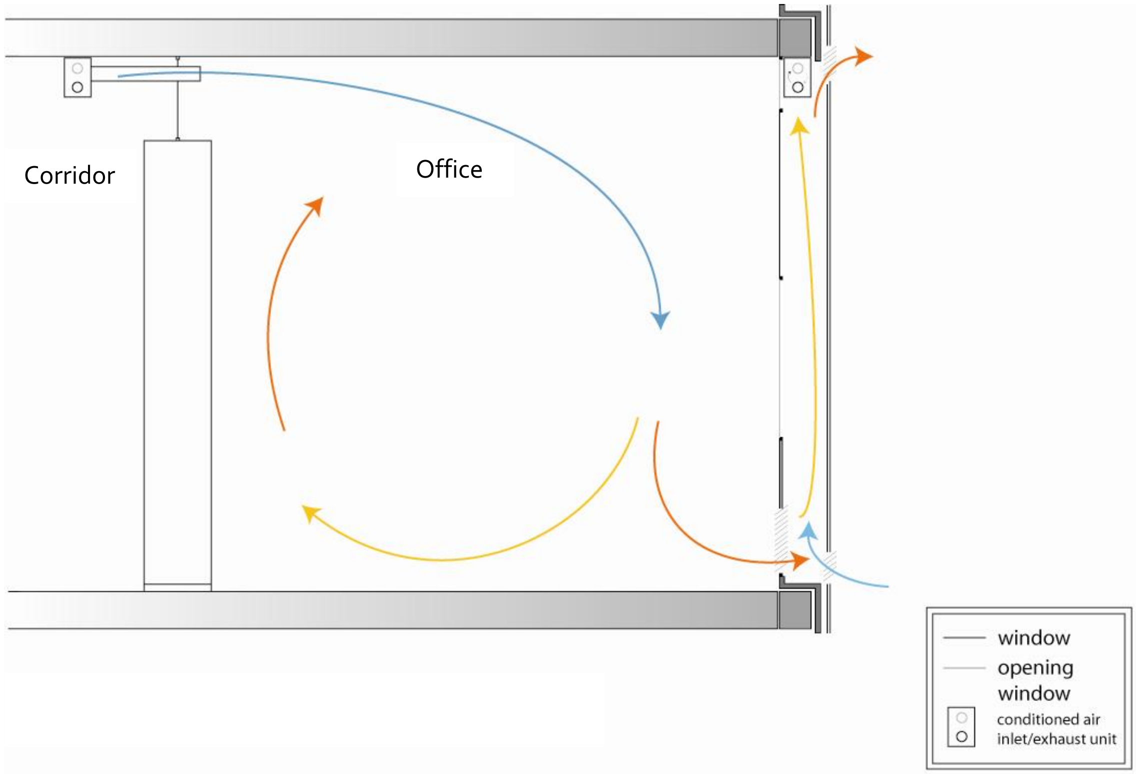


Figure 3.18 Possibility to ventilate cavity in summertime

Computer models

To make correct simulations for the Climate facade, some adjustments need to be done to the basic computer models. For the standard input of the Capsol and Trisco model, there is referred to paragraph 3.3 Computer models and Appendix 5 and 6. The adjustments will briefly be explained.

A few interventions are applied to the input data of the standard section in Capsol, because a new glass layer and air cavity are introduced in this façade principle. The wall types, walls, zones, ventilation zones and points need to be adjusted. The controls are changed as well, because a cooling power is introduced. The input data for the heating control stays the same because, even though a different heating system is used in this façade principle, the differences between water based systems are not possible to simulate in Capsol.

The extra wall types that are introduced for the Climate façade are:

- *Insulating_glass*: new outside glass layer
- *Cavity:* cavity between new and old façade

To create the new glass layer, a new wall is added to the input data, a new zone 'cavity' is introduced, which is not conditioned. However it has a mild climate because the conditioned exhaust air of the office flows through this zone. The ventilation path has also changed. From the 100 percent incoming air, 90 percent is exhausted through the façade cavity and 10 percent is exhausted through the corridor. Then it will be exhausted to the outside again, passing the heat recovery system, which could not be simulated.

For Trisco the basic model is expanded with a connection joint and a new insulated glass layer. The bold is simulated as steel and the glass has an U-value of 3 W/m^2K.

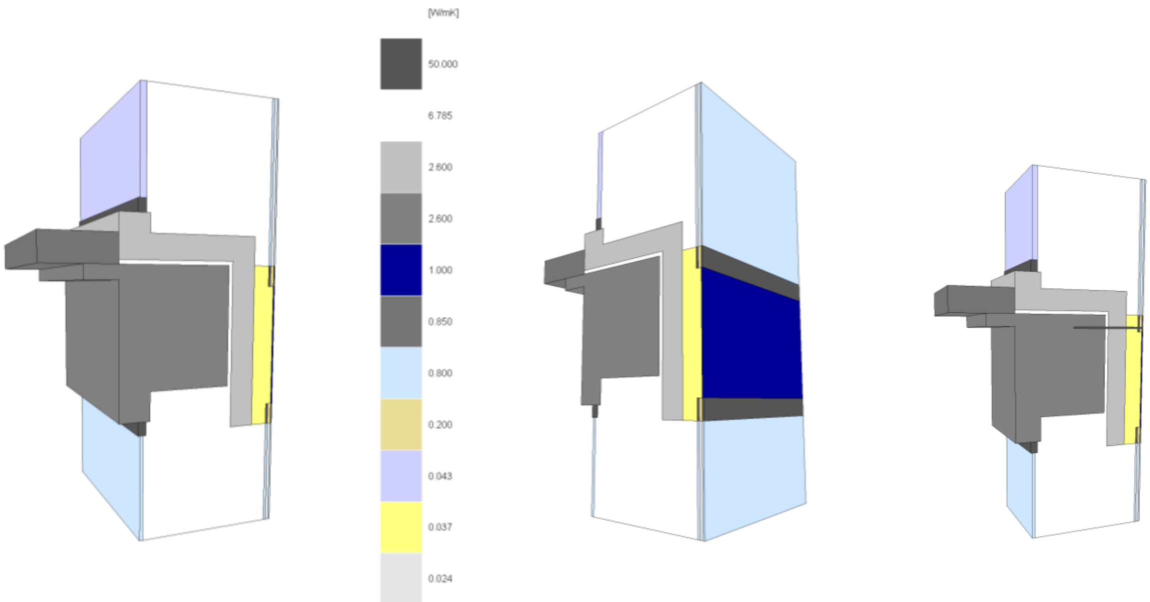


Figure 3.19 Input model 'Climate façade principle' in Trisco ;total overview and section at the joint

3.4.2. Upgrade facade strategy

The Upgrade façade principle reuses the original façade structure and aims to improve the thermal performance by replacing the single glazing by insulated glass and if necessary by insulating the ring beams.

Principle and Construction

The original steel façade framework is constructed of T-shaped profiles, into which the glass is luted. The original glass panes are removed and the profiles cleaned. New insulated glass panes are placed in the original profiles using structural glazing silicone. Thus, a weather proof sealing is achieved. The silicone sealant, that is used to connect the windows, covers the thermal bridges of the steel framework, as can be seen in Figure 3.21.The steel frames are initially designed based on the exposed wind load, which is many times larger than the dead load of the window that the frame needs to carry. Therefore the steel frames are strong enough to bear the extra load of double glazing without further measures. The external venetian blinds are replaced .

The prefabricated concrete elements of the facade cannot be removed, as the façade structure rests on these. If the energy losses through the ring beam are not acceptable, the elements can be covered with a ventilated and insulated cladding. This way the building is totally insulated without removing the initial structure of the façade.

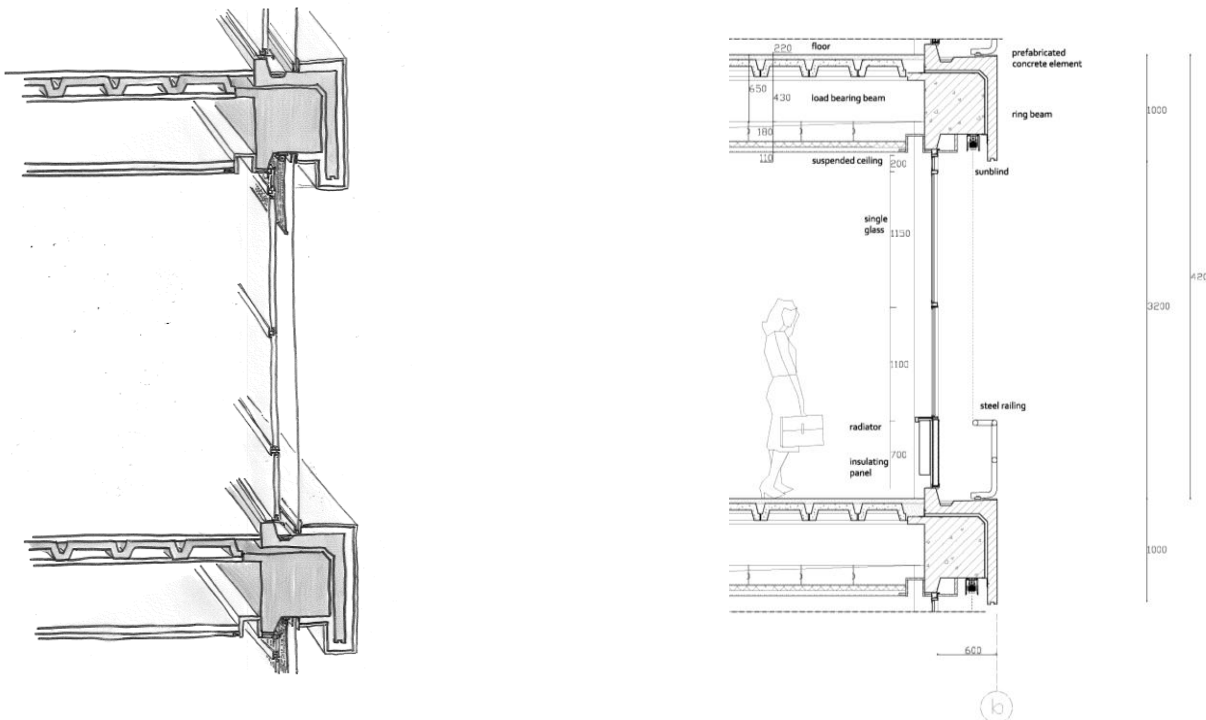


Figure 3.20. concept sketch 'Upgrade façade'

Figure 3.21: Concept detail wind and water proofing

Building physics

The climate concept has not changed in comparison to the initial situation. The offices are naturally ventilated by opening windows. The existing radiators can be reused. However, it is recommendable to replace the radiators with smaller and faster convectors, because the improved façade demands less heating against the downdraft.

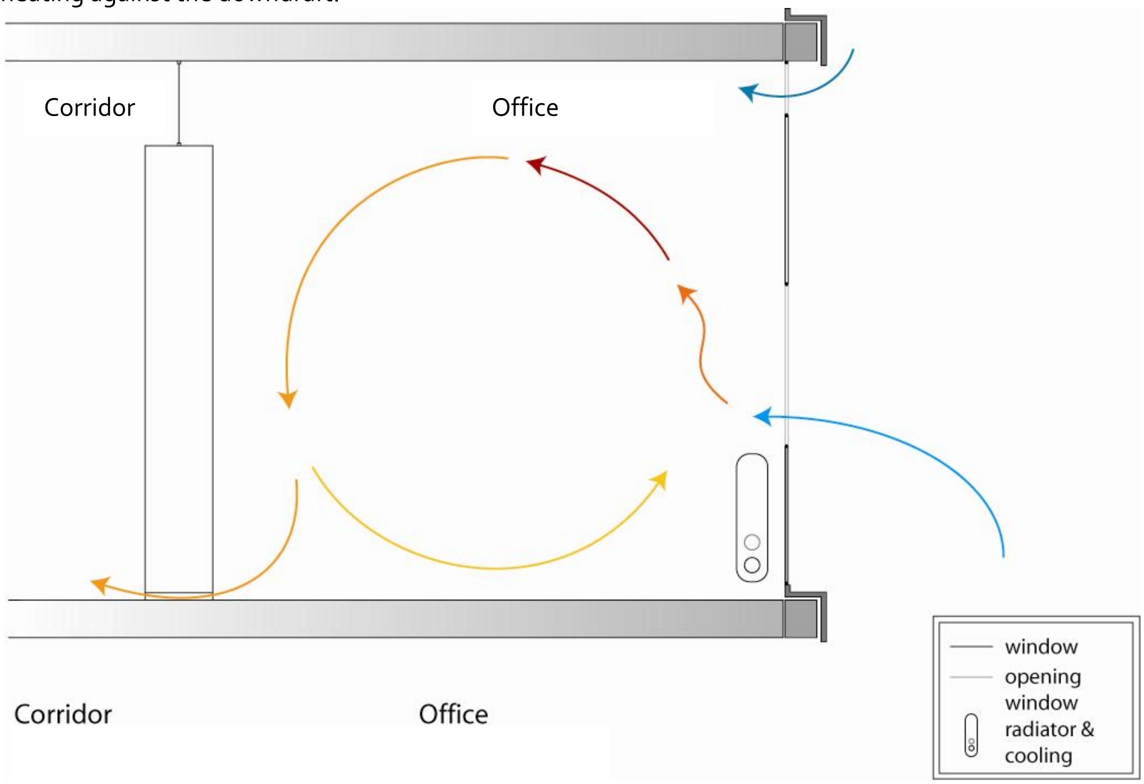


Figure 2.2.2: airflows in the 'Upgrade' façade

Potentials and threats

The Upgrade façade principle provides a solution for the reuse of the existing façade. By using the same steel frames, an authentic look from the inside will be realized. When the glass panes are removed, the window frames have to be checked carefully to make sure the steel structure is undamaged. Broken or corroded members have to be replaced of repaired. If the thermal simulation in Trisco has shown that, with double glazing, there still remains a risk of condensation; it is necessary to use triple glass.
An alternative would be to add a non insulated glass screen on the outer edge of the balconies, as can be seen in Figure3.21. This buffer will reduce extreme temperatures, wind and rain on the façade. The weather screen also allows for simpler detailing of the inner primary façade.

Computer models

Because a new façade and possibly new insulation is used in the Upgrade façade principle, some interventions need to be done within the input data of the Capsol and Trisco model.

A sandwich panel is added as wall type in Capsol to replace the insulating panel and insulated glazing will be used to replace the single glazing. To make cooling possible, the controls of the model are completed with a cooling power. A layer of insulating material is added in the Trisco model. This insulation can be applied on the outside of the prefabricated concrete element as is shown in Figure 3.22 or to the inside of the ring beam, as can be seen in Figure 3.23.

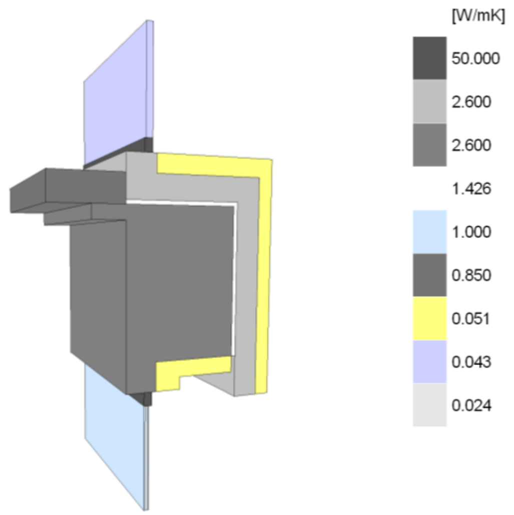


Figure 3.22 Input model with additional insulation on the outside of the prefabricated concrete element

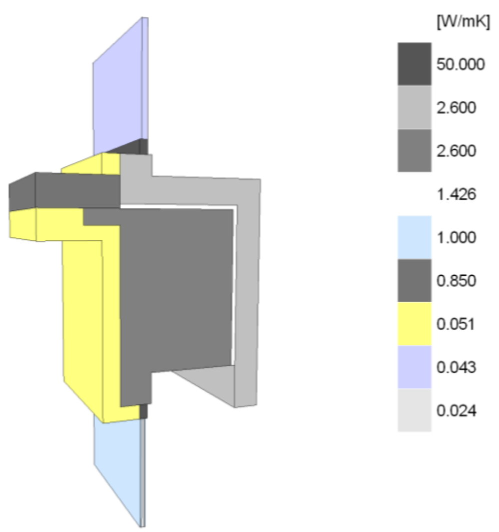


Figure 3.23 Input model with additional insulation on the inside of the ring beam

New models are built in Trisco to simulate the effect of double and triple glazing in the initial steel window frames, see Figure 3.24. The influence of the earlier mentioned folding or sliding façade is also simulated in a new model, which is shown in Figure 3.25.

