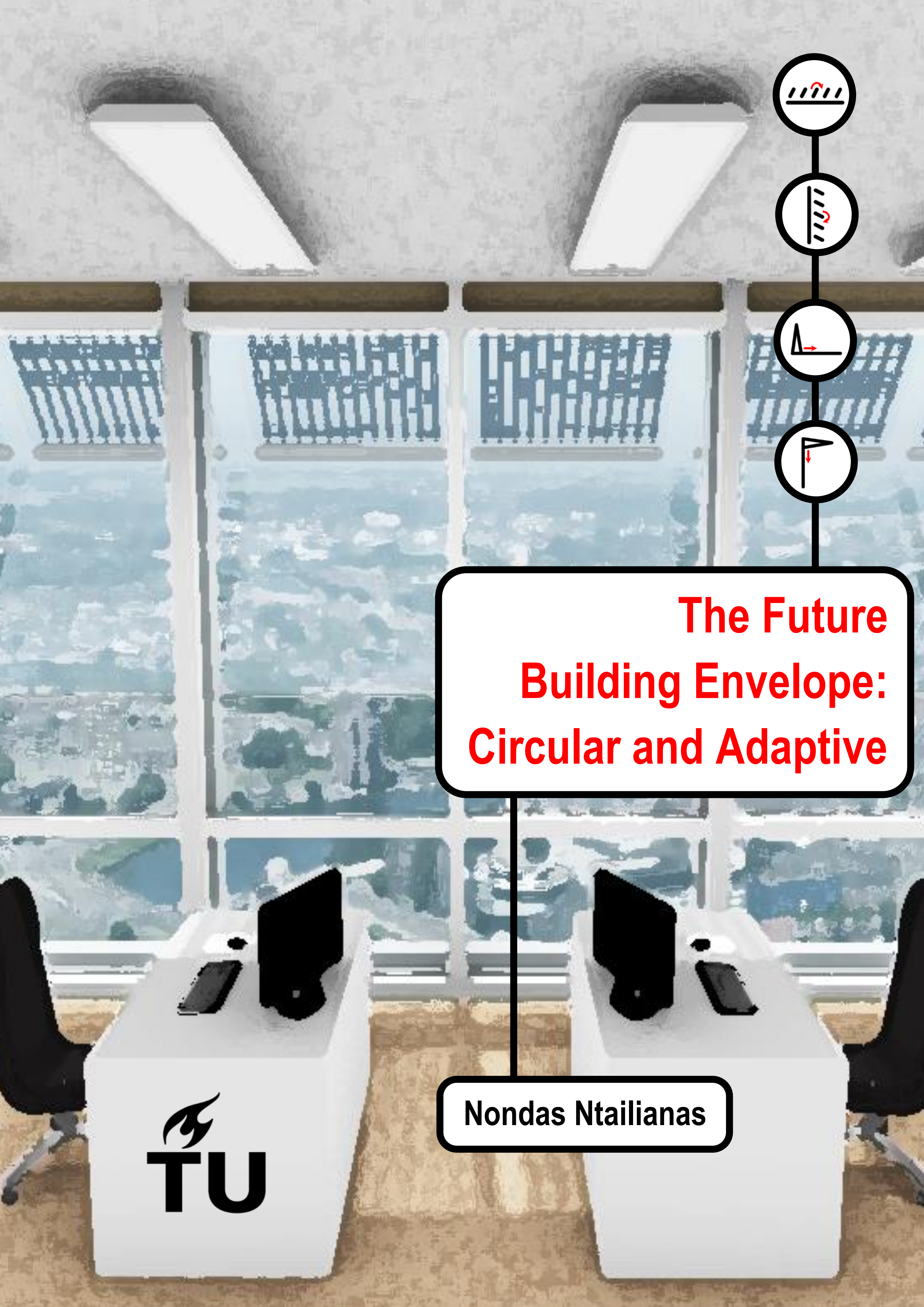

The Future Building Envelope: Circular and Adaptive

Nondas Ntailianas

The Future Building Envelope: Circular and Adaptive

A strategy for designing demountable unitized curtain walls,
with an application on 4 adaptive concepts

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abstract

This report includes all the research conducted during the last phase of the Master of Science Building Engineering within the faculty of Civil Engineering. The main aim is to form a strategy for designing demountable unitized curtain walls; one that could actually be used in practice by future engineers and architects. This is why this graduation project includes an application on 4 chosen adaptive concepts. Having already been applied in a comparison study of these quite complicated and costly designs, this framework can provide one extra consideration that will be critical in the near future at the very early stages of designing a building: *the Design for Disassembly*.

acknowledgements

My thesis has been overall a quite challenging and interesting experience, on the course of which I managed to acquire both theoretical and technical knowledge on this field.

For this reason, I would like to first thank my supervisor Dr.ir. Roel Schipper for guiding me in this research, right from the selection of the specific topic, up to the finalization. In addition, I would also like to express my gratitude to Dr. Henk Jonkers for his valuable guidance on Life Cycle Assessment. I also owe special thanks to Prof.ir. Rob Nijsse and Dr.ir. W.H. van der Spoel for their contribution on the group meetings, by giving me important feedback.

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Last but not least, I would like to thank my family and friends for supporting me in their own way through all these years, and my girlfriend Danai for dealing with patience every situation daily.

contents

1 INTRODUCTION

image source:
www.vanceva.com

1.1 prelude

A significant amount of research has been carried out over the past 50 years for the investigation of the causes of climate change, and the way we can slow it down, if not reverse it. We may have been impacting the ecosystem for more than 300 years, but only recently did we start to realize the consequences of our actions. Our awareness for nature has been radically changed through having unpredictable and severe weather conditions and rising energy prices.

However, due to the fact that during the 20th century a lot of progress and economic growth was made, an inevitable rise on the use of environmental harmful resources took place. This applies to the building industry as well, which has been using a linear economy model, the end of which is disposal. This came at a price, with huge amounts of waste piling up in the landfils, impacting directly both nature and society and many resources being scarce due to the exhaustive use of certain materials. A solution to the problem was given through the creation of a circular economy model, with closing loops of materials. As first introduced by the Ellen MacArthur Foundation, circular economy is a restorative economy built through creativity and innovation with the goal to minimize the resource inputs and waste, emissions and energy leakage aiming for the design of a better future.

There is still, however, a gap among the circular economy model and the way it can be applied in certain building parts, such as the facade of a building, the application of has been proven quite challenging. There is a strong need, therefore, to identify a specific strategy and the individual key guidelines that can be used to promote the Design for future Disassembly in building envelopes. This is why this research aims at removing all ambiguities regarding the Design for Disassembly (DfD) in curtain walls with a special focus on the modular systems – also known as unitized curtain walls. Such systems promote prefabrication and are ideal for deconstruction and refurbishment.

However, it is not only the resource scarcity and the huge amounts of waste that constitute some of humanity's biggest problems. It is also the rising CO2 emissions in the building sector that call for immediate action. Decreasing the energy consumed during the use phase of a building is vital. This is where the building envelope plays a key role. By definition, the facade is the interface between interior and ambient climate, thus regulating the energy consumed by the occupants.

Due to the fact that there is a constantly changing environment both in the short term –weather– and in the long term –seasonal cycles–, there is also a changing preference of the occupants in terms of comfort. This cannot be easily adjusted in the common 'static' building envelopes, where the optical and thermical properties remain constant, thus calling for significant energy consumption by heating or cooling the building every time the interior climate does not 'feel' right. In contrast to these rigid facade systems, climate adaptive building skins are able to adjust their form or function in order to respond to a shifting climate. This results in significant energy savings, while at the same time they fulfill the desirable comfort level of the occupant.

The aim of this research is to provide a framework with the key principles for designing 'circular' unitized curtain walls together with a strategy to rate the different selected designs. In this thesis, there is the aforementioned strategy will be applied on 4 different unitized Climate Adaptive facade concepts. These concepts are carefully selected, designed and eventually rated for their DfD performance based on the aforementioned strategy. This is performed for 2 different mullion materials in each case, thus comprising a total of 8 different concepts. Finally, conculsions will be drawn on which adaptive design performs best compared to the rest, and how handy this strategy can be for future use.

1.2 research background

In this first chapter, the choice of the specific topic and its paramount importance in the construction industry will be shortly explained, as well as its contribution into the current base of knowledge. This can be achieved by first posing some questions that may arise and then trying to give some short answers that will be further investigated in the core of this thesis.

---

1. **Why should we design the buildings and especially the Building Envelope in an energy-efficient way?**

Buildings nowadays account for more than 1/3 of the total energy consumption of human activities, as Figure 1.1 shows, and they emit about half of the CO_2 through cement production, burning of fossil fuels (coal, oil, gas) and greenfield development. Since carbon dioxide heats the planet by trapping the solar energy in the atmosphere and causing the greenhouse effect, it can be considered that buildings are highly responsible for what is known as climate change or global warming.

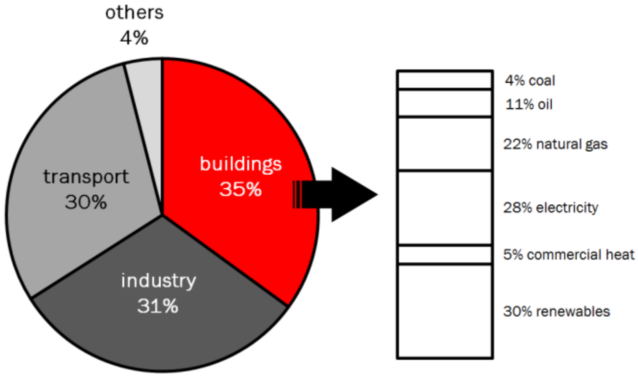


Figure 1.1 Final energy consumption by sector and buildings energy mix, 2010 (adapted from: International Energy Agency)

By definition, the building envelope is the physical separator between the interior and exterior of a building, and hence the regulator of the heat exchange to the outdoor environment (Figure 1.2). Therefore, when it comes to energy consumption in a building, the focus is on the facade and the roof; i.e. the building envelope.

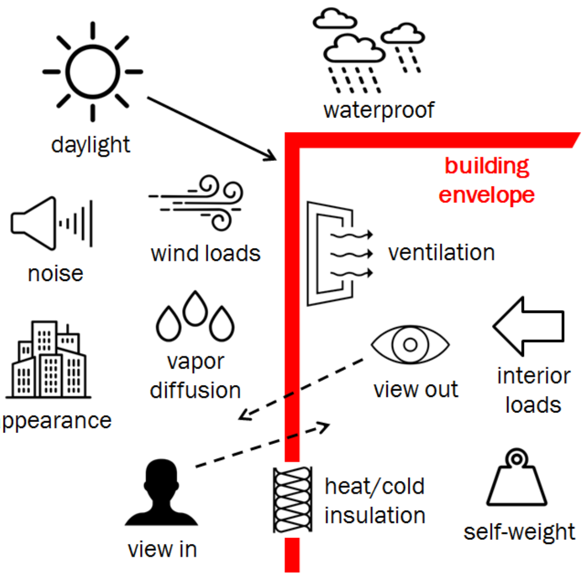


Figure 1.2 Requirements of Facades (adapted from: Knaack 2007)

2. **Why should Curtain Walls be the focus of energy-efficient designs? And why is there a distinction to designing a unitized system?**

First of all, it is emphasized that curtain walls are frequently used in high-rise buildings because they are extra lightweight construction elements that are hanging from the structural elements. High-rise buildings should be the main target of the energy-efficient designs. It is calculated that 54% of the world's population were residing in urban areas in 2014, and that by 2050, 66% of the world's population is projected to be urban (Figure 1.3). High-rise buildings have the potential to host these high population densities inside the urban environment and thus limit the emergence of urban sprawl. The more urban the environment, the more the reduction on transportation energy, which results in an overall more sustainable urban system. Northern Europe (with a Temperate Climate) has a much higher number of high-rise buildings compared to the southern part of Europe, a fact that shows the tendency of urbanisation, as described above.

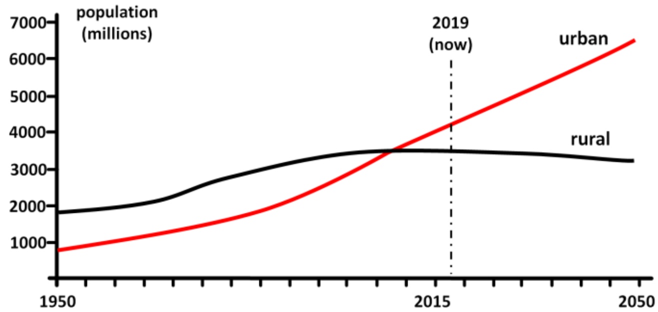


Figure 1.3 Urban and rural population of the world, 1950-2050 (adapted from: United Nations, Department of Economic and Social Affairs, 2014)

This thesis focusses on curtain walls, but by no means is the topic only restricted to high-rise buildings. A curtain wall can be defined as a thin and lightweight (usually aluminium-framed) wall, that contains in-fills of glass, metal panels, or other kinds of panels. For instance, Figure 1.4 shows a fully glazed curtain wall of a modern office building in Munich, Germany. The frame is attached to the building structure, and it does not carry the loads of the floors or roof. It should however be able to resist wind and gravity loads, which are then transferred to the structure of the building.

The scope of this thesis is also narrowed down to the **unitized systems**. Generally a curtain wall can be classified according to the way that is fabricated and then installed to either stick or unitized (modular) system. The stick system stands for piece by piece installation and connection on building site. On the other hand, unitized curtain walls entail factory fabrication and assembly of the panels, and once completed, they are installed on the building structure to form the enclosure of the building. Figure 1.5 shows a real example of how the assembly of a unitized curtain wall can be done on the construction site.

Except for known advantages of the unitized system when it comes to large projects, such as higher speed of assembly, lower field installation costs, economic benefits and quality control, the choice of this system was mainly made because of the modular design, which works ideally for refurbishment, and enables simple deconstruction of the different modules. This is also addressed in the Design for Disassembly further on in this introductory chapter.

Figure 1.4 Fully glazed curtain wall (photo by: Westend61)

Figure 1.5 Unitized curtain wall assembly

3. Why is the focus on office buildings?

In the most recent comparative pie chart depicting the percentage of the building sector in the total energy consumption of the US for 2017 (Figure 1.6), one can observe that the 38% of the building sector is somewhat shared among residential (20%) and commercial (18%) buildings.

Offices, wholesale and retail trade buildings account for more than 50% of energy use of non-residential buildings in Europe (Buildings Performance Institute Europe 2011), as shown in Figure 1.7.

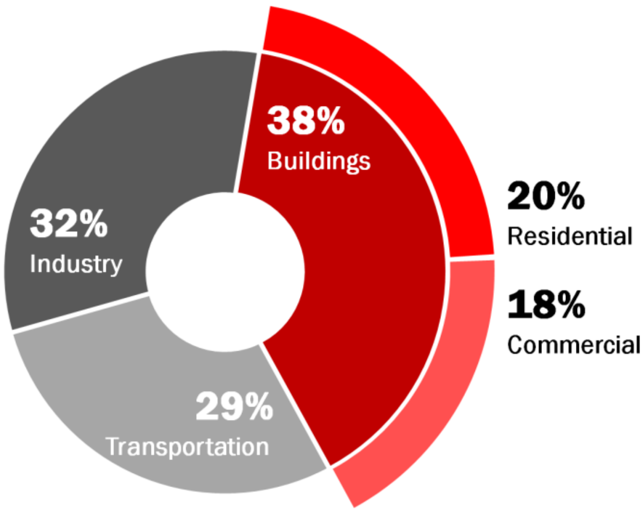


Figure 1.6 Energy Consumption in the US (adapted from: US Energy Information Administration 2017)

Higher amount of electricity consumed in commercial buildings because of:

- adoption of new types of electronic equipment
- increased use of existing technologies such as computers and servers, office equipment etc.
- many of these electronics require additional cooling, humidity control, and/or ventilation equipment, that also increase electricity consumption

It is also much more common for office buildings to make use of standardized techniques such as Unitized Curtain Walls, as mentioned before. This stems from the fact that such building techniques are used in larger and more standardized building concepts, such as high-rise offices in city centres for instance.

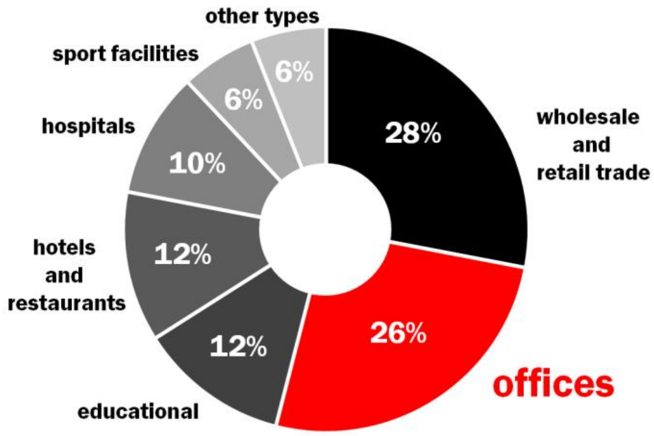


Figure 1.7 Share of total energy use in non-residential building types for different countries across Europe (adapted from: Buildings Performance Institute Europe (BPIE), 2011)

4. Why should architects and engineers integrate the Circular Economy principles into their projects?

Nowadays, the general economy system is based on a take-make-dispose sequence, as depicted in Figure 1.8. However, it is expected that the world population will grow to 9 billion people by 2050, and the earth should be multiplied by six in order to facilitate people's needs. The current linear material economy has negative effects which are dominant in the construction supply chain.

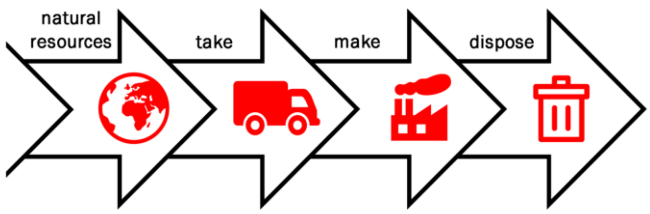


Figure 1.8 The Linear Economy model (adapted from the European Commission)

According to Ellen MacArthur Foundation, a circular economy model (Figure 1.9) looks beyond the current take-make-dispose extractive industrial model, and instead it aims to redefine growth, focusing on positive society-wide benefits.

The basic three principles of the circular economy model are:

- Design out waste and pollution
- Keep products and materials in use
- Regenerate natural systems

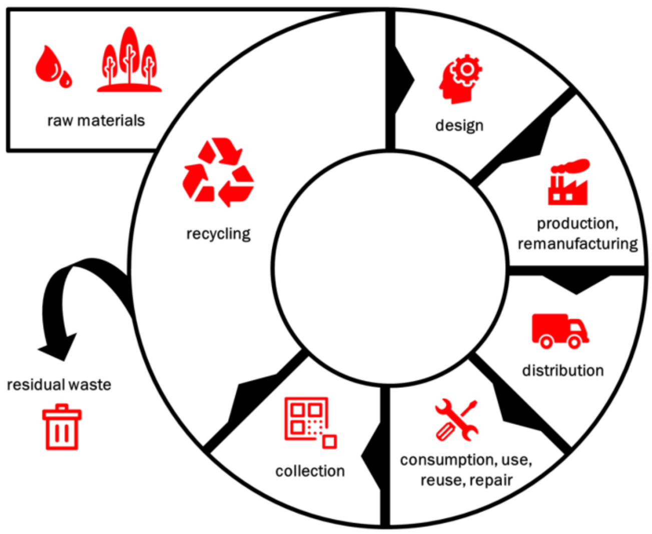


Figure 1.9 The Circular Economy model (adapted from the European Commission)

In other words, Circular Economy is a regenerative system, in which the goal is to slow, close, and narrow energy and material loops in order to minimize the resource inputs and waste, emissions and energy leakage. To achieve this, there is a need for long-lasting design, maintenance, repair, reuse, redistribution, re-manufacturing, refurbishing, and closed recycling loops (Figure 1.10).