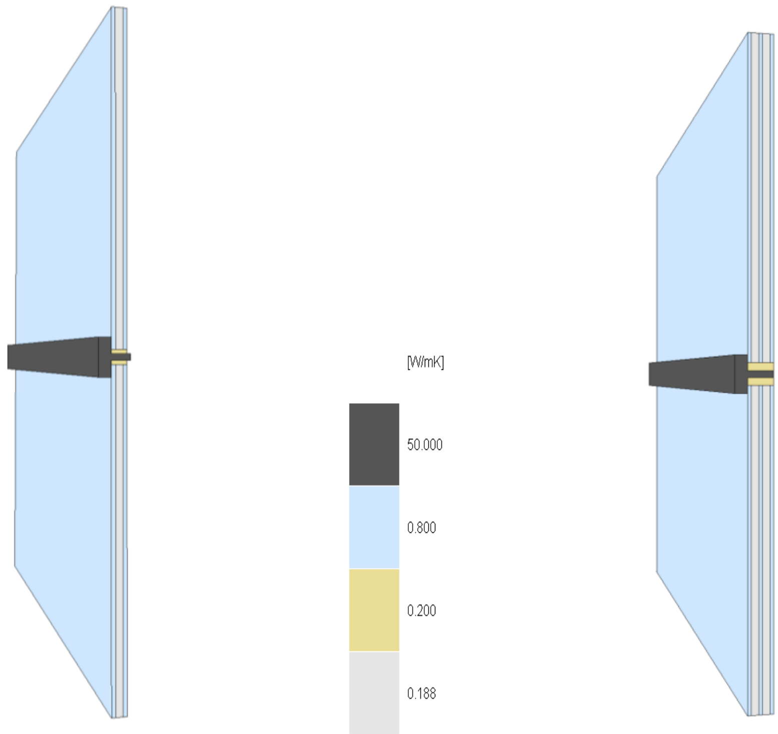


Figure 3.24 Input model with double and triple glazing in the initial steel window frames

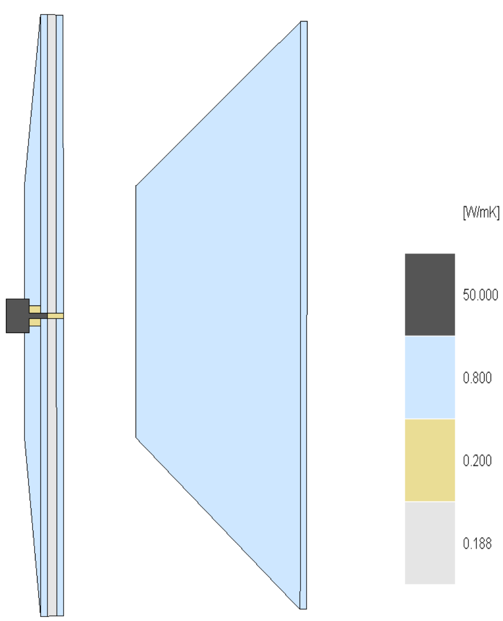


Figure 3.25 Input model of the Folding facade façade combined with double glazing in the initial steel window frames

3.4.3. Retrofit façade principle

This refurbishment principle was originally sketched by Paul Coenen and Wouter Hendrikson in a student workshop. It takes advantage of the prefabricated construction of the building. Te thermal insulation is improved without affecting the characteristic look of concrete bands on the buildings.

Principle and construction

In a first step, the façade and prefabricated concrete elements are removed from the building. The concrete elements are brought to an on-site workshop where they are cleaned. In the mean time the concrete structure of the building is insulated with mineral wool. On the top of the ring-beams foam glass is used, because it will have to carry the concrete elements. When theses are brought back into place, they are fixed by new bolts and come to rest some 80 mm higher and further outward than before. The space thus created between concrete element and original top floor provides a connection possibility for a new insulated window system which will be mounted from the inside. The Venetian blinds on the outer edge of the service platforms are replaced.

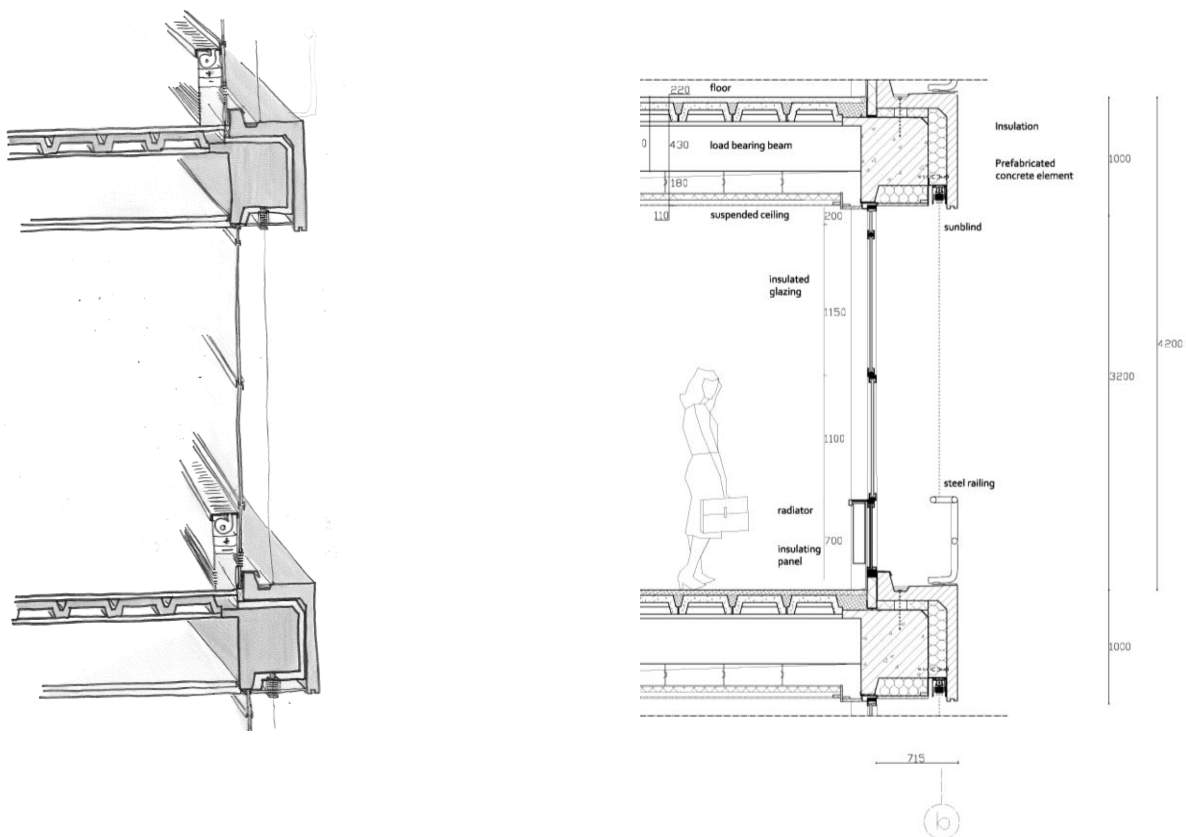


Figure 3.26 Concept sketch 'Retrofit façade'

Building physics

The existing building service concept is maintained. After the refurbishment, the offices can be naturally ventilated. The original radiator heating can generally be reused. Nevertheless, it is recommendable to place new, more efficient, radiators along the façade. Thanks to the improved insulation, the amount, and size of radiators can be reduced.

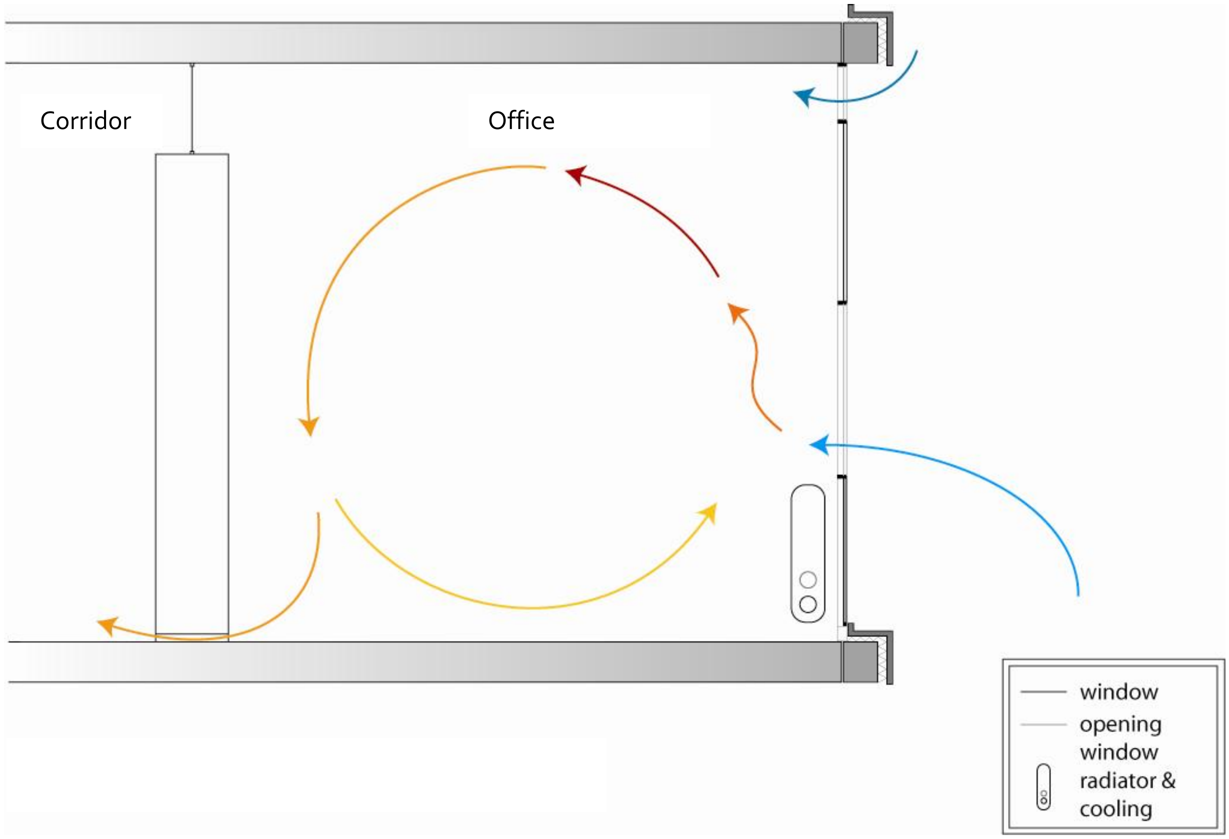


Figure 3.27 Airflows in the 'Retrofit façade' principle

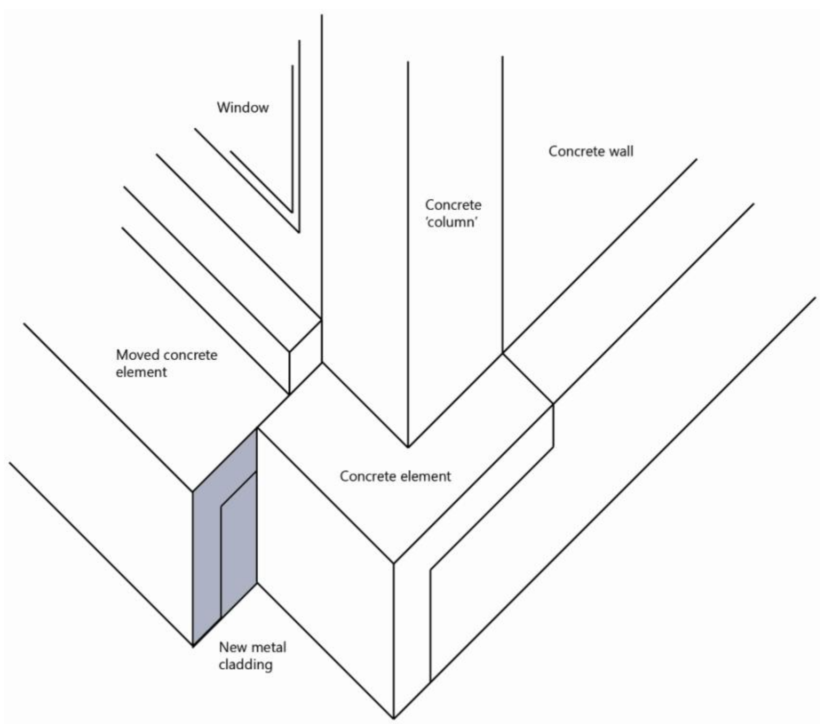


Figure 3.28 corner situation

Potentials and threats

The Retrofit façade principle provides an easy solution for the regular façade detailing. Only for the corner situation, where the thickness of the façade becomes evident, a special design needs to be considered. This can either be a special cover for a wider seam or a newly manufactured corner element. The existing steel-glass façade can be recycled and the concrete elements are reused in the new façade, so the end of life quality of the initial façade is pushed to the maximum within this refurbishment principle.

The new window system should be designed as similar to the initial façade as possible. This way the outer appearance of the building will not change much, which goes along with the buildings future appointment to city monument. New sun blinds and individually controllable heating installations contribute to comfort and energy performance.

Computer models

Because the Retrofit façade principle uses insulated glazing, natural ventilation and a heating and cooling device, the simulation in Capsol is similar to the Upgrade façade principle. The difference in window frames between the Upgrade façade and the Retrofit façade will not affect the simulations in Capsol much. A brief explanation on the Capsol program has previously been given in paragraph 3.3 'Computer Models'. Because the Retrofit façade principle uses additional insulation between the ring beam and the prefabricated concrete element, a new input model is made which is shown in Figure 3.29.

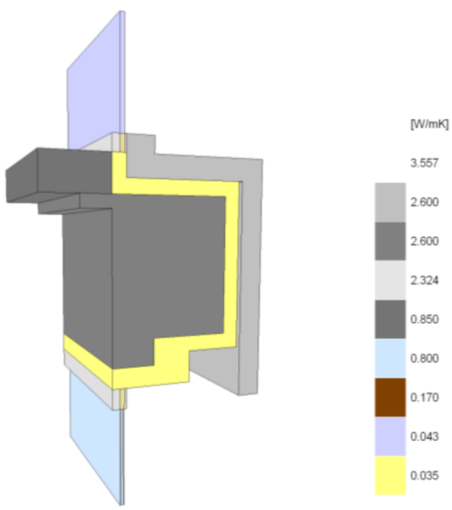


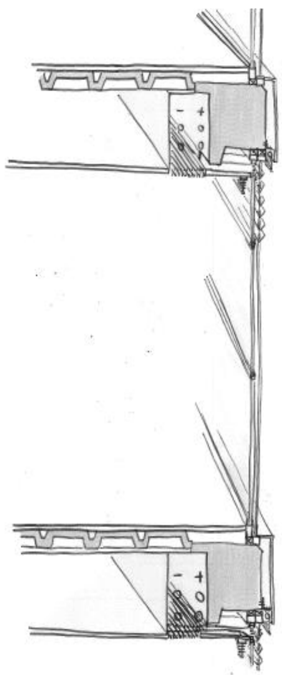
Figure 3.29 input model for the 'Retrofit façade'

3.4.4. Make over façade principle

A total replacement of the façade can result in major improvements in the inside climate. This replacement is the starting point of the Make over façade principle. With the use of modern façade novelties, the new façade will be optimized to raise the indoor comfort.

Principle and construction

First, the façade and prefabricated concrete elements are removed. Then, the new façade is placed on the far end of the construction so that the office space is optimized. The remaining part of the ring beam can now be covered with insulation and cladding. The floor covering is removed and an under floor heating and cooling system is applied on the floor. Finally a new suspended ceiling is placed.
The upper part of the façade is used as inlet to provide air for ventilation. The middle part contains openable windows for extra ventilation and the lower part can be filled in with a solid panel so that the solar gain of the office through glass is reduced. By using sun blinds that contain light redirecting louvers, not only the sunlight will be blocked to reduce heat gain inside the offices but also daylight is brought deeper into the space.