5. How is the Circular Economy related to designing a Sustainable Façade?

There is a tendency to think of a building as a complete entity. This is also the way it is designed most of the times; from conception to disposal – a complete entity. A building has, however, many different parts with different life spans. There is a need therefore, to consider it as a structure made out of layers. Figure 1.11 shows the different layers of a building with their average lifespans. This was first published as the 6S in the 1994 book named: *How Buildings Learn: What Happens After They're Built*, written by S.Brand. Apparently, the structure of the building has both the largest volume and highest weight, and thus it can be considered the main problem in waste generation. It can be observed, however, from the figure, that the facade and roof of the building (also called 'skin' in a more collective term) have a significantly lower lifespan, thus having a big impact on the environment as well. Of course, as years went by, these numbers increased with the use of more resistant materials and better coatings, but still, the general picture is about the same. That being the case, there is a high potential for decreasing the building industry waste with the application of sustainable design for building skins.

6. What is the Design for Disassembly (DfD)?

Design for Disassembly is the optimization strategy of the way that construction products will be treated in the end of their life and includes a number of guidelines for the feasibility of future separation of the many subcomponents of a product (example shown in Figure 1.12). These design guidelines refer to both material choice and connection properties.

For material choice, the overall environmental impact of the building component needs to be calculated via an evaluation technique for environmental impact. In this thesis, a cradle-to-gate assessment is used for that reason. The durability of the components is also important to consider, regarding their life expectancy, maintenance and resistance to wear. Last but not least, the end-of-life activity and the side effects that a certain material is going to have are necessary to consider. As for the connection-related design guidelines, reversibility of the joining techniques is of primary importance. The ease and speed of disassembly are also considered necessary to a large extent, in terms of complexity and accessibility of the connection techniques, total amount of connections and the number of their different types.

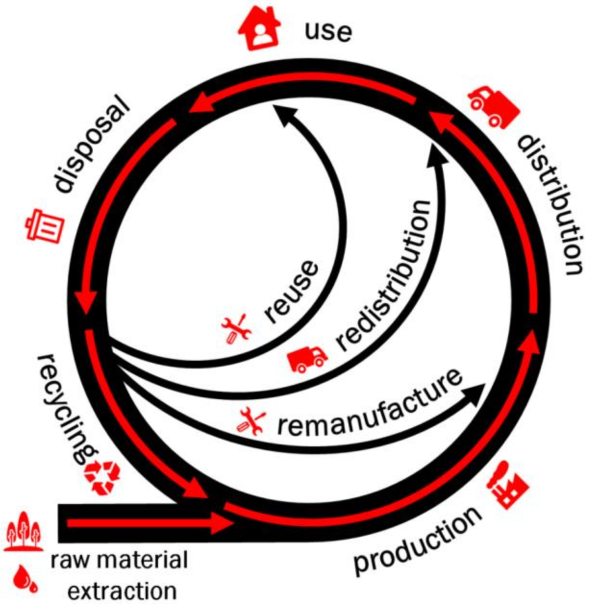


Figure 1.10 Closing the loops (own illustr.)

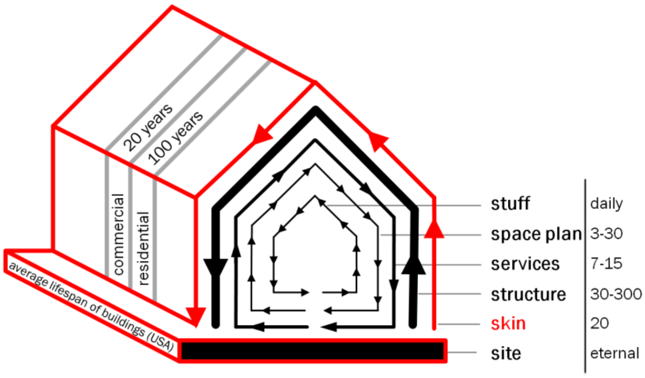


Figure 1.11 The building layers and their average lifespans (adapted from: Brand, 1994)

Figure 1.12 Fully disassembled rotary phone (source: www.designboom.com/art/todd-mclellan-disassembly)

7. **What are the Climate Adaptive Building Skins (CABS) and why are the designs used for the case study adaptive? What are the restrictions?**

Generally, ‘Climate Adaptive Building Skins’ is only one of the different terms used in literature. The following are some of the other terms that can be found in the literature: dynamic, kinetic, responsive, smart, etc. Although these expressions have a somewhat different meaning, they are often used interchangeably.

If we were to define CABS, one could say that a climate adaptive building shell ‘has the ability to repeatedly and reversibly change some of its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance’ (Loonen, 2013). A well-known realized project is the Al Bahr Towers in Abu Dhabi, the adaptive facade of which is shown in Figure 1.13.

Figure 1.13 Al Bahr Towers
(source: compositesandarchitecture.com)

As regards the physical parameters that are related, there are four main domains, namely thermal, optical, air-flow and electrical, as shown in Figure 1.14. By overlapping, the aforementioned parameters create 15 different possible combinations, also called multi-physical overlaps (Loonen, 2013). Of course, there are also some other domains, such as moisture and sound, but in this thesis the focus will only be on the thermal, optical and electrical domain.

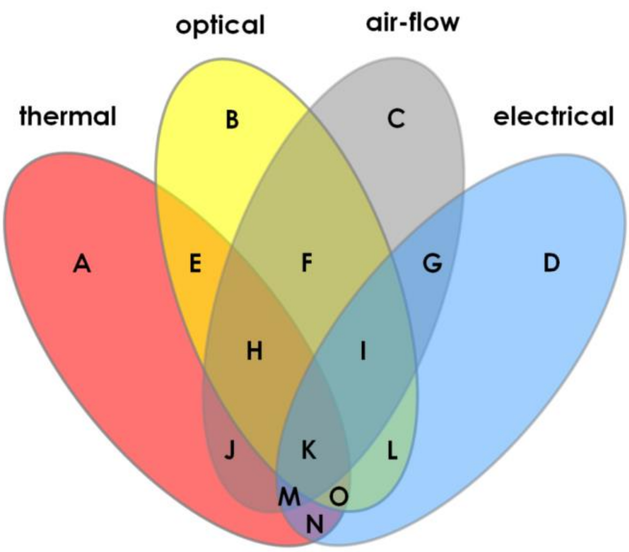


Figure 1.14 Classification of relevant physics
(adapted from: Loonen, 2013)

Moreover, the adaptation is either based on a change of properties or behaviour in the macro-scale or in the micro-scale, but also combinations are possible. Macro-scale refers to the whole building skin or parts of it moving, by folding, shifting, rotating or opening and closing (Figure 1.15). This macro-scale adaptation will be the focus of this thesis. On the other hand, micro-scale is more about the changes in the thermophysical and optical properties of the structure of the material. This class of adaptation was excluded from the thesis, because it highly depends on the type of material itself that makes the adaptation possible.

Figure 1.15 Kinetic Façade of the Syddansk Universitet communications and design building in Kolding, Denmark
(source: www.dezeen.com)

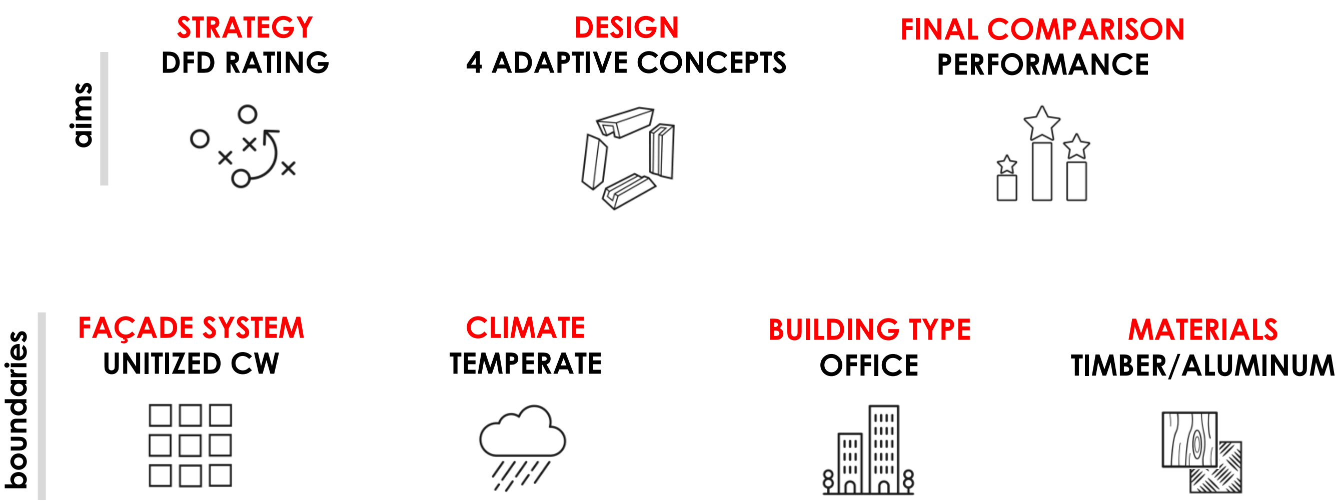
All the information related to the adaptation of these building systems will be explained in more detail in Chapter 4, by providing examples and case studies.

1.3 main objective

The main objective of this MSc Thesis is:

> Formation of the strategy for rating the Design for Disassembly in unitized curtain wall modules, with the focus on comparing 4 adaptive unitized curtain walls for high-rise office buildings on temperate climate conditions for 2 different materials used for mullions: aluminum and timber.

In an attempt to clarify the main objective, the 3 aims of the thesis are shown in the next scheme, and below them, the 4 boundaries of the research are provided.



1.4 research questions

The research questions that will be addressed in this thesis are the following:

1. Which of the principles of designing for a **Circular Economy** apply for **unitized curtain walls**?
2. What kind of **rating system** will be adopted in order to form the new DfD strategy?
3. How can the many different **subcomponents** of a unitized curtain wall be disassembled?
4. What could be the preferred **material for mullion** in terms of reducing the environmental impact and in terms of future disassembly?
5. Which **adaptive** system could eventually be the best choice (from the ones compared) for the circular building envelope?

1.5 methodology

The thesis was split in two main parts, but is presented in an integrated way. The two parts are:

- Literature review and research
- Case Study designs and rating

Being integrated means that each chapter containing a research domain has an output that affects either the strategy or the application(design).

1. For the Literature review and research, the following strategy applies:

General research: It aimed for the studying of some previous projects where CABS were applied and some where the Circular Economy principles for facades were taken into account. Also general information regarding the design of building envelopes was gathered, and especially for unitized curtain walls.

In-depth research: This focussed on four main domains:

- Curtain wall design principles and subcomponents
- Circular economy in the building industry, especially for constructing facades and roofs (Design for Disassembly)
- Climate Adaptive Building Skins, especially for thermal, optical and electrical adaptation in the macro-scale.
- Life Cycle Assessment of building products

Research methods included:

- Searching for relevant literature online
- Investigating the TU Delft Library in order to find and study literature
- Frequent communication and discussions with my supervisors and colleagues at the engineering firm ABT bv.
- Meetings with my graduation committee members in order to get some fruitful feedback
- Learning from past projects that were either realized or not.

2. As regards the **Design Project**, a case study building was provided, for which the building envelope ideas were first conceptualized and then designed. The starting point was to come up with the 4 most suitable adaptive designs and sketch them. Then these were applied for a unitized (modular) system. Hardly any **adaptive and unitized** facade was found in my thorough search of the literature, something that proves the uniqueness and importance of this research.

Then, it was turn for the detailing of the 4 aluminium designs, which provided the quantities and types of materials used in the LCA. Finally, the 3d designs were made using the software Rhino and Illustrator, which were used to illustrate some of the connection types, and eventually rate them. The 8 different adaptive concepts were then assessed based on principles for circularity which are both material-related and connection-related.

In the end, conclusions are drawn with respect to the ratings, and recommendations for future research are provided.

Figure 1.16 on the next page graphically illustrates the methodology that was followed in the thesis and described in this section. It should be mentioned that the white boxes represent the subjects of the literature review, while the dark grey ones stand for the outcome of the research, from initial conception to conclusion.

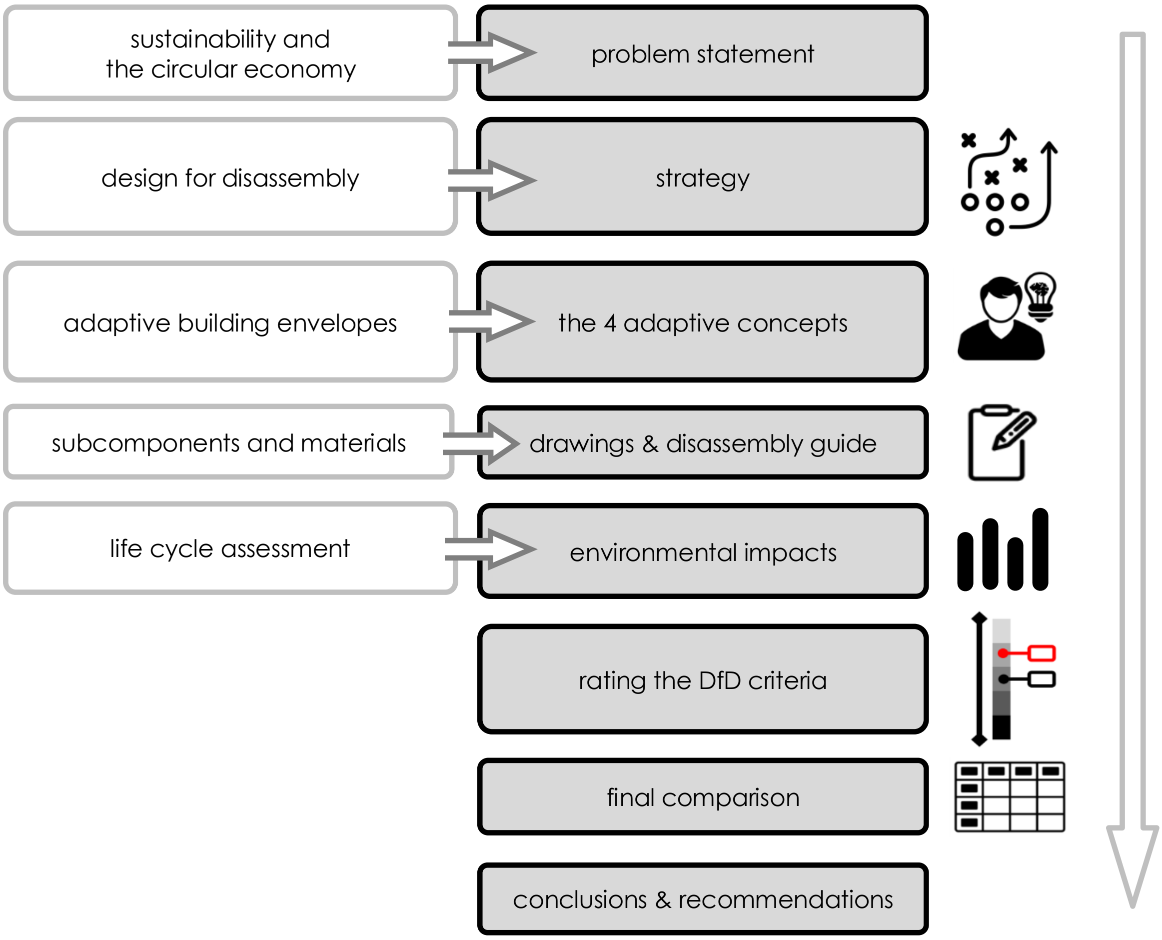
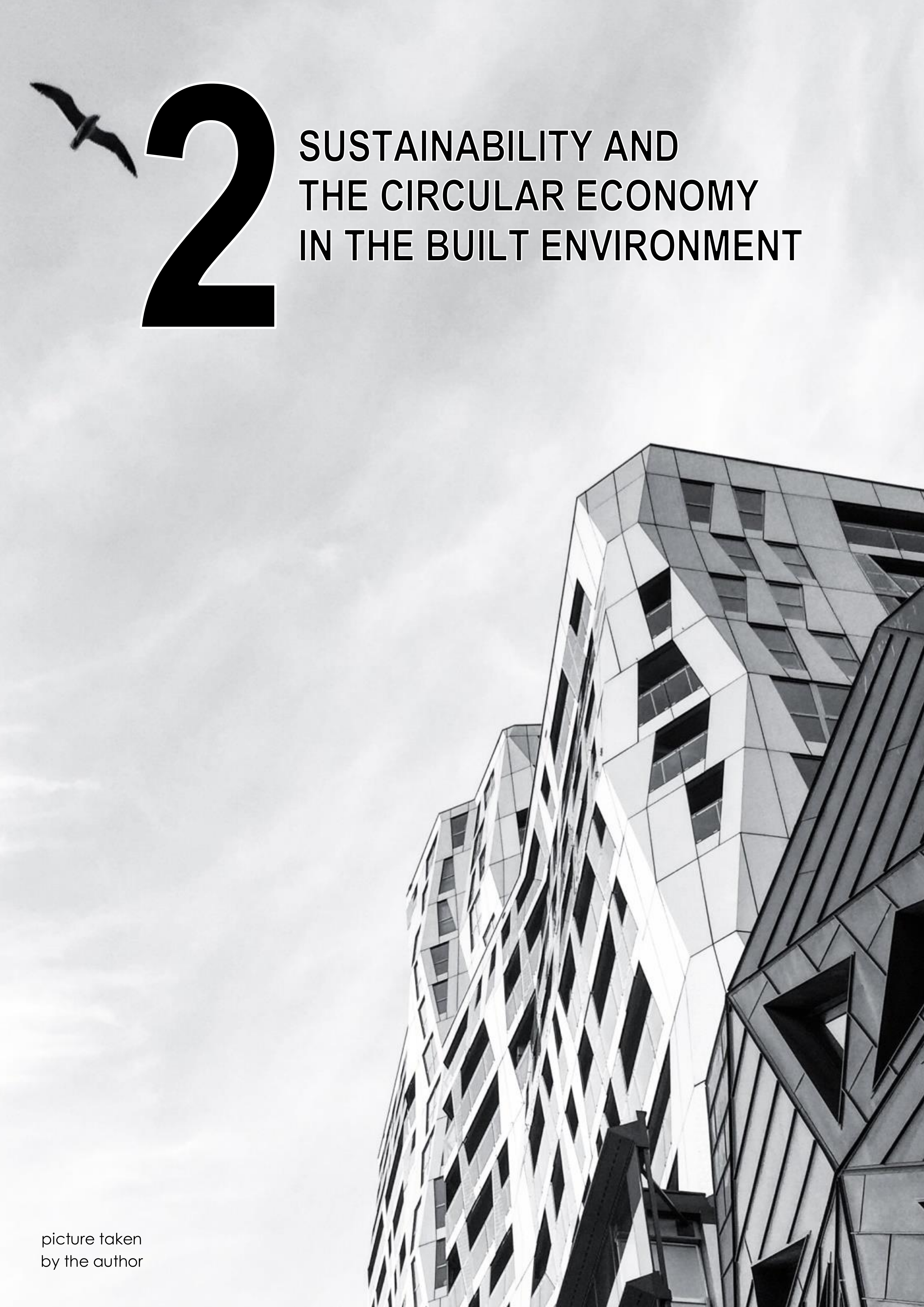