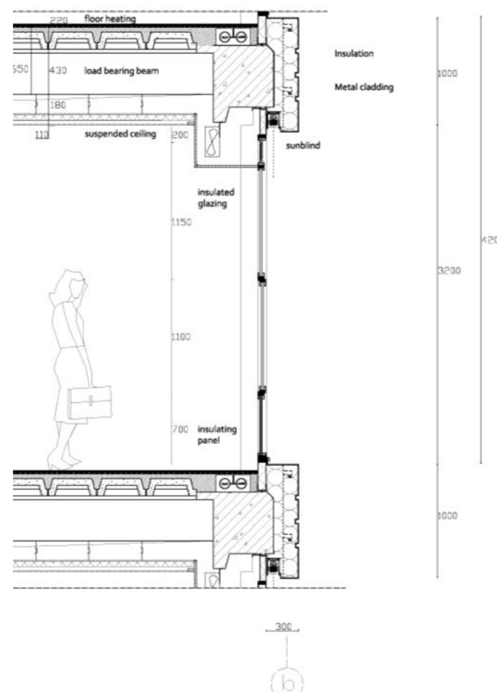


Figure 3.30 concept sketch of the 'Make over façade'

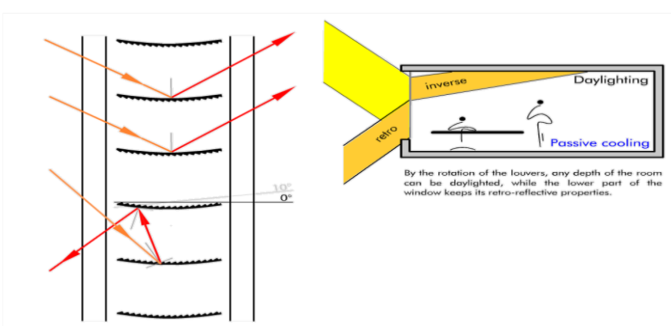
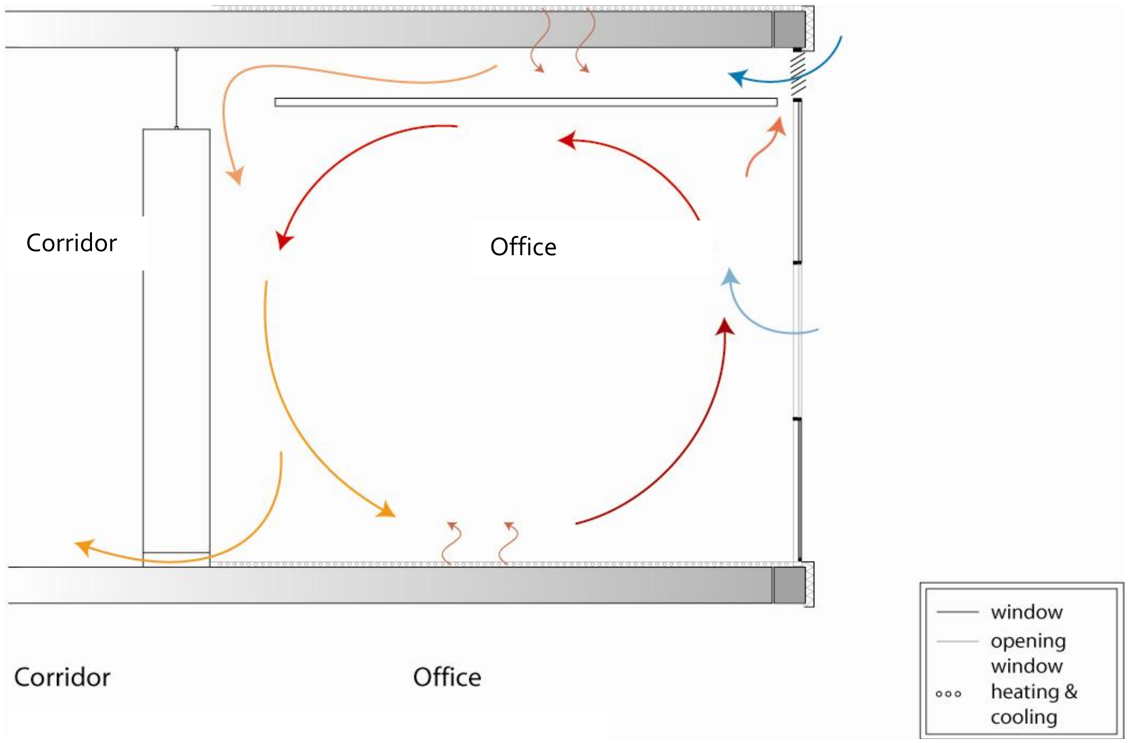


Figure 3.31 Principle of Light redirecting louvers, image from http://www.koester-lichtplanung.de/flash/retroflex_e

Building physics

The ventilation system of the Make over façade uses outside air. A ventilator, which is placed above the new suspended ceiling, draws the air into the office. The air is pre-heated or -cooled while it flows along the ceiling, as can be seen in Figure 3.32. A circulation of air will occur inside the office, which draws in more fresh air from the outside. Some air is recirculated to increase the amount of ventilation air; the rest is exhausted through the corridor and let out through the roof where it passes a heat exchanger. The extracted energy will be used for the heating / cooling floor-system. Thanks to the well insulated new façade, the heating and cooling load of the building will decrease.



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Potentials and threats

With use of some simple and effective techniques, a high indoor climate with decentralized control can be realized. The light redirecting louvers will Upgrade the light comfort within the office and will reduce the cooling load of the building.

A total strip down of the building and the use of high standard materials will push the expenses to a maximum. However, placing the façade to the far edge of the construction increases the office space. The new façade will decrease the heat load of the offices and thus a decrease in energy expenses.

The outer appearance of the building will change, so there first has to be decided if this new look is acceptable. To meet the requirements of the future appointment to city monument, the horizontal lines are preserved in the façade.

Computer models

The Make over façade principle has enlarged offices and a new façade. This will have its influence on the Capsol and Trisco simulations.

The Capsol model of this refurbishment principle is quite similar to the model of the second principle. Besides the similar simulation of ventilation and the controls, the size of the office is enlarged with 0,6 meter. This enlargement is carried through in the 'wall' input data.

Because the insulation of the ring beam will be similar to the applied insulation of the Retrofit façade principle, no other simulation models in Trisco are made.

3.5. Wheel of potentials

The wheel of potentials is a very helpful tool to get insight in the opportunities and threats of each façade principle. Especially the relations between different aspects become clear in the graphic overview. However, some important aspects are not yet developed within the wheel enough to give a total view on the potentials of a façade principle. The working, shortcomings, and qualities of the evaluation tool will be discussed in this paragraph.

3.5.1. Operation

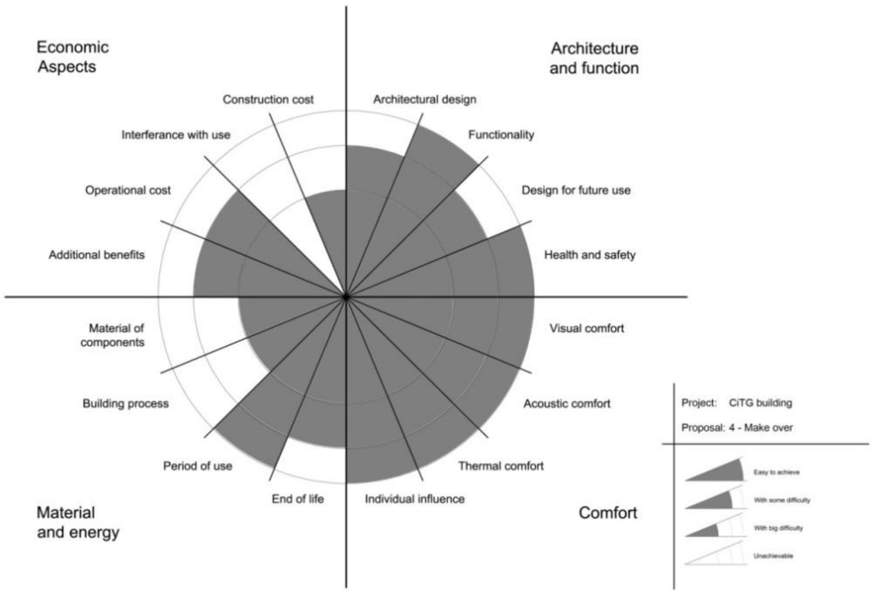


Figure 3.33 Wheel of potentials

Before the graphic of the wheel of potentials can be created, as shown in Figure 3.33, an excel sheet has to be filled in to define the scores on which the graphic is based. This excel sheet can be found in Appendix 8.
To arrange the questions in a clear way, the four categories with sub aspects that are shown in the graphic overview are used. Because the questions are categorized, a clear structure is created and the questions are easy to answer. If there is enough information about the façade known, a realistic overview of the façade's potentials and relations between aspects can be given. If there is not enough accurate data is present, the tool is still useful to make a rough comparison, given that all the proposals that are compared have the same level of detail.

3.5.2. Qualities

The graphic output reveals very quickly characteristics of the façade principle and the relation between several aspects. Comparison of refurbishment principles supported by visuals will prevent miscommunication. The wheel gives a brief summary of the façade's potentials and the four main aspects of refurbishment can be evaluated at the same time. Relations are revealed between

- comfort and costs
- comfort and architecture
- material & energy and architecture
- material & energy and comfort
- material & energy and costs
- costs and architecture

3.5.3. Shortcomings

The wheel of potentials has many qualities, which are mentioned previously. Like graphic overview of relations between different aspects of the refurbishment process. Still there are some shortcomings in the system behind the Wheel of potentials. These will be pointed out next.

The graphic overview makes it possible to see relations in one glance. In comparison to other wheels of potentials, the wrong conclusion might be drawn in first instance. An example is shown in Figure 3.34 to make the clear which kinds of miscommunication can occur, with the use of the Wheel of potentials.

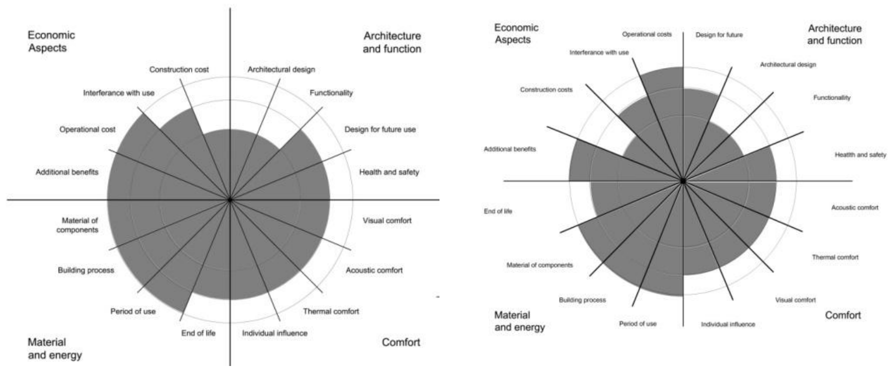


Figure 3.34 Different images created by changing the arrangement of sub aspects.

On the left, the initial wheel is showed, and on the right another arrangement of sub aspects is applied. The image of the wheel changes while the content is similar, therefore a logical arrangement of sub aspects need to be made. To make sure the wheels of different façade proposals are comparable, the arrangement of the initial situation will be used in this project. Besides the arrangements of the sub aspects, the importance of the sub aspects needs to be improved in the wheel. Now, the importance of a sub aspect has no influence on the image. So, for example, the individual influence is very important within the comfort quarter as is explained in chapter 2. In the initial situation it seems like the acoustic comfort is just as important as the individual influence. To make sure the four main aspects are represented correctly by the sub aspects, the size in the graphic representation is adjusted for each sub aspect according to their importance within the main category. An example is shown in Figure 3.35. Within this example a quite common position is taken to determine the percentages per sub aspect. Individual influence and thermal comfort are graded highly within the comfort section, while acoustics and visual comfort are downgraded because now-a- day's facades take often care of these aspects in any case.

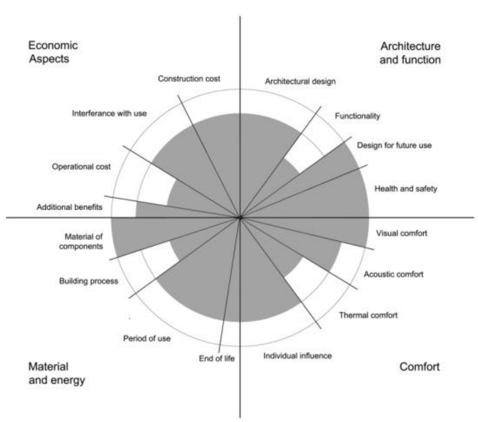


Figure 3.35New division of sub aspects within the four categories

Within the four main categories, there is no deviation in importance possible. So if, for example, the comfort aspects are most important for the refurbishment of the CiTG faculty building, it cannot be traced from the visual overview. However, one could say that this tool is used by professional parties that will decide themselves which of the aspects is most important.

4. Results

Within this chapter, the results of the previous mentioned simulation models are given. The outcomes will shortly be explained; however they will be discussed in the next chapter 'Discussion'.
Outcomes of the simulations calculated by Capsol, are represented in graphs. The Trisco simulation results are given in figures, that show the temperature flows, and in an alpha numeric output that shows the energy flows. For the temperature flows, a minimum of -10°C and maximum of 9.28 °C is used. The maximum represents the dew point. This way condensation problems can be predicted.
Furthermore, a Wheel of Potentials is given for each façade principle. This wheel origins from an excel sheet, which can be found for each façade principle in Appendix 8.

4.1. Standard section

Capsol

To find out which cooling load is sufficient, to reach a high comfort standard, certain cooling loads are simulated which can be found in Table 5. To find the capacity of the given cooling load per m^2, the given load is divided by the surface of the office, which is 38 m^2 for the offices in the standard, climate and Upgrade façade principles and 41,4 m^2 for the office in the Make over façade principle.
Solar gain plays a large role in the total heat and cooling load of a building. The glass type will influence this. The chosen glass type is a normal insulated glass type of which the properties are shown in Table 6. The energy use over one year is calculated to make the energy uses of the façade principles comparable.

Cooling type	Total cooling load	Standard, Climate, Upgrade	Make over
cooling 0	0 watt	0 W/m²	0 W/m²
cooling 1	50 watt	2,89 W/m²	2,57 W/m²
cooling 6	100 watt	5,79 W/m²	5,14 W/m²
cooling2	250 watt	14,47 W/m²	12,86 W/m²
cooling 3	500 watt	28,94 W/m²	25,72 W/m²
cooling 4	750 watt	43,40 W/m²	38,58 W/m²
cooling 5	1000 watt	57,87W/m²	51,44 W/m²

Table 5 Cooling types with total cooling and cooling per m^2 for each façade principle

Glass Type	G-value	U-value (W/m²*K)	Name
glass 2	0,47	1,40	Climalit Ultra N Antelio

Table 6 Glass types' properties

The initial situation is simulated with a single glazing which has a g value of 0,75 and a U value of 3,3 W/m²*K and cooling 0. The amount of exceeding hours of the initial situation is given in the result graphs. The comfort boundary of 100 hours above 26 °C, is shown in the charts as well. This way the results per façade principle can be compared well to the initial situation and the required standards. The simulation of the initial situation results in 391.17 temperature exceeding hours without an external sunblind and 166.17 temperature exceeding hours with an external sunblind.

Trisco

The standard façade element is calculated in Trisco, which results in the following temperature flows

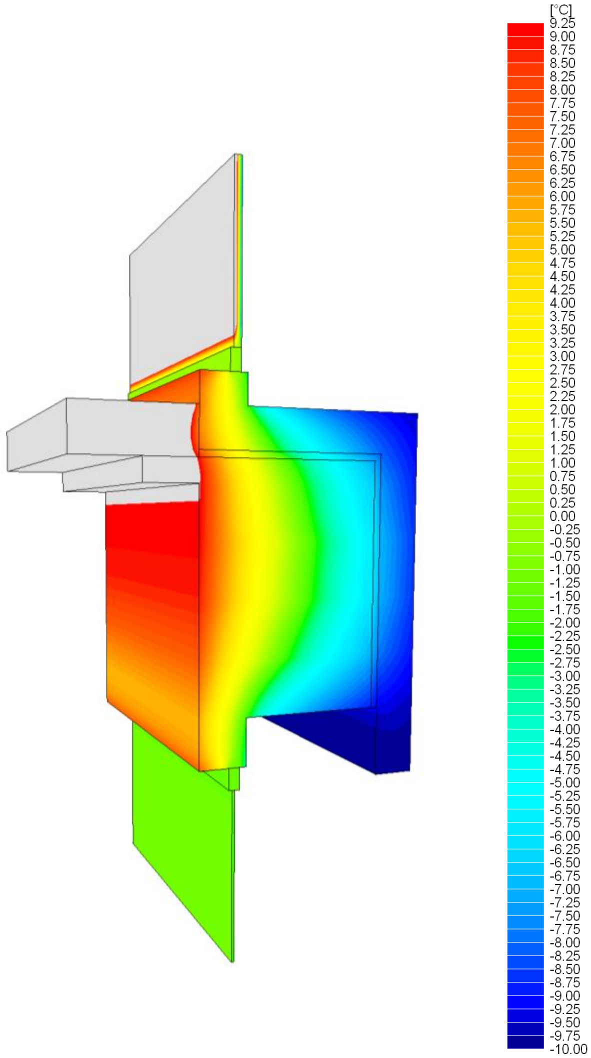


Figure 4.1 Temperature flows in the standard façade

4.2. Climate façade principle

Capsol

Different glass types, which are mentioned previously, are used to calculate the amount of exceeding hours. They are calculated for the different cooling types, see Figure 4.2. The amount of exceeding hours for glass type 2, with and without external venetian blinds, is given **Fout! Verwijzingsbron niet gevonden.** and the amount of exceeding hours plotted against the used energy is showed in Figure 4.4.