Figure 1.16 The Methodology followed in the Thesis – presented in a graphical way

2 SUSTAINABILITY AND THE CIRCULAR ECONOMY IN THE BUILT ENVIRONMENT



picture taken
by the author

2.1 sustainability in the construction sector

The main idea of the so-called ‘Sustainable Development’ is to ensure that meeting the needs of the present happens without compromising the ability of the future generations to meet their own needs (Report "Our Common Future" or the "Brundtland Report", 1987). Another famous definition refers to sustainability as a concept based on the balance of different aspects, a space of compromise; this balance is defined by some authors as solidarity. It must be emphasized that the sum of partial approaches to sustainability does not provide a sustainable outcome. There is a strong need for a global and united action, a holistic approach. This concept is based on three pillars: social, environmental and economic as shown in Figure 2.1. The aforementioned are also known as the 3 P’s: People, Planet, Profit.

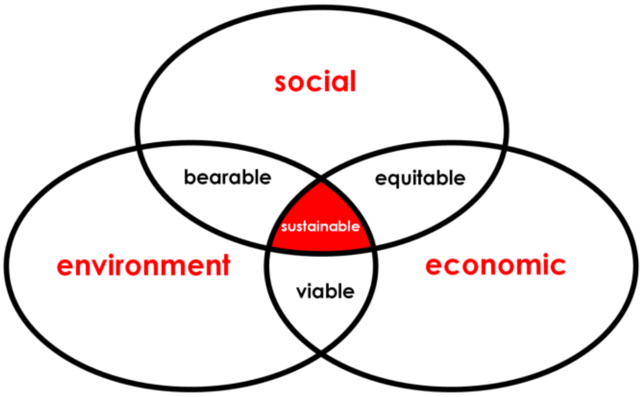


Figure 2.1 The three pillars of Sustainable Development (adapted from: www.thwink.org)

Sustainable Architecture aims at minimizing the negative environmental impact of buildings by being efficient and moderate when using materials, energy and development space. Thus the built environment is designed with a conscious approach to both the conservation of energy and ecology. In Figure 2.2, the famous Bosco Verticale towers in Milan, Italy is shown as an example of contemporary sustainable architecture.

Figure 2.2 Bosco Verticale, Milan, Italy (source: www.arup.com)

In other words, when speaking about sustainable design, the main objectives that are of primary importance are:

- reduction of critical resource depletion (e.g energy, water, land, raw materials)
- prevention of environmental degradation by infrastructure or facilities through their life cycle.
- creation of built environments that are safe, liveable, comfortable and productive.

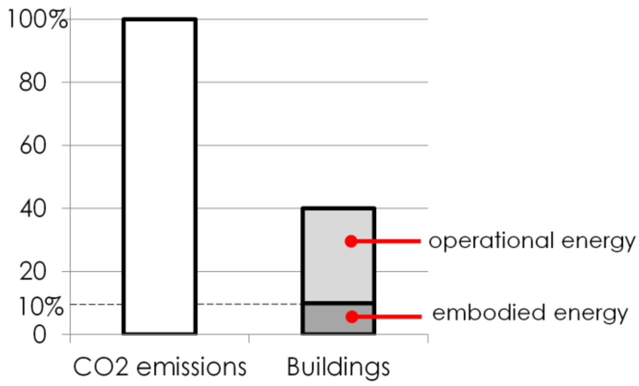


Figure 2.3 Operational and embodied energy percentages (adapted from: Thormark, 2002)

As already mentioned in the first introductory Chapter, it is estimated that nowadays buildings are responsible for approximately 40% of the energy consumption and 36% of CO_2 emissions in the EU. As it can be noticed from Figure 2.3, operational energy accounts for the largest part of a building, while the embodied energy is only responsible for 10-15% (Thormark, 2002).

According to Garcia Navarro, J., 2004, Sustainable Construction means:

- a friendly approach and commitment to the environment and a proper use of water and different types of energy;
- the selection of the resources, technologies and materials from the beginning of the project and their efficient application in construction
- avoidance of the environmental impacts
- management of the waste generated throughout its life cycle
- proper maintenance and conservation of heritage buildings
- reuse and recycle whenever possible
- profitability
- more comfortable, healthy and accessible buildings

The main 5 objectives of Sustainable Development are:

- to rationalize
- to save
- to preserve
- to improve
- to humanize

In 2005, Fermin Vasquez said that ‘Perhaps what had always been named common sense is now called sustainability’. And this is translated to ‘building sustainably’ meaning ‘doing things properly’.

2.2 zero energy building definitions

In short, a Zero Energy Building (ZEB) is one that consumes about the same amount of energy as it produces. Thus, its energy use is 0 kWh/(m2a) of primary energy per year. Other definitions can be found in the literature for the same concept, such as Energy Neutral Building, Net-Zero Energy Building, and even Net Zero Building. A distinction should be made between ZEB (or net ZEB) and nearly Zero Energy Building. The latter term refers to buildings that are almost Net Zero.

In a somewhat more concise definition given by the U.S. Department of Energy (DOE) Building Technologies Program and used by Torcellini, et al. (2006) for ZEB, 'a ZEB is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies." There are four commonly used definitions, which are distinguished and pointed out by Torcellini, et al. (2006):

- **Net Zero Site Energy Use:** The energy production is as much as the consumption, when accounted for at the site.
- **Net Zero Source Energy Use:** The energy production is as much as the consumption, when measured at the source.
- **Net Zero Energy Emissions:** The production of emission-free renewable energy is as much as the consumption derived from emissions-producing energy sources.
- **Net Zero Cost:** The financial credit received for the exported energy is as much as the utility bills charged.

There are two additional definitions which are worth to explain:

- **Net Off-Site Zero Energy Use:** Produces at least the amount of energy it consumes, while being connected to a smart grid for electricity.
- **Off the Grid:** It stores energy locally, rather than being connected to the grid.

All the aforementioned definitions are shown in an illustration in Figure 2.4, which clarifies their differences. Of course, zero energy buildings are designed with the aid of certain standards and ratings, which are explained in the following section.

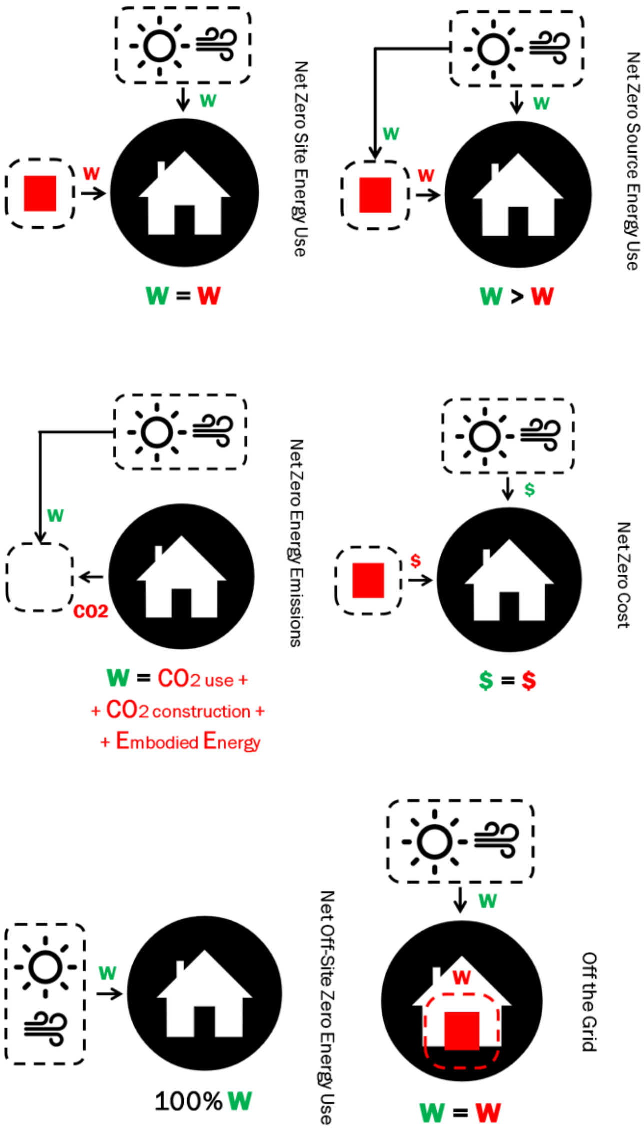


Figure 2.4 NZEB definitions (adapted from Conci, 2014)

2.3 green building standards and rating

The last few decades, environmental certification schemes are introduced to the construction sector, which aim at reducing the environmental impacts of buildings and providing a credible environmental label. This results in a differentiation of buildings in terms of their environmental performance and allows a transparent comparison of buildings. These qualitative assessment tools usually have broad scopes and are based on checklists, that reflect what is supposed to be the best practice. When various specific requirements are achieved, points are awarded by most of these labelling systems.

There are currently various labelling tools for buildings universally (Figures 2.5 and 2.6), the most well-known of which are: BREEAM (UK), LEED (USA), GREENSTAR (Australia), DCBA (The Netherlands), DGNB (Germany), HQE (France), GPR, CASBEE (Japan). Some of the aforementioned are based on energy performance measurements and calculations of emissions, while others have more subjective criteria. The sustainability assessment tools have a fierce competition between each other, since all the proponents want their tool to be the most popular in this relatively recent market.