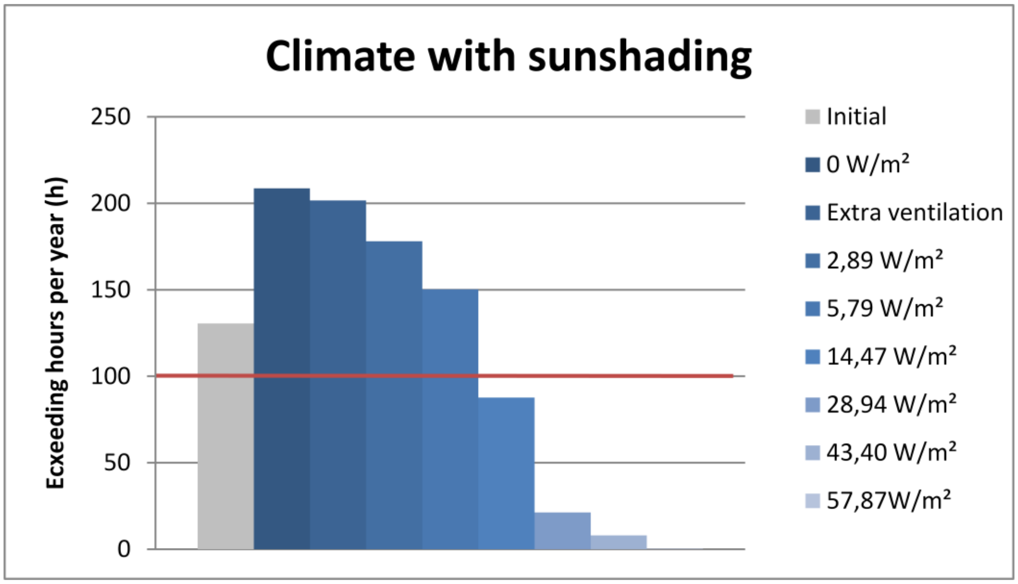


Figure 4.2 Exceeding hours per cooling type for the Climate façade

Trisco

The calculation of the 'Climate façade' Trisco model results in the following temperature flows. And has a heat flow of 74,2 W

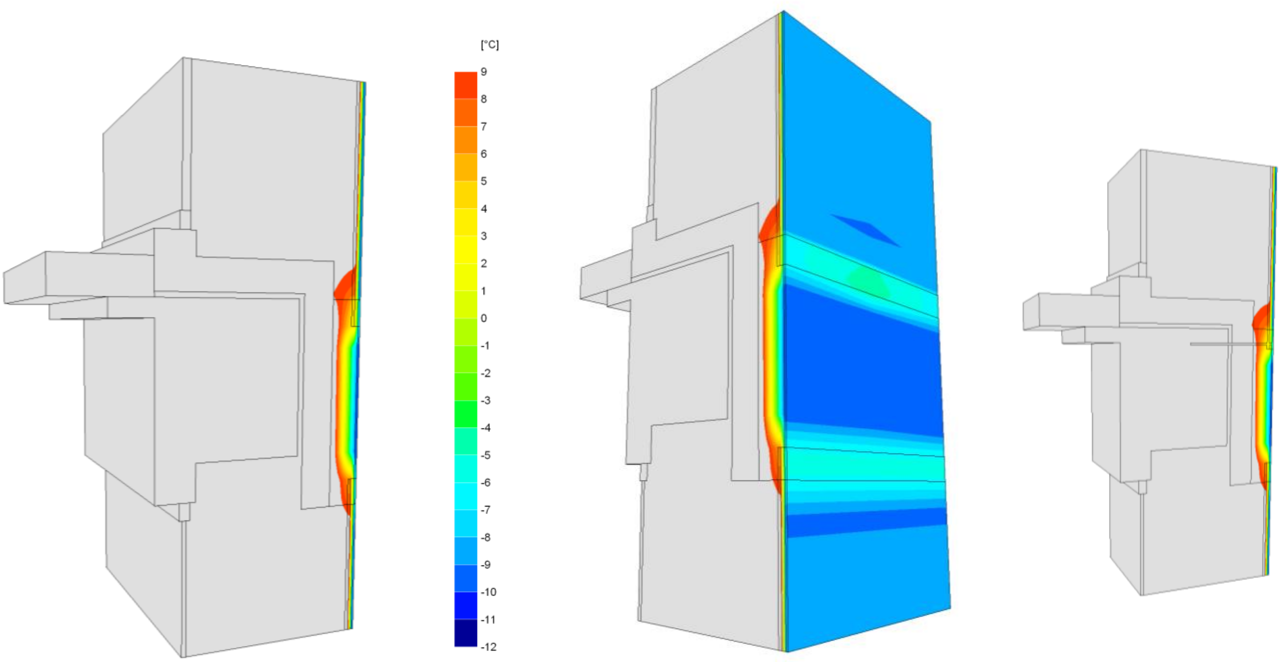


Figure 4.3 Temperature flows in the climate façade and connection joint

Wheel of potentials

This wheel of potentials origins from an excel sheet that can be found in Appendix 8.

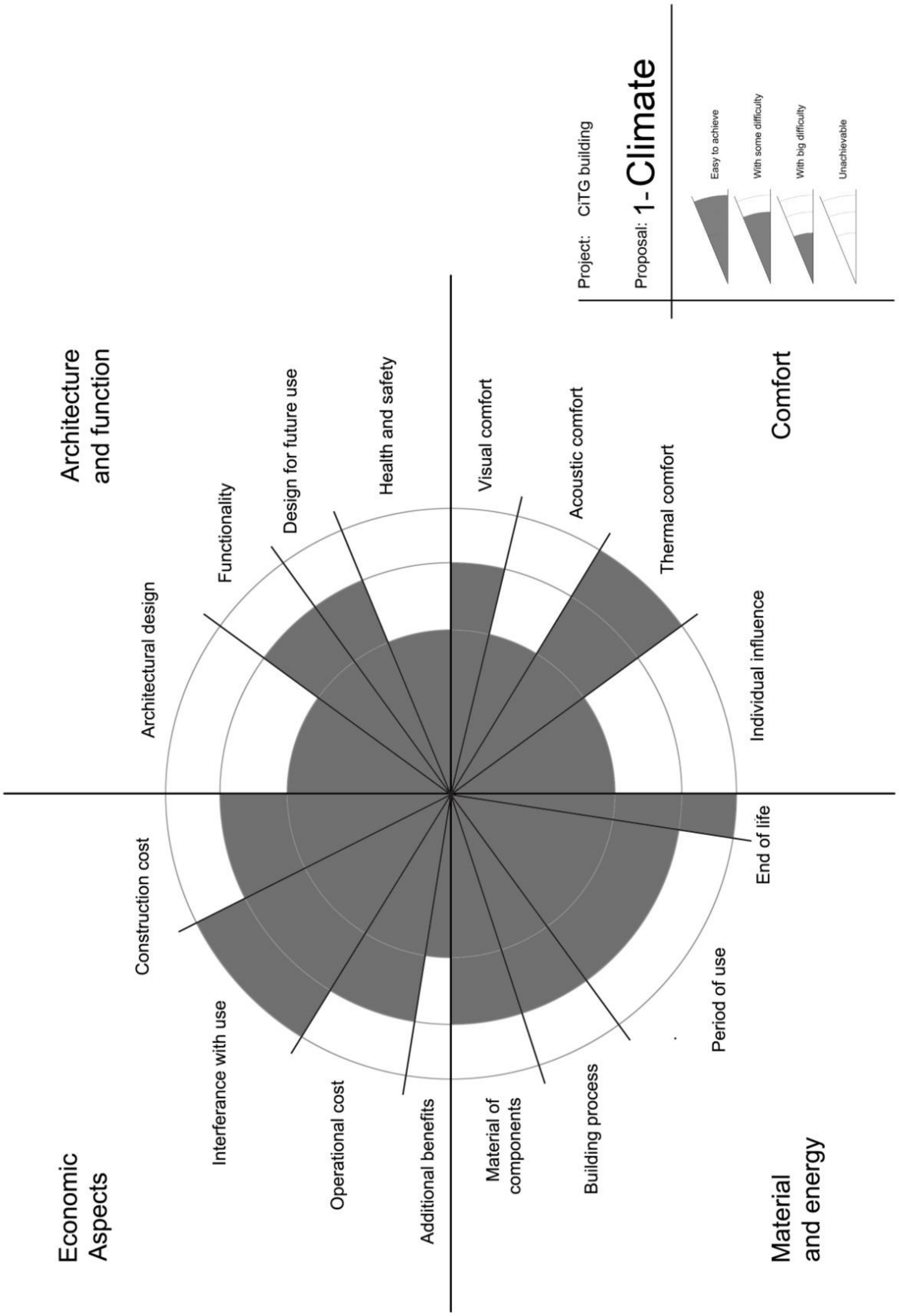


Figure 4.4 Wheel of potentials for the Climate façade

4.3. Upgrade façade principle

Capsol

The previously mentioned glass and cooling types are set out in a graph (Figure 4.5) to the exceeding hours. The exceeding hours for glass type 2 with and without external sunblind are given in **Fout! Verwijzingsbron niet gevonden.**. The graph that is shown in **Fout! Verwijzingsbron niet gevonden.** gives the amount of exceeding hours plotted against the amount of energy that is used.

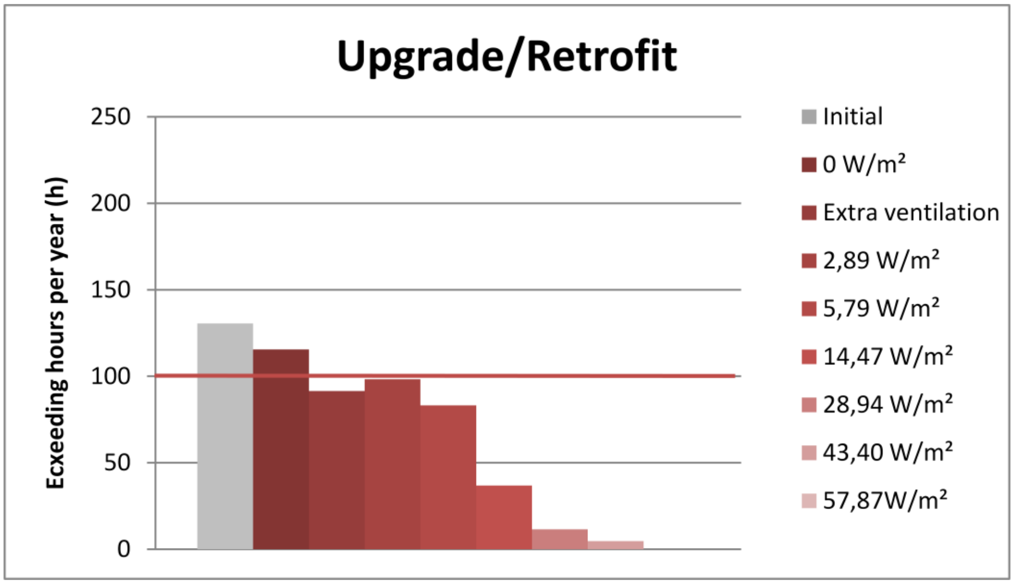


Figure 4.5 Exceeding hours per cooling type for the Upgrade façade

Trisco

The simulation models for the Upgrade façade are calculated and result in the following temperature flows

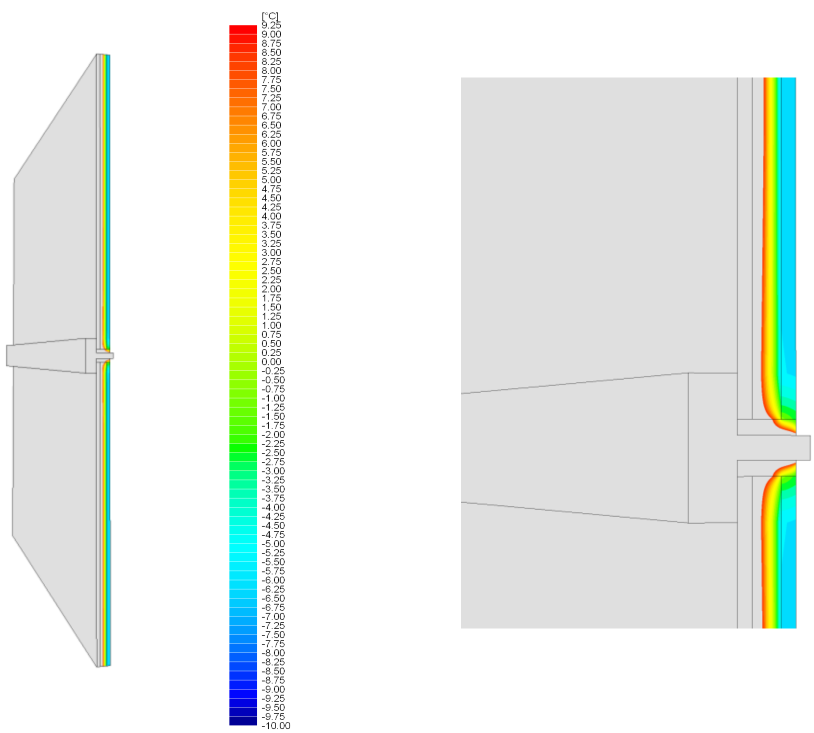


Figure 4.6 Temperature flows in the Upgrade façade's double glass pane and window frame

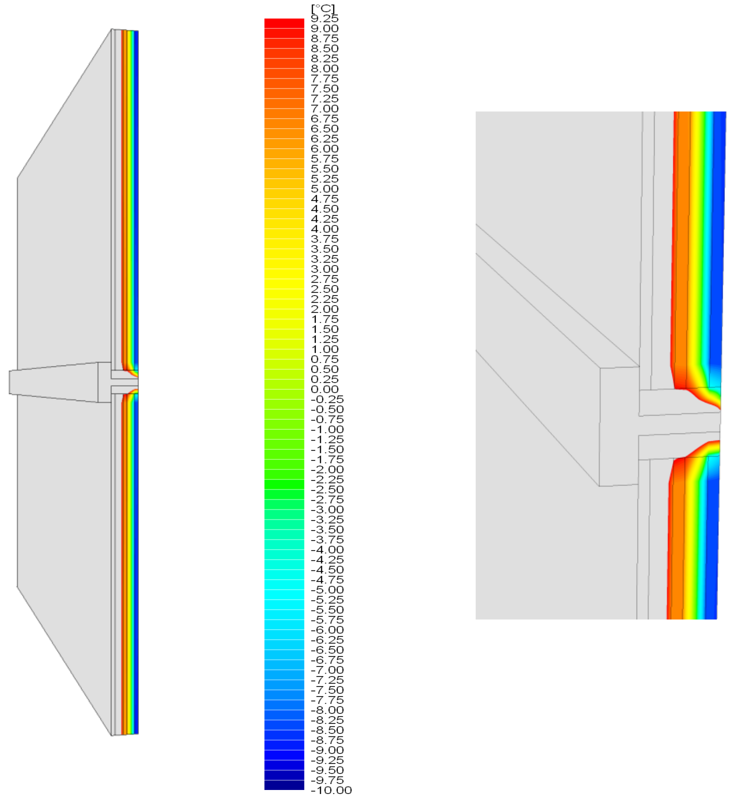


Figure 4.7 Temperature flows in the Upgrade façade's triple glass pane and window frame

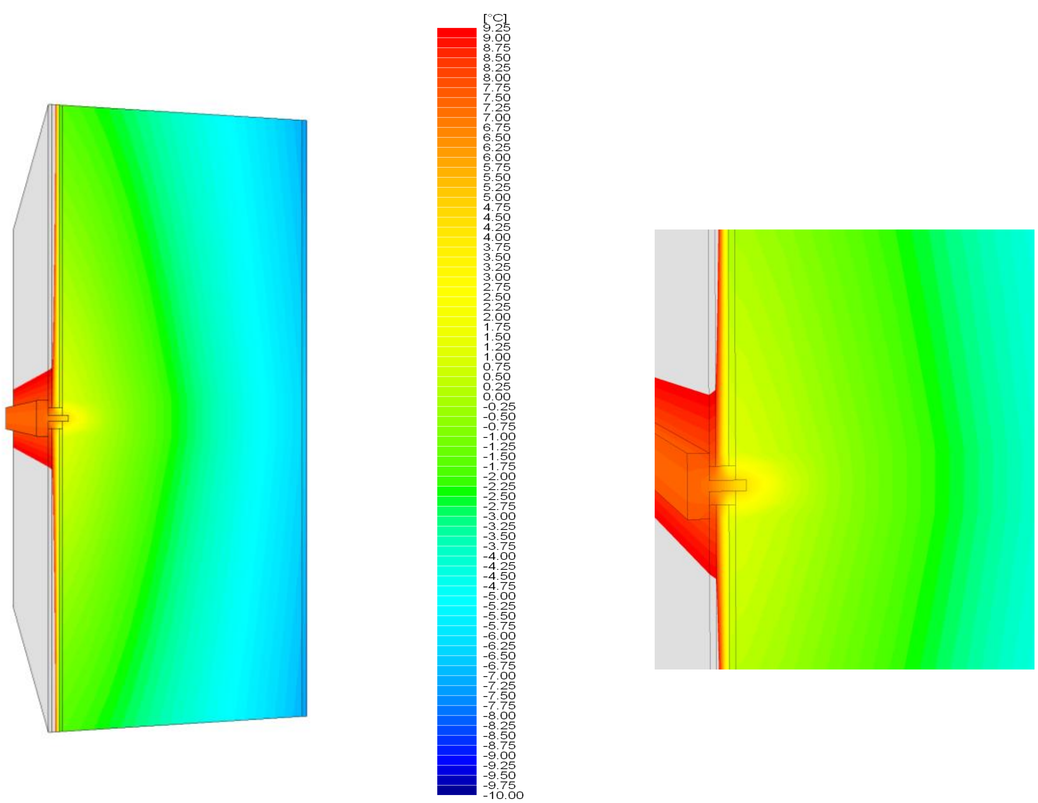


Figure 4.8 Temperature flows in the Upgrade façade combined with the Folding facade