Figure 2.5 Well-known Green Building Certification logos (source: http://www.sfiprogram.org)

Certifications and countries don't match one to one. There are countries like Canada and the USA, where many different green building certifications are used, and there are some certifications (BREEAM, LEED, etc.) which are applied to multiple countries, as illustrated in the world map in Figure 2.6.

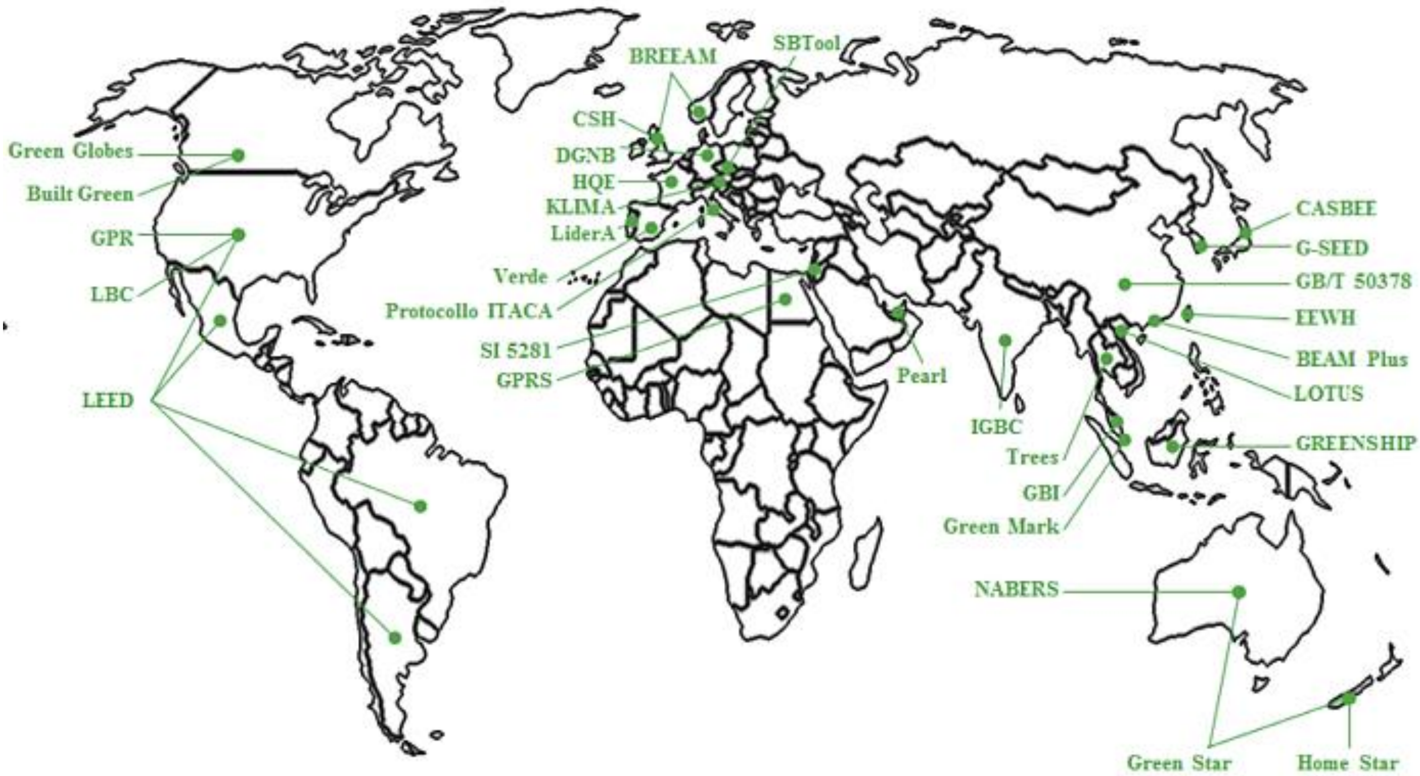


Figure 2.6 Green building certifications worldwide (source: Wei, 2015)

Below, the BREEAM and LEED certifications will be briefly described, in order to illustrate the differences in the approach of different tools.

2.3.1 BREEAM

Breeam is the result of the UK Code for Sustainable Homes, and it is obligatory from May 2008 and on, which means it is a national standard. The rate to which a home can be classified as sustainable is divided into categories, all of which together can be considered as a complete package. The overall sustainability performance is rated using a 1-6 star system, and it is valid also for non-residential buildings as well now. The logo of BREEAM is shown in Figure 2.7.

Figure 2.7 BREEAM logo

The environmental rating assessed by BREEAM is calculated by the award of points/credits for fulfilling the requirements of various criteria, each of which is worth a single credit. An exception is when a large variation takes place regarding the performance of buildings that meet the criteria requirements. The rating scale of BREEAM is shown in Table 2.1.

RATING	SCORE (%)
Outstanding	≥85
Excellent	≥70
Very Good	≥55
Good	≥45
Pass	≥30

Table 2.1 The BREEAM scale

2.3.2 LEED

The Leadership in Energy and Environmental Design (LEED) Green Building Rating System, developed by the U.S. Green Building Council, brings a set of standards for sustainable construction, by using an assessment method based on BREEAM. Its evaluation is valid for both new and existing buildings, and it is based on a variety of rating systems. The logo of LEED is shown in Figure 2.8.

Figure 2.8 LEED logo

Once every five years the existing buildings should be re-certified, if they are to maintain a LEED Certification, but it can also be done as often as once per year. The latter enables the owners or managers to incorporate LEED into annual performance reviews of their buildings. The system of grading is as shown in Table 2.2.

RATING	SCORE (%)
Platinum	≥80
Gold	70-79
Silver	50-69
Certified	40-49
No rating	≤39

Table 2.2 The LEED scale

2.4 end-of-life of buildings

It is well-known that the Building Sector consumes huge amounts of energy. This was shown in the illustration of Figure 1.1 of the 1st Chapter. But aside from the energy consumption, this sector also produces huge amounts of waste, also known as Construction and Demolition Waste (CDW). To give a size reference, the CDW in the Netherlands in 2012 was more than 80Mt (incl. soils). Figure 2.9 illustrates the partial percentages of all the Dutch waste for 2012, emphasizing that over 40% was derived from the building sector, thus posing it the 1st contributor for waste. It should be mentioned that in an optimistic and approximate estimation, 93% of all CDW was recovered (Deloitte, 2015).

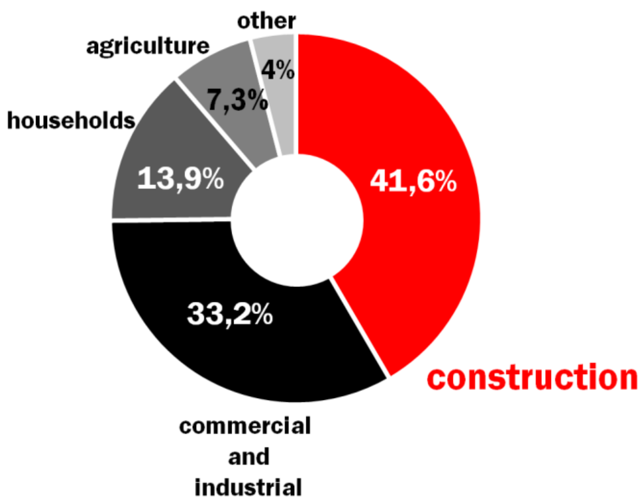


Figure 2.9 Production of Waste per sector, the Netherlands 2012, (adapted from BAMB, 2016)

It is well-known that the performance of the waste management in the Netherlands is very good when compared to other countries in Europe. This comes as a result of the high amounts of recycled waste. Nevertheless, it is expected that the numbers of the Construction and Demolition Waste will still go up the following years (Deloitte, 2015). Since some raw materials are scarce and resource depletion is critical, it is crucial to diminish the CDW and improve the end-of-life strategies.

Nowadays, it is pretty much known how energy and waste are used and handled in the building industry. The current building stock is constantly improved by national and European regulations, through the stimulation of measures of energy efficiency and renewable energy generation. As regulations become stricter and stricter for new-built buildings, more renovations take place, and new structures are much more efficient. However, the rate of the aforementioned is still not high enough, and most renovations taking place are 'shallow'; meaning that only small interventions occur with minor energy benefits (Greco et al., 2016).

Having the current stock replaced by new buildings may appear to be an appealing option, since such buildings are suited to modern living standards and architectural criteria. Nonetheless, only 55.000 buildings are constructed on a yearly basis; just 0,7% of the total existing ones. On the other hand, only 0,2% is annually demolished (CBS, 2017b), as shown in Figure 2.10.

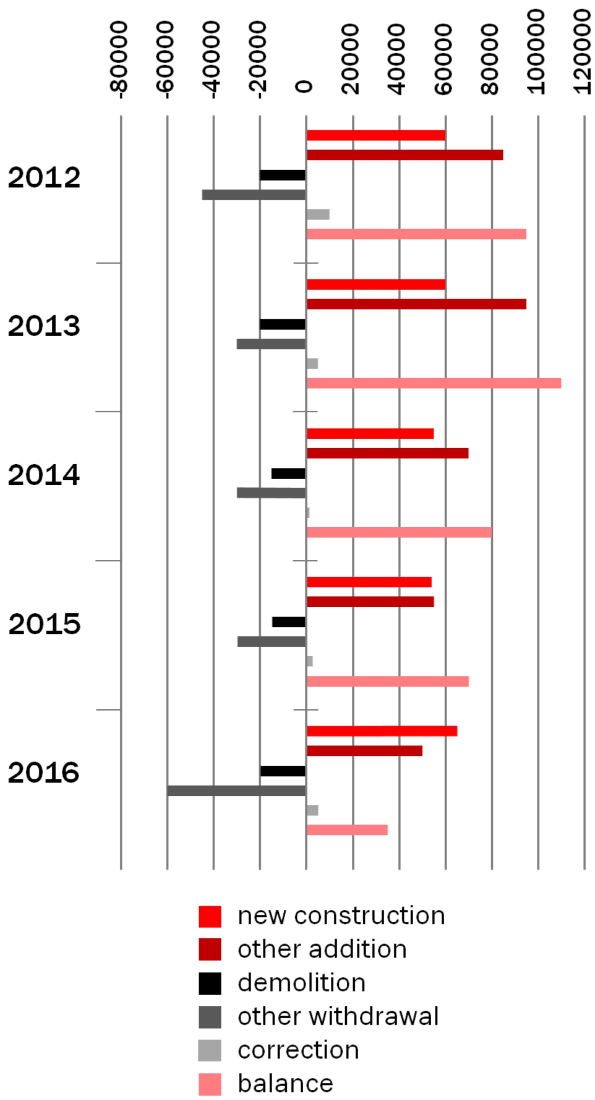


Figure 2.10 Changes in the building stock in the Netherlands 2012-2016 (adapted from CBS, 2017c)

On the current speed of change, achieving the targets of Zero-Energy may seem impossible by only creating new buildings. Although the stimulated demolition could aid for new efficient buildings and energy consumption reduction, the demolition rate in the Netherlands is too low to make it feasible and it can be considered a big waste of embodied energy.

Having the rest 99,1% refurbished may seem the solution that makes most sense right now. But although people recognise the need for refurbishment, its rate appears to be too low. There is an urgent need for an improved refurbishment in terms of quality and scale (Greco et al., 2016). In order to achieve it, more investments should take place on energy savings, even though this is hardly ever an even comparable motive to financial and social incentives. In the rental sector, such investments are a challenge, since mainly the renters, rather than the owners benefit from the changes of the refurbishment (Konstantinou, 2014). The Dutch housing stock is 43% rental, while the office stock is even more (CBS, 2017a).

To conclude on the end-of-life, not only will refurbishments have a greater impact than new-built, but also there will be preservation of the existing embodied energy. In general, there is a loss of value and energy for anything that enters the CDW cycle through demolition. This is why an introduction to the circular approach and the resource efficiency hierarchy will be given in Sections 2.5 and 2.6, and a more in-depth research is done on Disassembly strategies in Chapter 3.

2.5 the circular approach

As already mentioned in Chapter 1, the current material economy model is highly based on a take-make-dispose sequence. This means that we extract natural resources from the earth, manufacture them into products, and then we dispose of the products in the landfill, as illustrated in Figure 2.11. It is however expected that the world population will grow to 9 billion people by 2050, and the earth should be multiplied by six in order to facilitate people's needs. Consequently, the current linear material economy has negative effects which are dominant in the construction supply chain. This why it is now time to turn to a circular approach, as indicated in Figure 2.12.

Although the Circular Economy model has its roots in concepts dating back to the 1970s, this approach has recently gained attention mainly thanks to Ellen MacArthur Foundation. This was established in 2010, aiming to accelerate the transition towards a circular economy. According to Ellen MacArthur Foundation, a circular economy model looks beyond the current take-make-dispose extractive industrial model, and instead it aims to redefine growth, focusing on positive society-wide benefits.

The basic three principles of the circular economy model are:

- Design out waste and pollution
- Keep products and materials in use
- Regenerate natural systems

In other words, Circular Economy is a regenerative system, in which the goal is to slow, close, and narrow the energy and material loops in order to minimise the resource input and waste, emission and energy leakage. To achieve this, there is a need for long-lasting design, maintenance, repair, reuse, redistribution, re-manufacturing, refurbishing, and **closed recycling loops** (Figure 2.13 in the following page).

In a circular economy, the materials circulate in material cycles, which operate according to many conditions. As illustrated in the so-called Butterfly Diagram (Figure 2.14 in the following page), there are two main cycles categories; namely the bio-cycle and the techno-cycle.

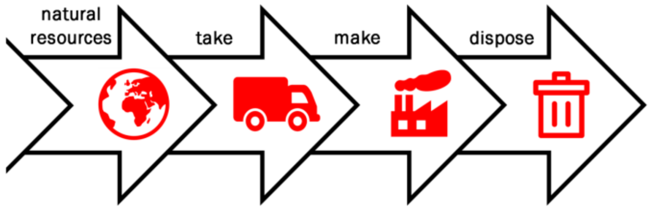


Figure 2.11 The Linear Economy model (own illustr.)

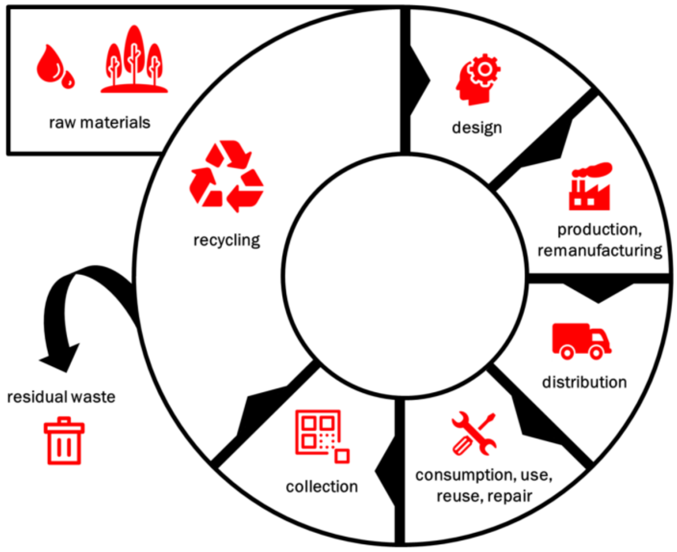


Figure 2.12 The Circular Economy model (own illustr.)

Organic materials follow different processes than technical or synthetic ones. This is the reason why it is important to separate the biological from the technical materials after use, in order for them to follow their respective reuse process, as shown in Figure 2.14.

Organic Materials such as water, food or cotton can be processed biologically in the ecosystem. It is vital to make sure that both the biological and ecosystem processes are enabled in the bio-cycle, in order to function properly. When there is no toxic contamination in this cycle, consumption may take place. The organic materials are renewable when the ecosystem is in balance.

Technical Materials on the other hand, such as metals, plastics or fossil fuels are not renewable; they are finite. It is of primary importance that there is a proper management of this finite stock of materials. There is 'use' instead of 'consumption', and recovery of the materials can happen by focusing on value retention.

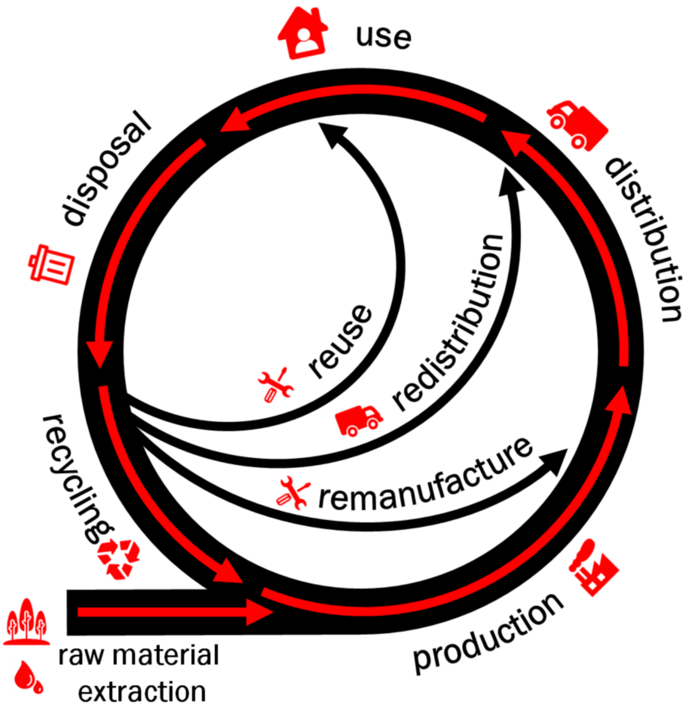


Figure 2.13 Closing the Loops (own illustr.)