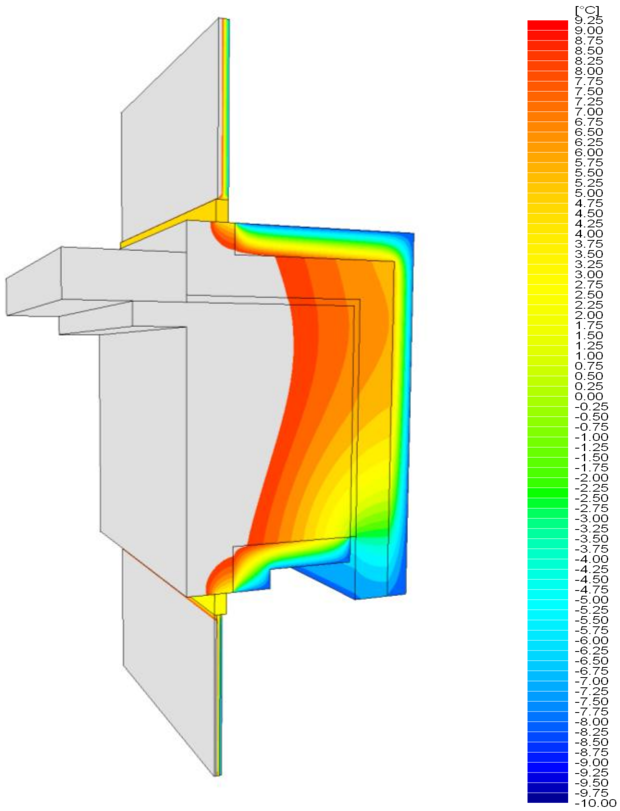


Figure 4.9 Temperature flows in the Upgrade façade with additional insulation applied on the prefabricated element

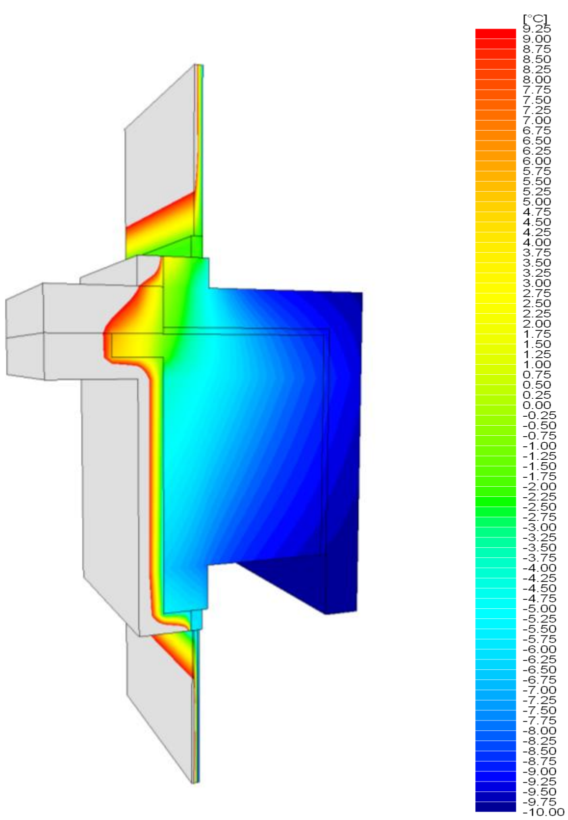


Figure 4.10 Temperature flows in the Upgrade façade with additional insulation applied on inside of the ring beam

Wheel of potentials
This wheel of potentials origins from an excel sheet that can be found in Appendix 8.

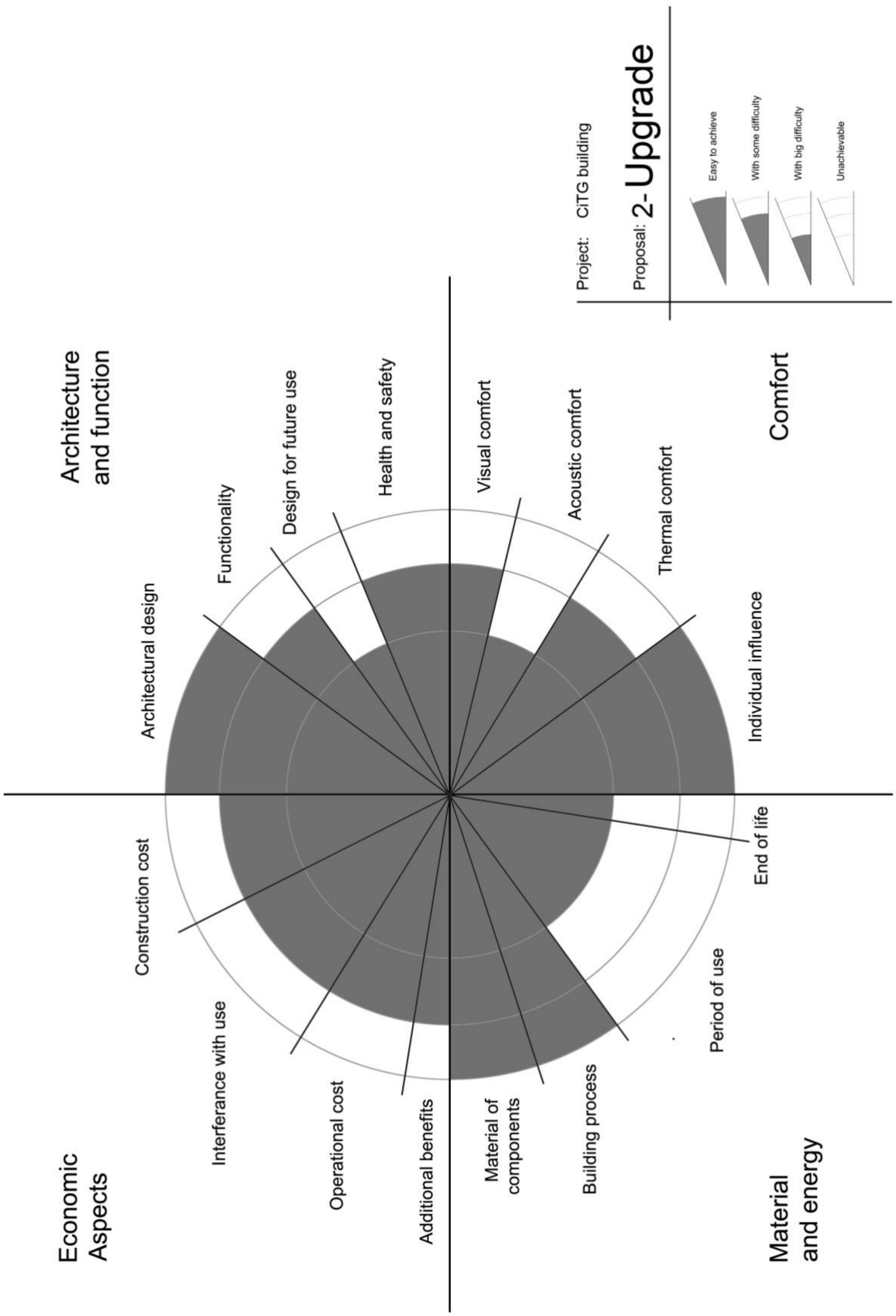


Figure 4.11 Wheel of potentials for the Upgrade façade

4.4. Retrofit façade principle

Capsol

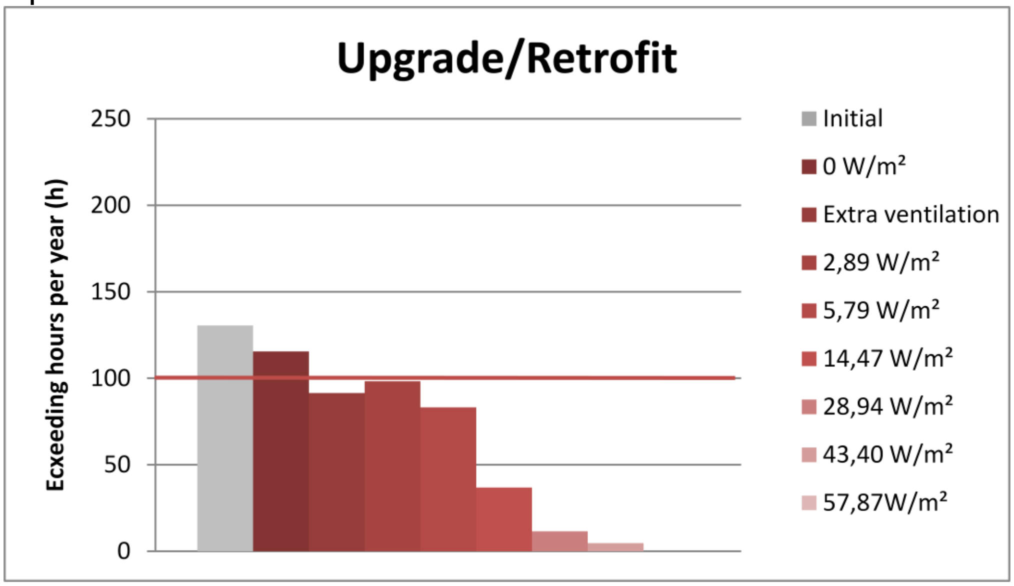


Figure 4.12 Exceeding hours per cooling type for the Retrofit façade

Trisco

The simulation model for the Retrofit façade principle, gives the temperature flows that are shown in

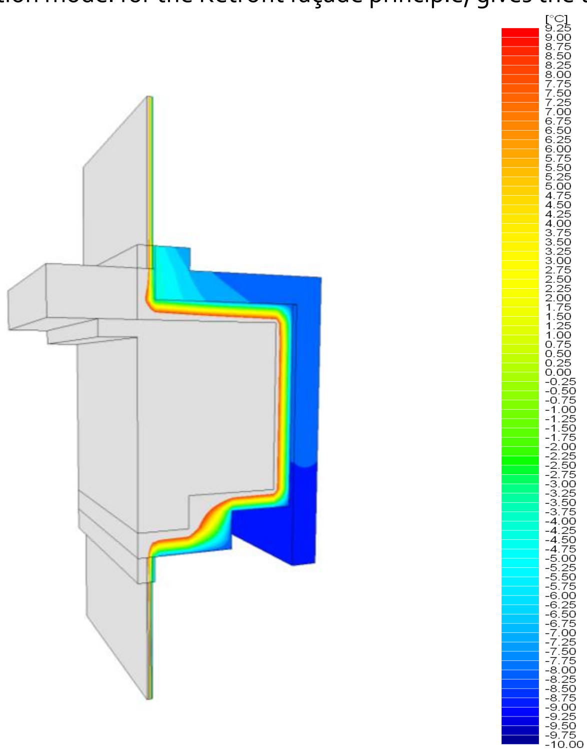


Figure 4.13 Temperature flows in the Retrofit façade with additional insulation applied between the ring beam and the prefabricated concrete element

Wheel of potentials

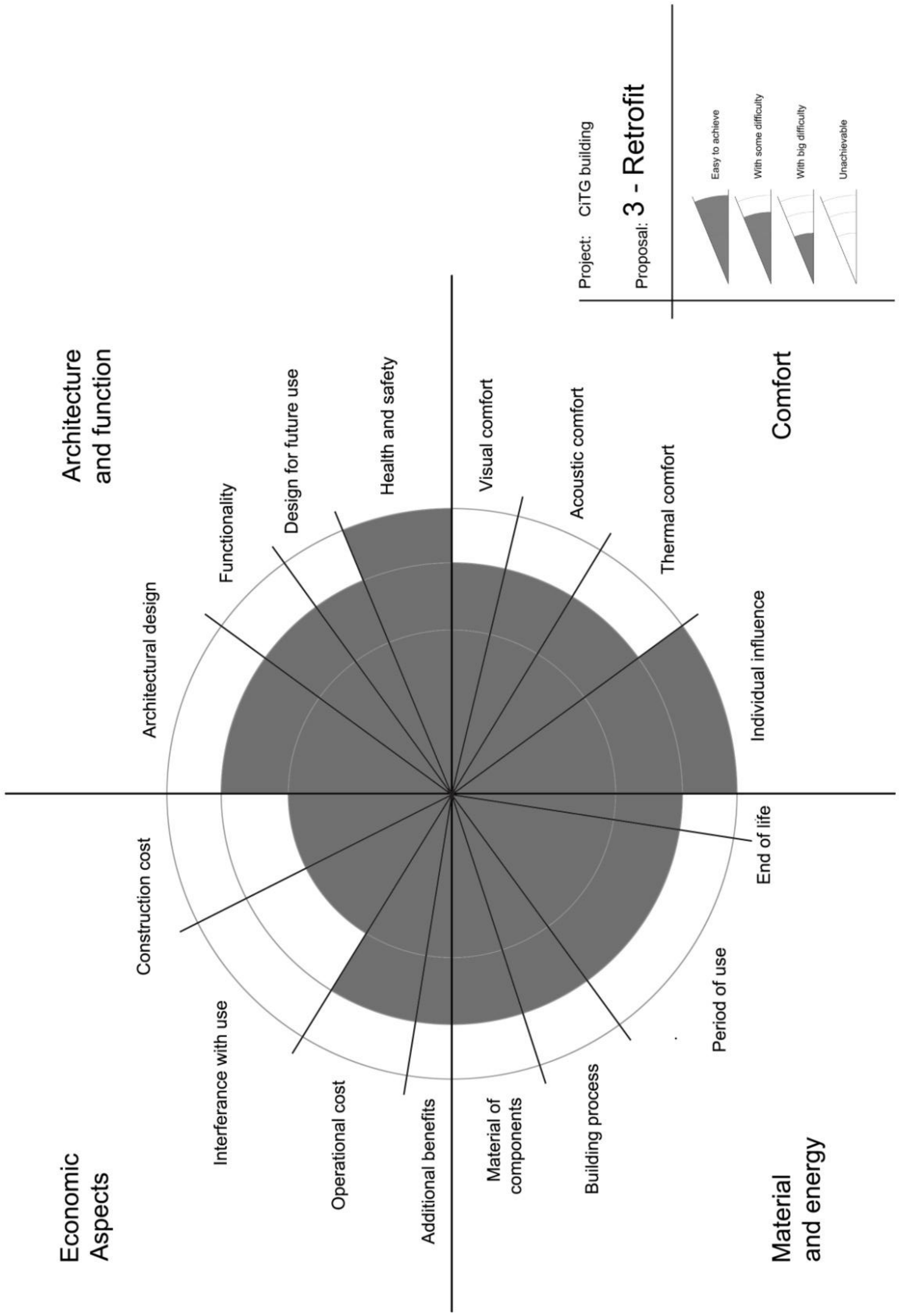


Figure 4.14 Wheel of potentials for the Retrofit façade

4.5. Make over façade principle

Capsol

The different glass types are plotted against the exceeding hours for several cooling loads, as is shown in Figure 4.15. The exceeding hours for the Make over façade principle, with glass type two set out against different cooling loads are shown in **Fout! Verwijzingsbron niet gevonden.**, in which the situation with and without an external sunblind is represented. The last graph shows exceeding hours plotted against the amount of energy that is used.

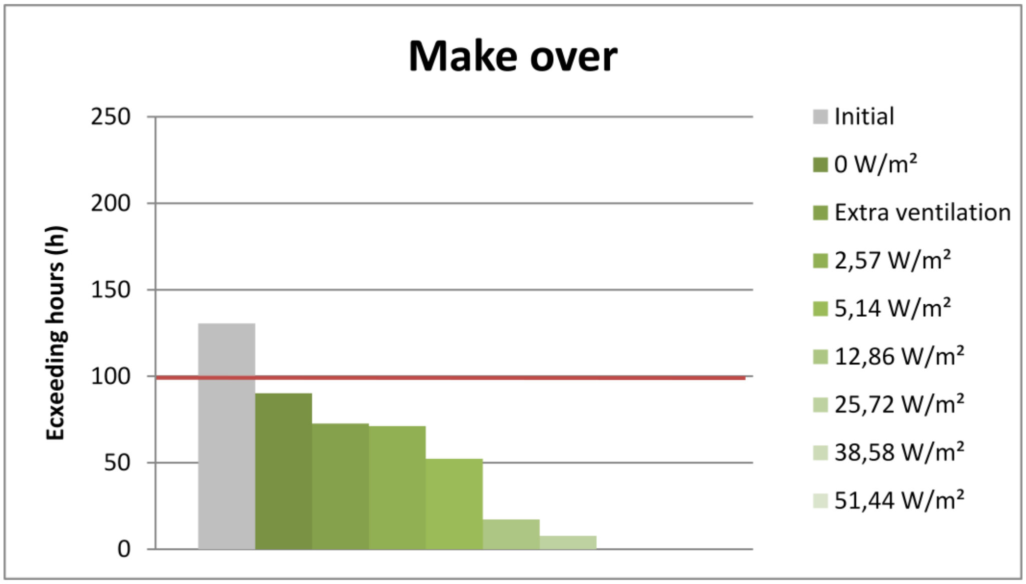


Figure 4.15 Exceeding hours per cooling type for the Make over façade

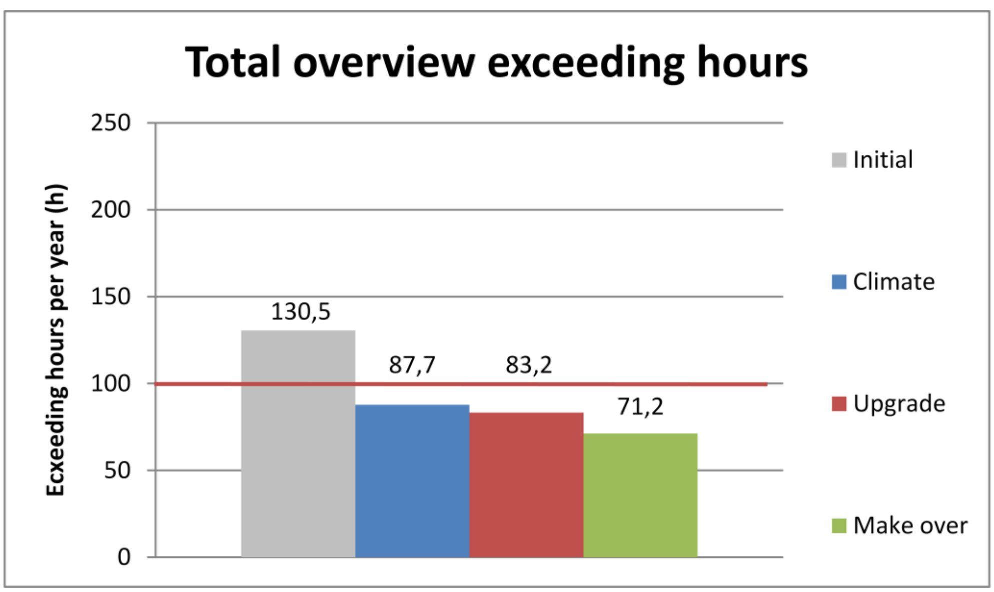


Figure 4.16 Exceeding hours per façade principle, the first cooling under 100 hours is chosen

Wheel of potentials

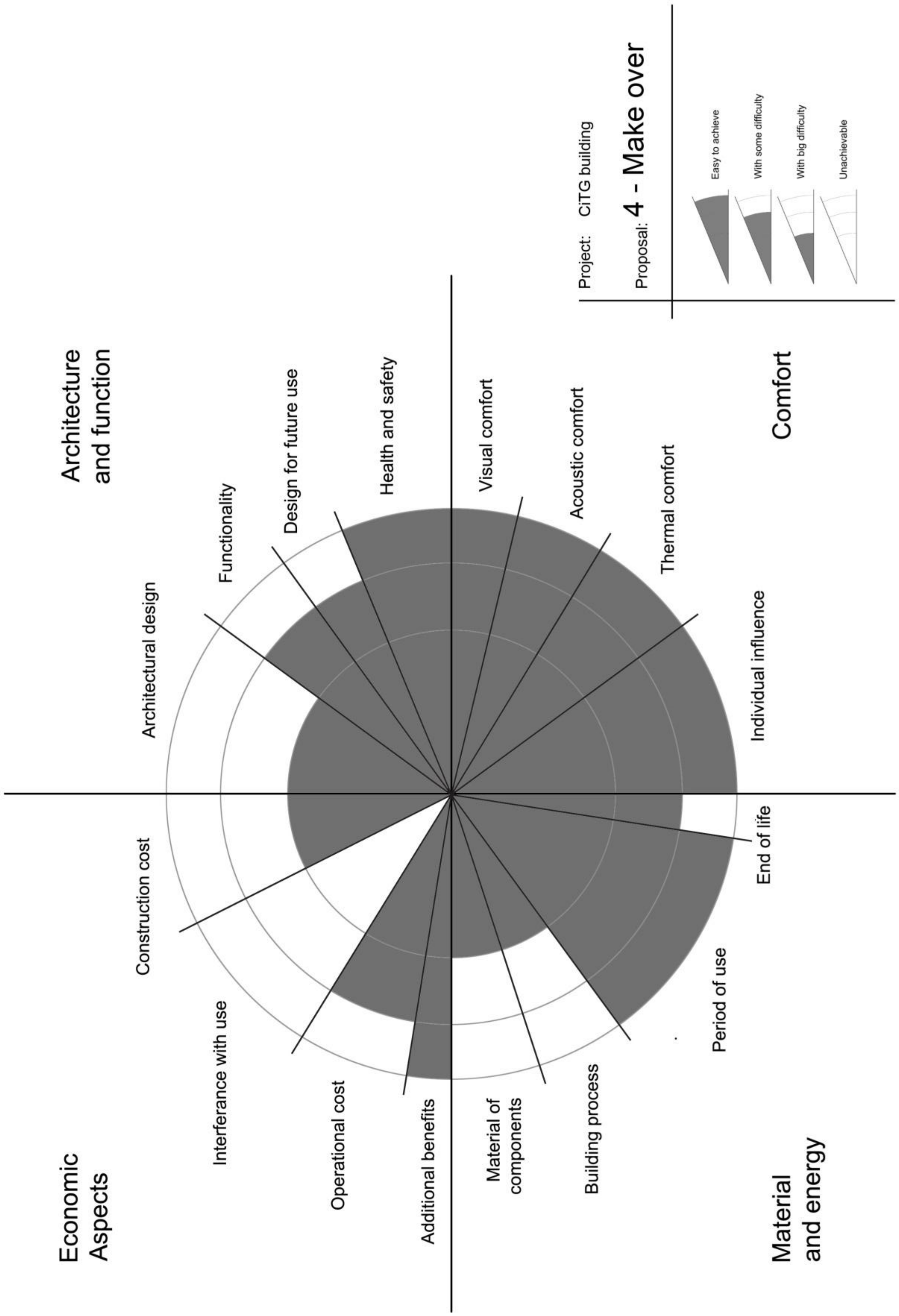


Figure 4.17 Wheel of potentials for the Make over façade

4.6. Energy use

Capsol

Energy use for heating

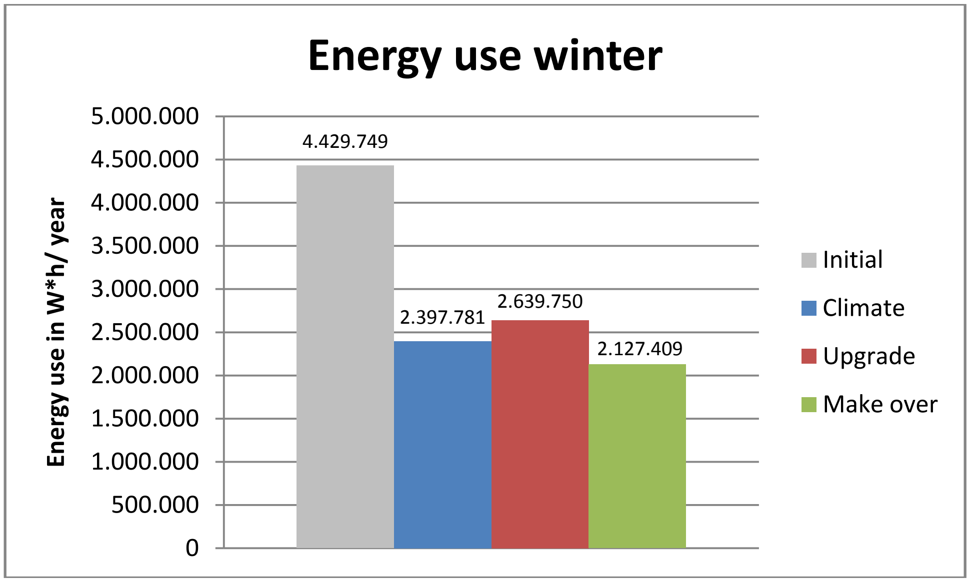


Figure 4.18 Energy use for each façade principle with 1250 W heating power per office and initial 4000W

Energy use for cooling

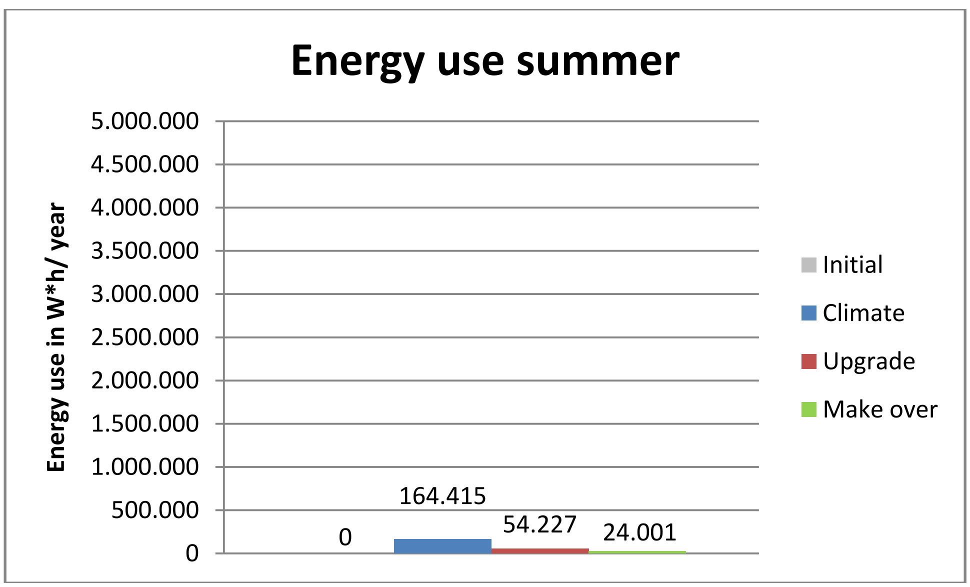


Figure 4.19 Energy use for each façade principle for the cooling power that realizes less than 100 exceeding hours per year

Trisco

Energy flows from the Trisco detail are used for the calculation of the U value per insulation priciple

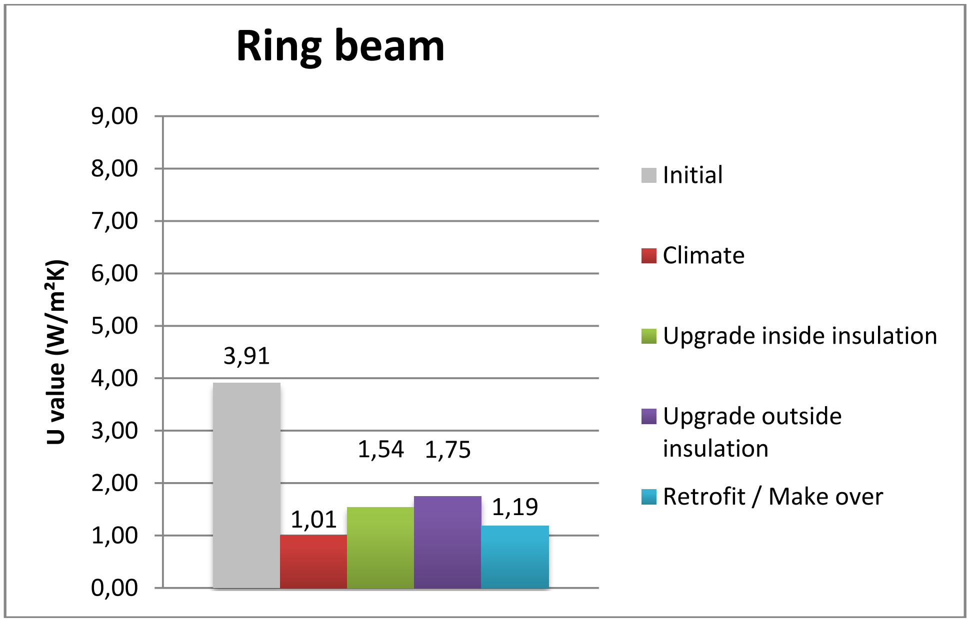


Figure 4.20 U values of different ring beam insulation principles

Energy flows are used for the calculation of the U value per glazing principle

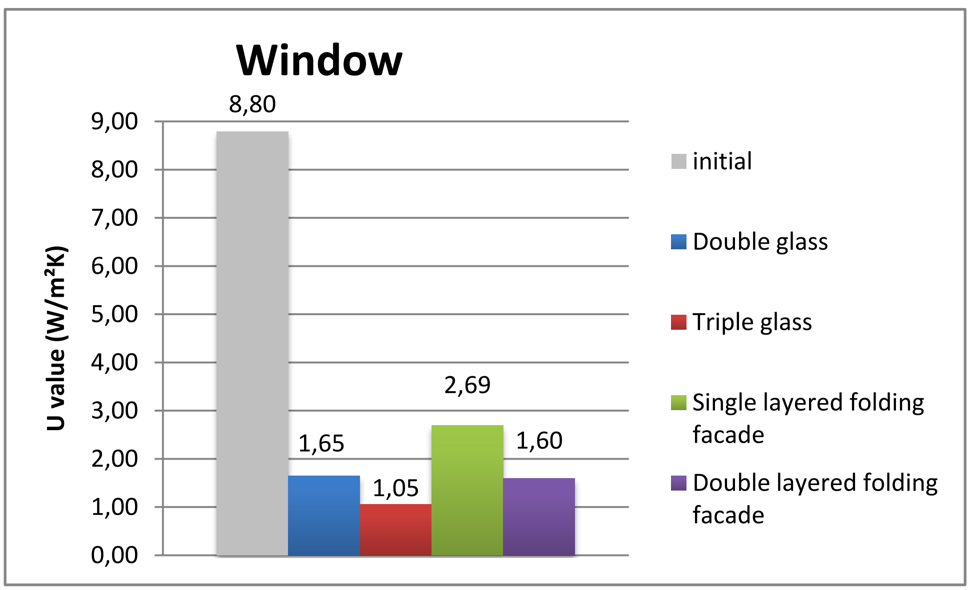


Figure 4.21 U values for different insulation glass principles in the initial steel window frames

5. Discussion

Within this chapter, the results are being discussed. In the first paragraph, the wheel of potentials as a tool is discussed and the effects on evaluation of the façade principles are made clear. In paragraph two, the wheel of potentials per façade principle is discussed and the evaluation of the façade principles is given.

5.1. Wheel of potentials

Within chapter 3 a description of the strengths and shortcomings of the wheel of potentials is given as a preview on its use. Now there will be looked more into dept to all of the steps that have to be done in order to create a realistic wheel of potentials and to use all the information that it contains for the further design process. The discussion will be built up step wise from detailed information in the excel sheet to final overview of the wheel. The excel sheet can be found in Appendix 8.

Within the excel sheet that is used to determine the score of a sub aspect per façade principle, several questions need to be answered. The average of these scores determined the score for a sub aspect within the wheel. For example, the architectural design was judged just as much by a question about a new architectural identity as well as a question about the respect to the initial building. In the case of the CiTG faculty building, the respect to the initial building is much more important than a new architectural image. Therefore a factor is introduced which will give the user the possibility to grade a question on its importance. The score per sub aspect can now be calculated according to the boundary conditions within each sub aspect. The factor can be found in the excel sheet in front of the score per question.
The first design intervention that was mentioned in chapter 3 was by creating different sizes in the graphic overview to represent sub aspects. Now that the sub aspects are represented well by their questions, it is important that the sub aspects itself are scaled on their importance as well. The size in the graphic overview shows a clear difference between all sub aspect, however it is not possible to grade these in the excel sheet. It could be possible that the construction costs are much more important to a client or investor then it is for normal projects. In that case the deviation between sub aspects needs to be adjusted. Therefore a percentage is introduced that is not only referring to the size of the sub aspect in the graphic overview but also to a weight that will be used in a calculation, which will be explained later.
Finally, a factor is introduced to make a calculation for different parties possible. This factor will influence the total score of a main aspect in relation to the other three main aspects. In this case comfort and energy are important, while architecture is less important and economy is graded the least. The previously mentioned percentages for each sub score, are used for the calculation of the score for each main aspect. The total of the percentages should always be 100.The excel sheet with the grading for this project is shown in Figure 5.1.

Aspect	Factor	Sub-aspects	Percentage	*Climate*		*Upgrade*		*Retrofit*		*Make over*	
					score		score		score		score
Economy	1	Construction cost	30		2		2		1		1
		Interference with use	35		3		2		1		0
		Operational cost	25		2		2		2		2
		Additional benefits	10		1		2		2		3
				69		61		34		40	
Materials and Energy	3	Production	20		2		3		2		1
		Building process	20		2		3		2		1
		Period of use	50		2		1		2		3
		End of life	10		3		1		2		2
				74		60		65		62	
Architecture	2	Architectural design	40		1		3		2		1
		Functionality	20		2		2		2		2
		Design for future use	15		2		1		2		2
		Health and safety	25		1		2		3		3
				43		63		67		65	
Comfort	3	Visual comfort	15		2		2		2		3
		Acoustic comfort	20		1		1		2		3
		Thermal comfort	25		3		2		2		3
		Individual control	40		1		3		3		3
				53		67		76		96	
Total	9				59,37		63,22		65,66		71,63

Figure 5.1 Grading system of sub and main aspects of the wheel of potentials

5.2. Façade principles

Strengths and weaknesses are singled out of each wheel of potentials and discussed per façade principle. The quarters in the wheel of potentials have different assessments, because of diversity in importance of the requirements. These are set in chapter 2 by the comfort standards, the energy efficiency, and the future appointment to city monument. Therefore, the amount of credits within the comfort and material & energy quarter is multiplied by a factor 3, the architecture credits by factor 2 and the economic credits by factor 1. In this way, the results can be interpreted and evaluated within the boundaries that are set for the CiTG faculty building. The wheels of potential can be found on larger scale in the previous chapter. The excel sheets that determine the amount of credits for each aspect, can be found in Appendix 9 and partly in Figure 5.2, where the total score for the façade principle is shown as well as the total score of the principle, which would be 100% for a perfect suitable façade principle.

5.2.1. Climate façade principle

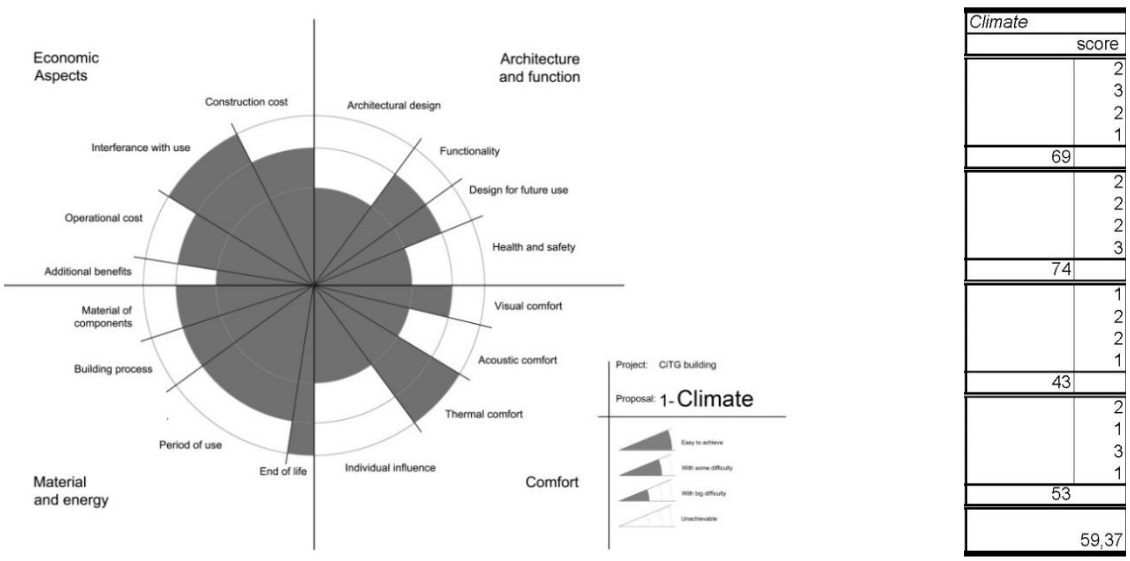
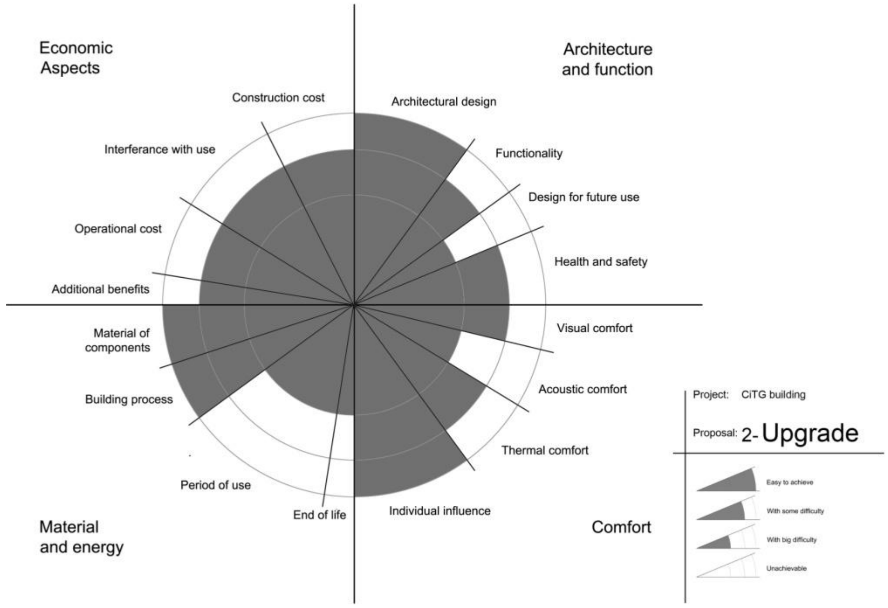


Figure 5.2 Results for the Climate façade principle

The climate façade principle seems to score overall a good. The energy quarter is represented more that average, and so is the economic quarter. Within the comfort quarter the individual influence aspect is achieved 'with big effort', which implies that the individual influence is not satisfying within this principle because it was one of the most important sub aspects. The low score will cause a large drop in value of the façade principle. Although visual comfort is not graded highly within the main aspect of comfort, it will influence the final score in this case negatively. This is because the visual comfort is not optimal because of the extra layer of glass which will block the view and daylight incidence of the office partly. The architectonic aspects score the least credits within this wheel, this is because the whole look of the façade will change which is not preferred within this refurbishment project. The climate façade has an overall score of 59,39 %. The energy use in for cooling, with a cooling power of 14,47W/m^2, is 9,5 KWh/m^2 per year with 87,7 exceeding hours. The energy use for heating would be 138,76 KWh/m^2 per year, which is much lower than the initial use of 256,3 KWh/m^2 per year, with a heating power of 72,3 W/m^2. The low energy demand for cooling is caused by the external sun blinds. However, the amount of cooling is larger than the other façade principles, but the climate façade principle uses a heat exchanger and which means that the normal energy loss of 40- 80 % by ventilation can be reduced. The façade makes use of a twin coil system, which transfers the heat or cold from the exhaust air to water which will be used to heat or cool the new ventilation air. A reduction of 60 %, however the system will use energy itself as well and therefore a total reduction on the energy use is estimated on 10%. This brings the total energy use for cooling on 8,55 KWh/m^2 and for heating on 124,88KWh/m^2. The energy loss through the ring beam in the climate façade principle, is expressed in an U-value of 1,01 W/m^{2}K, which is a large reduction compared to the initial 3,91W/m^{2}k.

5.2.2. Upgrade façade principle

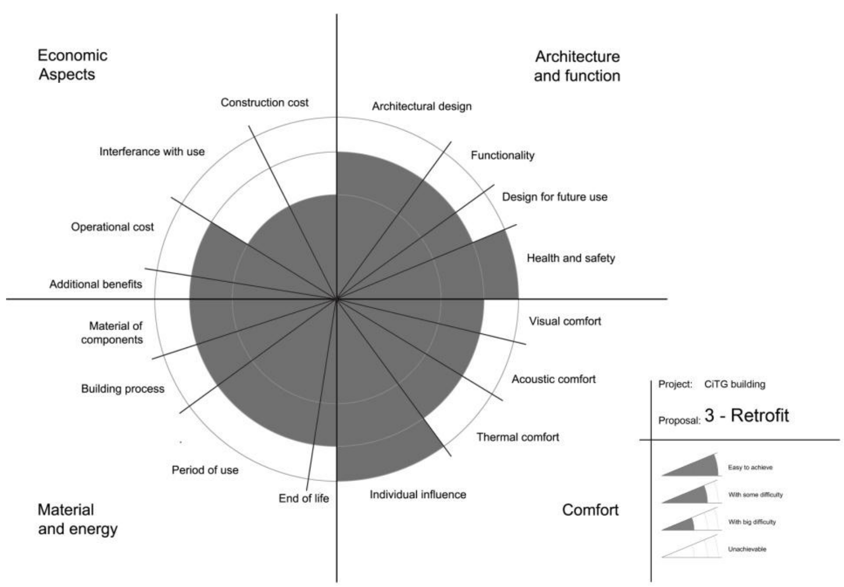


Upgrade	
	score
	2
	2
	2
	2
61	
	3
	3
	1
	1
60	
	3
	2
	1
	2
63	
	2
	1
	2
	3
67	
	63,22

5.3 Wheel of potentials for the Upgrade façade principle

The Upgrade façade principle shows a quite good overall score with 63,22%. The Wheel shows clearly that the energy demand during the period of use is not optimal for this façade principle. This is caused by the energy losses through the glass and window frames and the partly insulated ring beam. The energy demand for cooling is 3,1 KWh/m^2 per year with a power of 5,79 W/m^2, and the heating demands 152,76 KWh/m^2 per year with a power of 72,3 W/m^2. The ring beam which can be insulated from the outside will cause an U-value of 1,75 W/m^2K, however, this will influence the architectural identity of the building, while the starting point of this façade principle was to maintain most of the initial façade. The insulation on the inside of the ring beam causes an U- value of 1,54 W/m^2K and has a better performance than the outside insulation. However, the inside insulation is not able to prevent condensation on the inside of the ring beam and therefore the possibility of rotten insulation has to be taken into account when this insulation principle is used. The thermal bride on the locations where a load bearing beam is attached to the ring beam will cause high energy losses.

5.2.3. Retrofit façade principle

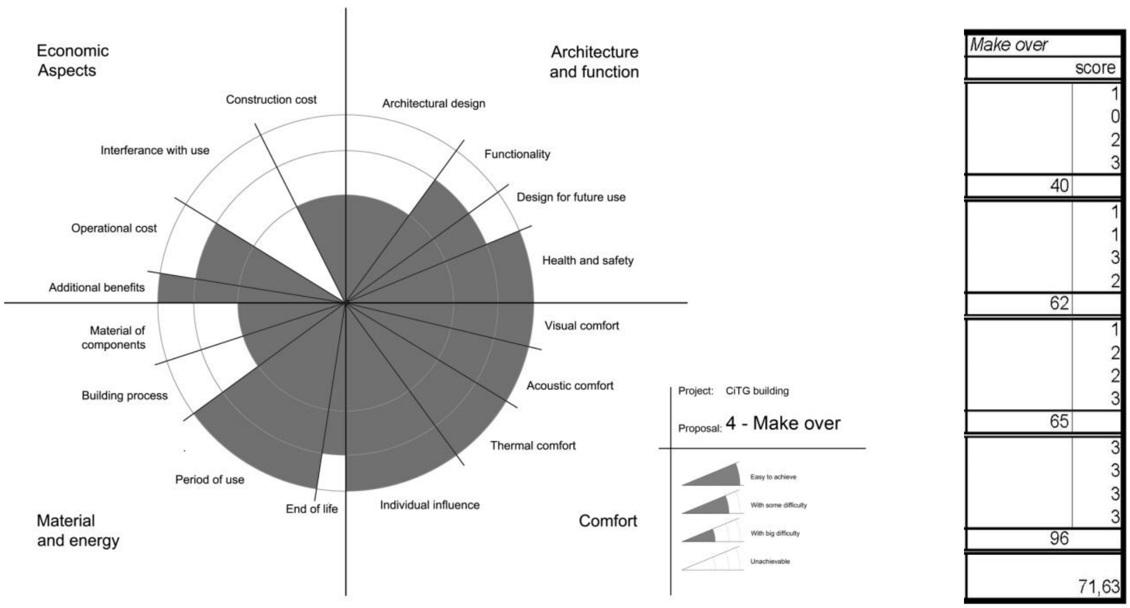


Retrofit	
	score
	1
	1
	2
	2
34	
	2
	2
	2
	2
65	
	2
	2
	2
	3
67	
	2
	2
	2
	3
76	
	65,66

5.4 Wheel of potentials for the Retrofit façade principle

A quite average score can be found on each of the quarters of the Retrofit façade wheel of potentials. Only the economic aspects are under graded compared to the other aspects. The construction costs and interference with use are the main problems within this façade principle. This is caused by the total strip down of the façade, and the labor intensive work on the prefabricated elements of the façade that are reused within this façade principle. Overall the Retrofit façade principle scores 65,66%.
The use is 3,1 KWh/m^2 per year for cooling with a cooling power of 5,79 W/m^2, and the heating demands 152,76 KWh/m^2 per year with a power of 72,3 W/m^2 which is similar to the Upgrade façade principle. However, the ring beam is insulated properly within this façade principle and has an U-value of 1,19 W/m^{2}K. Therefore Retrofit scores better on energy aspects than the Upgrade façade principle.

5.2.4. Makeover façade principle



5.5 Wheel of potentials for the Makeover façade principle

The interference with the use in the economic quarter, scores zero because of the major interventions that are done on the interior and exterior, that cause high disturbance to the user. The Makeover façade principle has a very good score on the comfort aspects. This can be related to the fact that the whole façade is designed for optimal comfort, with light redirection louvers and a highly controllable indoor climate. The energy and material scores are not optimal, because of the large amount of new materials that are used. However, the period of use scores optimal. Because of the good integrated installations, like a heat exchanger, this façade principle will not consume much energy. For cooling 1,2 KWh/m^2 per year and for heating 109,4 KWh/m^2 per year is needed. The cooling power is 2,57 W/m^2 and the heating power is 64,3 W/m^2. With the use of a heat exchanger the amount of used energy can be decreased. Because the windows are open able within this façade principle, the heat exchanger will provide a lower total reduction, which is estimated for a twin coil system on 7% percent because heat recovery from hot air has a higher efficiency and in wintertime natural ventilation will not be used often. With 7% of reduction the cooling demand is 1,1 KWh/m^2 per year and the heating demand is 101,7 KWh/m^2 per year. The makeover façade principle scores 71,63% in total.

5.3. Scenarios

By adding a factor to each result, as previously explained, a realistic overview of the façade's qualities is given within the boundary conditions of a project. Within this master thesis, the comfort and energy aspects are important. In reality, different factors might be of importance which will influence the choice of most suitable façade principle for the CiTG faculty building. To get insight in these different interpretations of the results per case, several cases are set out next and their total scores are presented.

When the economical crisis becomes a threat to the refurbishment project, the economic aspect will be most important. Probably the energy efficiency will not change in importance because the MYA3 has to be met within a few years. Therefore the economical aspects and the energy efficiency will be graded with factor 3 and the architectonical and comfort aspects are graded with factor 1. The total scores are shown in Figure 5.6.

Aspect	Factor	Sub-aspects	Percentage	*Climate*		*Upgrade*		*Retrofit*		*Make over*	
					score		score		score		score
Economy	3	Construction cost	30		2		2		1		1
		Interference with use	35		3		2		1		0
		Operational cost	25		2		2		2		2
		Additional benefits	10		1		2		2		3
				69		61		34		40	
Materials and Energy	3	Production	20		2		3		2		1
		Building process	20		2		3		2		1
		Period of use	50		2		1		2		3
		End of life	10		3		1		2		2
				74		60		65		62	
Architecture	1	Architectural design	40		1		3		2		1
		Functionality	20		2		2		2		2
		Design for future use	15		2		1		2		2
		Health and safety	25		1		2		3		3
				43		63		67		65	
Comfort	1	Visual comfort	15		2		2		2		3
		Acoustic comfort	20		1		1		2		3
		Thermal comfort	25		3		2		2		3
		Individual control	40		1		3		3		3
				53		67		76		96	
Total	8				65,44		61,76		55,05		58,59

Figure 5.6 Result interpretation for economy and energy point of view

When the CiTG faculty building has become a city monument, the architectural aspect will become important and the comfort aspects might not be of significant influence, which results in the following total scores showed in Figure 5.7.

Aspect	Factor	Sub-aspects	Percentage	*Climate*		*Upgrade*		*Retrofit*		*Make over*	
					score		score		score		score
Economy	1	Construction cost	30		2		2		1		1
		Interference with use	35		3		2		1		0
		Operational cost	25		2		2		2		2
		Additional benefits	10		1		2		2		3
				69		61		34		40	
Materials and Energy	2	Production	20		2		3		2		1
		Building process	20		2		3		2		1
		Period of use	50		2		1		2		3
		End of life	10		3		1		2		2
				74		60		65		62	
Architecture	3	Architectural design	40		1		3		2		1
		Functionality	20		2		2		2		2
		Design for future use	15		2		1		2		2
		Health and safety	25		1		2		3		3
				43		63		67		65	
Comfort	0,25	Visual comfort	15		2		2		2		3
		Acoustic comfort	20		1		1		2		3
		Thermal comfort	25		3		2		2		3
		Individual control	40		1		3		3		3
				53		67		76		96	
Total	6,25				57,41		61,91		61,41		61,21

Figure 5.7 Result interpretation for an architectural point of view

If a new energy plant for the whole university campus will cause major energy efficiency, the case could become that only the economic aspects are taken into account while designing the new façade. Then the results as shown in Figure 5.8 will give an estimation of the total scores per façade principle.

Aspect	Factor	Sub-aspects	Percentage	*Climate*		*Upgrade*		*Retrofit*		*Make over*	
					score		score		score		score
Economy	2	Construction cost	30		2		2		1		1
		Interference with use	35		3		2		1		0
		Operational cost	25		2		2		2		2
		Additional benefits	10		1		2		2		3
				69		61		34		40	
Materials and Energy	1	Production	20		2		3		2		1
		Building process	20		2		3		2		1
		Period of use	50		2		1		2		3
		End of life	10		3		1		2		2
				74		60		65		62	
Architecture	1	Architectural design	40		1		3		2		1
		Functionality	20		2		2		2		2
		Design for future use	15		2		1		2		2
		Health and safety	25		1		2		3		3
				43		63		67		65	
Comfort	1	Visual comfort	15		2		2		2		3
		Acoustic comfort	20		1		1		2		3
		Thermal comfort	25		3		2		2		3
		Individual control	40		1		3		3		3
				53		67		76		96	
Total	5				61,37		62,56		55,24		60,74

Figure 5.8 Result interpretation for an economical point of view

6. Conclusion

Within this chapter, the conclusion is drawn from the research which is based on answers to the research questions.

The aspects of indoor comfort are represented by temperature, ventilation, acoustics, daylight and fire protection. Here, temperature and ventilation are the main problems within high levels of comfort. Individual influence on these aspects cause a higher comfort standard within a building. The requirements for a high comfort class are estimated on The Adaptive Temperature Boundary value (ATG) with an acceptation of 90%. This means that at least 1.3 dm^3/s ventilation per m^2 floor space, 200 to 500 lux and a daylight factor of 1%, and an indoor reference level of 30 to 35 dB(A) should be present. The façade connection has to be fire resistant for more than 60 minutes. To make the ATG with an acceptation of 90% possible to measure, the amount of hours that the indoor temperature exceeds 26 degrees, is set to 100 hours per year. At this moment the exceeding hours are estimated on 130 hours a year by a computer simulation. However the simulation uses an external sunblind that can be used permanently in summertime. In reality the external sunblind experience hindrance by the strong winds along the CiTG's façade and therefore they cannot be used permanent. An uncomfortable situation inside offices is the result of this problem. In wintertime an uncomfortable situation is created by the thermal bridges in the initial façade. Through the steel window frames and the single glazing, a high energy transfer occurs. The radiation of the cold surfaces and the downdraft also created by the cold surfaces makes the area near the façade uncomfortable to work. Unfortunately, the offices within the CiTG faculty building are not large enough to rearrange the interior and therefore the employees have their workspace close to the façade. The radiator that is installed in the offices helps to prevent the cold air flows. However, the radiator only has an on or off switch and no regulation is possible in between these positions. By placing a new radiator, a higher energy efficiency can be realized. The use of double glazing and new window frames will help to increase the energy efficiency a lot. By insulating the ring beam which, in the initial situation is not insulated, a large thermal bridge will be solved and condensation will be prevented. Insulation on the inside of the ring beam will be less efficient because the structural joints within the construction cannot be insulated well and large energy losses will still appear.

The service platforms play a key role within the façade of the CiTG faculty building. The load bearing construction is hidden behind the prefabricated concrete elements and therefore the service platforms do not only have an architectural but also a constructive value. Because the ring beams are not insulated as previously mentioned, the ring beams are of big influence on the thermal behavior of the façade. Therefore several ideas about insulation the ring beam and about upgrading the initial façade are represented in façade principles which are developed by an increasing scale of interventions on the existing building. In exception of the first façade principle, which uses an insulated layer of glass on the outside of the service platforms and is called Climate façade principle, the comfort level is assumed to increase together with the amount of interventions that is done. The Upgrade principle is the second façade principle in which the single glazing is replaced by insulated glazing and an insulation is added to the mullions of the initial façade. The ring beam can be insulated on the in or outside, however the inside insulation will cause condensation problems and the outside insulation will change the architectural look of the building. The last aspect is not acceptable when the architecture is protected by an appointment of the building to be a city monument. The third façade principle contains a smart solution to maintain most of the initial architectural look, however the comfort standard and energy efficiency will increase. By replacing the façade and placing insulation in between the ring beam and prefabricated elements the total façade will be insulated and will have quite the same architectural appearance as the initial façade. The last proposal does not respect the architectural appearance, however it will provide a high comfort standard and energy efficiency.

From the results of computer simulations, a conclusion can be drawn according to the performance of each façade principle on energy efficiency and comfort standard. The climate principle scores well on material and energy aspects because a minimal amount of material is used and the material that is used is quite sustainable compared to the other façade principles. The comfort aspects are not represented well in this principle because there is a low individual influence possible. Furthermore, the simple construction and short building time causes a good score on economical aspects.

The Upgrade façade principle has a low energy efficiency because of the thermal bridges that are caused by the initial steel frames. The low amount of material that is used decreases the economical aspects, however the cleaning and reparation of the initial steel frames is labor intensive work which makes the costs for the building process rise. The comfort level insight will not be optimal because of the earlier mentioned thermal bridges that are not totally solved within the Upgrade façade principle. As starting point, the architectural appearance is used. However in the grading system of the wheel of potentials, the health and safety, and design for future use is taken in account as well. The Upgrade principle does not meet these requirements fully and therefore it will not be the principle that scores highest on architecture aspects. The Retrofit façade principle performs much better on energy, architecture and comfort aspects, however the cleaning and replacement of the prefabricated elements in the facade cause a low score on the economic aspects. The Make over façade principle will be expensive because a whole new façade is created. However the quick building process causes that the Make over principle scores better on the economical aspects then the Retrofit façade principle. The comfort aspects are represented optimal within this façade principle which assures the Make over façade principle of a big advantage compared to the other façade principles.

The computer simulations showed that the initial facade uses 256,35 kWh/m² per year for heating (simulated with 231,48 W/ m² heating power, which is an estimation for present radiators) and 0 kWh/m² (with no cooling installations and *130,5 exceeding hours*). The climate façade principle uses 138,76 kWh/m² per year for heating (with 72,3 W/ m² heating power, which is estimated by simulations) and 9,5 kWh/m² per year for cooling (with 14,47 W/m² cooling power and *87,7 exceeding hours*). The Upgrade and Retrofit have a heating demand of 152,76 kWh/m² per year (with 72,3 W/m² heating power, which is estimated by simulations) and a cooling demand of 3,1 kWh/m² per year (with 5,79 W/m2 cooling power and 83,2 exceeding hours). The Make over façade principle needs 109,43 kWh/m² per year (with 64,3 W/m2 heating power, which is estimated by simulations) for heating and 1,2 kWh/m² per year for cooling (with 2,57 W/m2 cooling power and 71,2 exceeding hours). Overall one could conclude that the Make over façade uses the least energy and the Upgrade façade uses the most energy. The difference between the Upgrade and Retrofit is made by the U- value of the ring beam which is in the initial situation 3,91 W/m²K. In the Upgrade façade principle the U-value is 1,54 W/m²K for inside insulation and 1,75 W/m²K for outside insulation. As previously mentioned, the in and outside insulation have both reasons not to be executed. The Retrofit façade principle has a fully insulated ring beam with an U-value of 1,19 W/m²K and will be possible to execute.

To draw a conclusion of the previous mentioned results, the wheel of potentials is used to summarize these results and give a clear overview. The visualization of the façade principle properties in a wheel of potentials is determined by an excel sheet which contains categorized questions for architectural, economical, comfort, and materials & energy aspects. To involve the boundary conditions of the CiTG faculty building, factors are used to grade the questions on their importance for the sub aspect. Then the sub aspects are graded with a certain amount of percentages that shows their importance within the main aspects of the graphic overview. Finally the main aspects can be judged on their importance within the refurbishment project by a factor. In the CiTG refurbishment project, the Energy and comfort aspects are graded with factor 3, the architectural aspect has factor 2 and the economy aspects is valued with factor 1. These factors are based on the boundary conditions for this master thesis. With these factors the Make over façade principle is the most suitable for the refurbishment of the CiTG faculty building. The second best solution is the Retrofit façade principle. The Upgrade and Climate façade principles are set as third best solution. This is caused because the Upgrade façade principle scores better, however the execution of this principle has many disadvantages because of the insulation problem. The climate façade principle scores the least in this comparison. This is mainly caused by the low individual influence of the system which is graded high in the calculation with a high factor. The new situation might be comfortable by good mechanical ventilation, however this is not valued much in this wheel. So both the Climate and the Upgrade façade principles are representing the third best option for the CiTG façade's refurbishment.

7. *Recommendations*

Recommendations are given in this chapter for further research on the CiTG project, and for further development of the Wheel of potentials.

7.1. CiTG façade's refurbishment

During the research that is done for this master thesis, some interesting aspects for further research occurred which are discussed in this paragraph. Some shortcomings on the research that is done are set out as well.

The simulations that are done in the research are representing the façade principals and the initial situation. These simulations do have some short comings. The infiltration through the façade is not represented well in the simulation, while the infiltration causes a large energy loss in the initial situation.
The sunblind that are used in the simulations cannot be used permanently in summertime because of strong winds along the façade. Only the climate façade has the possibility to use the sunblind without disturbance of the wind outside. Now the influence of the wind is not calculated and the Climate façade principle is underestimated compared to the other façade principles. In the future simulations a solution for these problems need to be found. The simulations that are made for the ring beam in the façade need to be adjusted so that the connection with the load bearing structure is also taken into account in the calculations. The heat recovery that is used for the Climate and Make over façade is not simulated in the computer , however by a certain amount of reduction the effect of the heat exchanger is taken into account in the discussion of the results. Within a future simulation, a program should be used that can simulate a heat recovery because then the influence of natural ventilation on the energy use, within the Make over façade principle, could be checked. Furthermore, the architectonic value of the building cannot be calculated and therefore is very subjective to judge. Because the building will become an city monument, the architectural look should be preserved as much as possible. When there is no possibility to preserve the architecture, the focus should be on a new aspect instead of finding a midway solution.
The poor performance of the Upgrade façade principle and the difficult corner detail of the Retrofit façade principle make these solutions hard to realize. If it is possible to optimize these solutions, both of them will be very suitable for the building, however it will be quite hard to solve all the problems that might occur by the use of the initial steel window frames and the initial prefabricated concrete elements.

Because the DUT will change its common heating installation, it is important that the installations which will be used in the refurbished CiTG faculty building are adjusted to the new type of heating and cooling. There should also be thought of a clear and simple method of regulating the temperature. Everybody understands the effect of an open window, however a switch that can be turned does not always have the desired effect. So a very good tuned system will create a higher energy efficiency and a higher comfort standard. Now the mechanical ventilation system on the sixth floor of the building is not understood by the users and therefore they keep opening their windows while this actually decreases the indoor comfort and energy efficiency. Because of the energy loss to the outside air and the insufficient cooling capacity for the room while it is ventilated natural as well. By creating a clear and consistent conditioning system, the previous described problems can be prevented. A research to the opinion on the indoor climate of the CiTG employees has already been done by Hannah van de Leij. However more investigation on this field can be done to understand the preferences of the user, so that the building will be useful and energy efficient in the future.

7.2. Wheel of potentials

The wheel of potentials has been used within this master thesis to evaluate the façade principles for refurbishment, and to evaluate the tool itself. Therefore some recommendations on the further development of the Wheel of potentials is given.

The size of the sub aspect per the quarter of the graphic overview have already been changed within this report, although this is a clear way of including the importance of each sub aspect in the total overview, a different method could be used as well. It might be worth to investigate different options. The arrangements of the subcategories has to be reviewed. This arrangement has a large influence on the look of the wheel and the understandability of it. So an arrangement of the sub aspects and an arrangement of the main aspect should provide a new wheel that will show relations more clear. An example is the main aspect of economics that is placed above the Material and energy aspect in the wheel. The building process and period of use have a large influence on the total costs of a façade, next to the construction costs. So if these aspects would be adjacent to each other a 'zone' of costs is created. When the construction costs are high but the building process, material use and period of use are low, the façade might be more profitable then it seems to be from the overview given in the Wheel of potentials. A new intervention in the initial tool is done by adding a factor to each question in the excels sheet. Now the factor is situated in front of each façade principal. The strength of the wheel of potentials is that for each façade principle a graphic overview is given that can be compared to each other. When it is possible to grade the questions with a different factor per façade principle, the comparison is not accurate anymore. Therefore the factor should be placed in front of all the façade principles. The scores that are used in the excel sheets are rounded off. This is not a problem for the initial tool, however if the final calculation is made a different score is presented in numeric output as in the graphic output. Therefore, the wheel should be split up in more sections that 3 per sub aspect or the value that represents the final output for a sub aspect should be rounded up in numbers without decimal places. Within the discussion of the results, it seemed that a wide spread in score for one of the aspects could influence the outcome of the final score quite a lot. So if four façade principles score on comfort aspects 10, 40, 45 and 99 percent, the influence of this very high score for the last façade principle in comfort becomes almost superlative in the final result, if the scores of the other aspects are more similar like 30, 40, 45 and 50 percent. A smart way of preventing this superlative behavior of one of the façade principles should be thought of to make the whole Wheel of potentials usable to calculate the most suitable façade for a certain project.

Summary

Within this master thesis, a research is done to find suitable façade solutions for the Civil engineering and geosciences faculty building (CiTG) of the Delft university of technology (DUT) with the focus on comfort and energy aspects. First the research question and several key questions are formulated, which are;

Which façade is the most suitable for the refurbishment of the CiTG faculty building, if the focus is on indoor comfort aspects and energy consumption?

- What are the (essential) aspects that determine inside comfort?
- What are the comfort requirements for the CiTG building?
- What are the shortcomings in comfort within the CiTG building?
- With what interventions can the comfort requirements be fulfilled?
- How is the CiTG building constructed and what does that mean for possible façade solutions?
- What are possible solutions for a new façade for the CiTG building?
- What are the comfort and energy performances of these solutions?
- How do the solutions perform in terms of other refurbishment aspects like execution, building technology, and architecture?
- How does the Wheel of potentials work, and can the refurbishment solutions be evaluated properly with this tool?
- What is the best overall solution?

To solve answer these questions, a research to important comfort aspects; temperature, ventilation, acoustics, daylight and fire protection is done in the first paragraph of chapter one. The requirements for the CiTG project concerning the indoor comfort are given in a brief summary in the end of this paragraph. The there is looked at the boundary conditions and the energy uses of the CiTG faculty building to find what the important aspects are for the refurbishment of the CiTG faculty building. The most important energy boundary condition is represented by the Multiyear agreement 3 (MYA3) that the DUT has with SenterNovem which means that an energy efficiency of 30% should be realized over the whole DUT in 2020. In chapter three the method of the research is explained in which the first paragraph is covered by an analysis of the CiTG faculty building. The second paragraph shows an standard section of the building in detail. This standard section is then schematized and used for computer models in the programs Capsol and Trisco which are shown in paragraph three of the second chapter. The third paragraph shows four façade principals that are representing different façade types. The principals are called Climate, Upgrade, Retrofit and Make over façade principal and they are arranged by the amount of interventions that are done to the initial building. The Climate façade principle is creates by adding an insulation glass layer on the outside of the building. The Upgrade principle replaces the initials single glazing with insulated glass elements. Retrofit replaces the whole façade; however it reuses characteristic elements of the initial façade. Make over will renew the whole façade and change the look of the building completely. The Wheel of potentials is then introduced as an evaluation tool which will be used during the discussion of the results in a later part of the report. This tool is based on an excel sheet which contains questions about the façade principal. With the scores of these questions a graphic overview is created that will show relation between different aspects of the façade principle. The tool is evaluated shortly in the last paragraph of chapter three. The fourth chapter contains the results of all the computer simulations and the Wheels of potentials for each façade principle. Then in chapter five, the wheel of potentials is evaluated as a tool first and some additions are made. In the second paragraph, the results are discussed based on the wheel of potentials. Important aspects are singled out and discussed for each façade principle. A few scenarios are presented in the last paragraph of this chapter to reveal the differences in final scores when boundary conditions are changed to other aspects then comfort and energy efficiency.

Then in the sixth chapter the conclusion is drawn. All the key questions are answered within the conclusion and finally the research question can be answered as well. The most suitable façade for the CiTG faculty building with the focus on energy efficiency and comfort will be the Make over façade principle, because of the high comfort standards that can be realized and the low energy demand of the new situation. The Retrofit principal will be the second most suitable façade principle and the Climate and Upgrade façade principles share the third place. The last chapter of the report contains recommendations for further research and for the further development of the Wheel of potentials as an evaluation tool for refurbishment projects.

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  Telephone contact with R. a.d. Berg October 20th about glazing for refurbishment

  Lectures

  Thermal comfort by Leo de Ruijsscher

Appendices