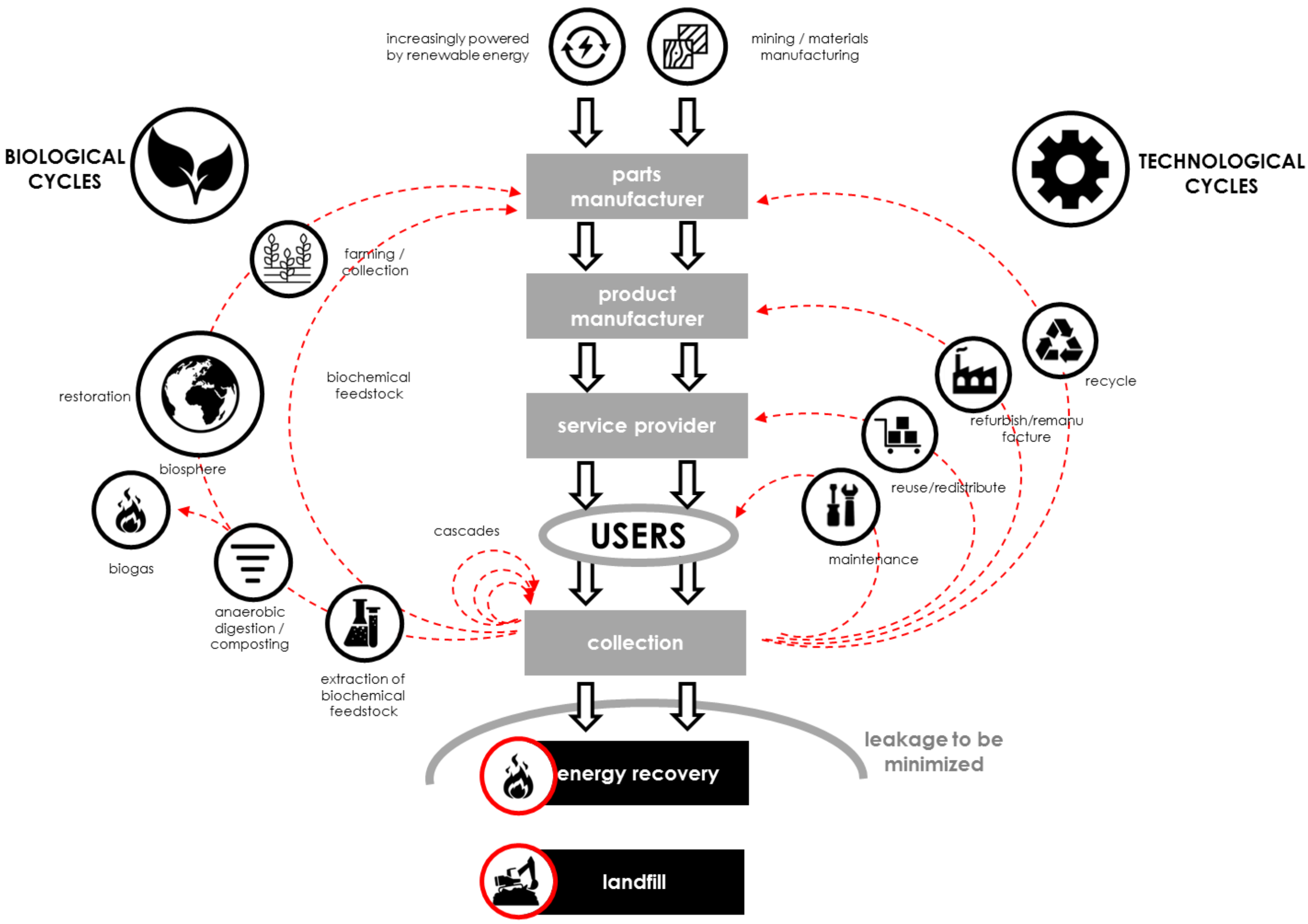


Figure 2.14 The Butterfly Diagram (adapted form: www.ellenmacarthurfoundation.org)

2.6 resource efficiency hierarchy

Not all the end-of-life strategies are similar. It is not just about avoiding to throw construction and demolition waste (CDW) to landfill, because this may not be enough. Although it is a good start, the eventual purpose of this CDW is the critical factor for assessing it either as a small or a big step. There is big scale for assessing resource conservation and the extent to which it works in a sufficiently sustainable way. Figure 2.15 provides a list of strategies for reducing waste and closing the material loops in the form of a reversed pyramid, together with their sub-strategies on the side. The hierarchy is given in a declining importance way from top to bottom.

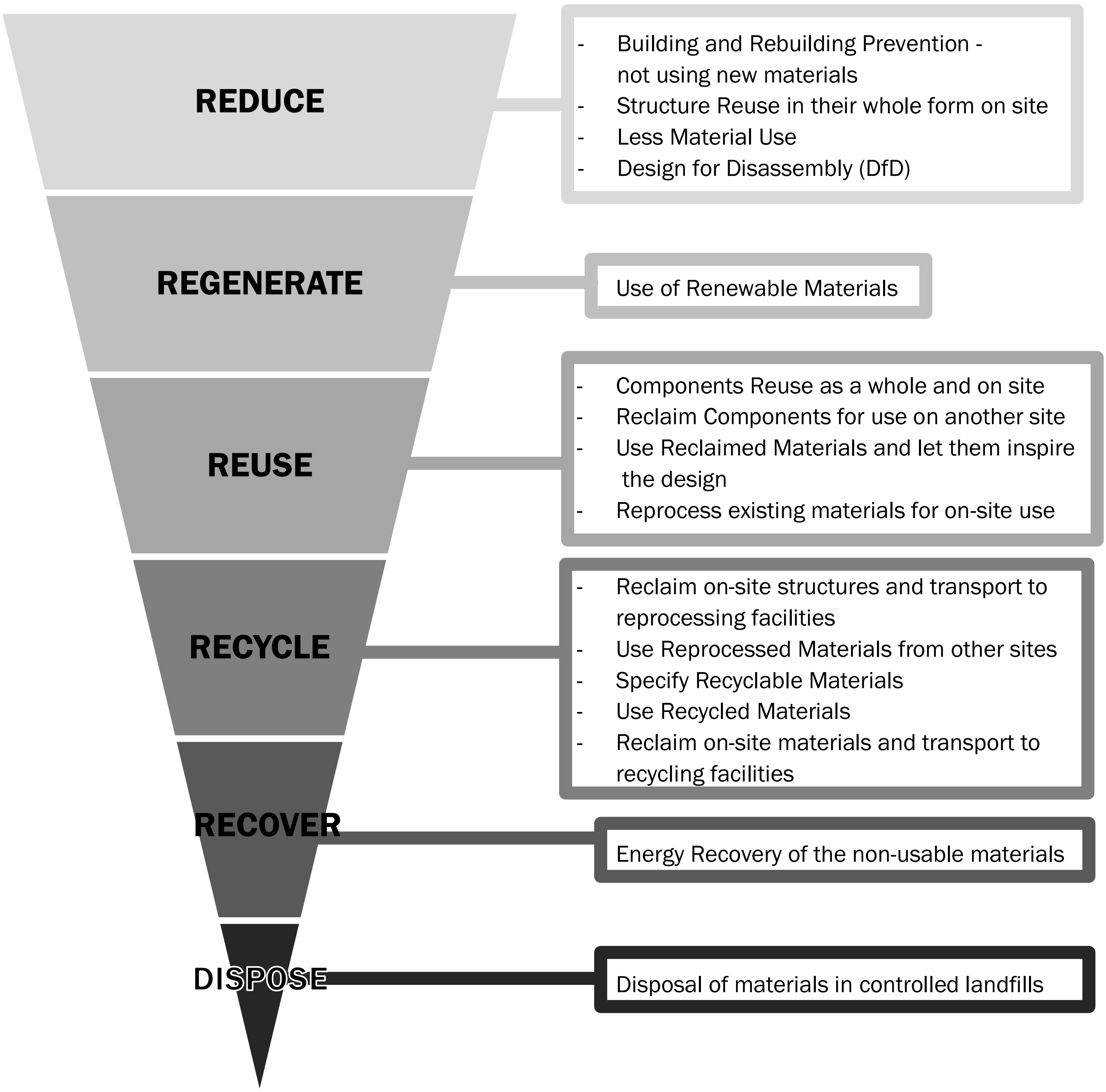


Figure 2.15 Strategies for resource efficiency
- adapted from Calkins (2009)

2.7 references

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3

DESIGN FOR DISASSEMBLY

image source:
unsplash.com – Pacific Austin

3.1 introduction

In general, it is very common for a building to be thought of as a complete entity. This is also the way it is designed most of the times; from conception to disposal – *a complete entity*. However, a building has many different parts with different life spans. There is a need therefore, to consider it as a structure made out of different layers.

Figure 3.1 illustrates the different layers of a building with their average lifespans. It can be observed that the structure of the building has both the largest volume and highest weight, and thus it can be considered as the main problem in waste generation.

It must be emphasized, however, that the facade and roof of the building – also known as the 'building envelope' or 'skin'- have a significantly lower lifespan, thus having a big impact on the environment as well.

The aforementioned is called **the theory of layers**, and it shows how buildings can be considered as a collection of functional layers, each with a different life duration, which should be designed independently from each other.

The research presented in this chapter can be applied on many different parts of the building, but the examples focus specifically on the building envelope, and the way that the guidelines for Design for Disassembly (DfD) can be applied on façades. But before diving into the DfD guidelines, the importance of deconstruction – instead of demolition – will be illustrated through their definition and a pros-cons list, shown on Table 3.1.

Deconstructing a building means dismantling it with the purpose to reuse or recycle its components. On the other hand, **demolishing** a building results in no preservation of its different components. which leads to big amounts of debris that end up in the landfill.

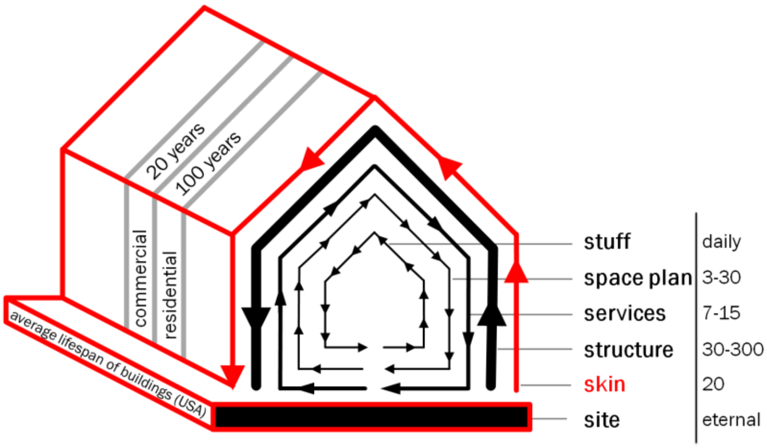


Figure 3.1 The building layers and their average lifespans (adapted from: Brand)

Pros of Disassembly	Cons of Disassembly
less debris on landfills	deconstruction takes more time than demolition
less impacts on environment and human health	higher costs compared to demolition
toxic substances can be managed	it takes a lot of time to clean, process and refurbish
recycling industry is strengthened	there is little space for reclaimed materials to store on site
history and uniqueness of reclaimed materials	higher risks for workers' health (e.g. toxic paints)
contribution to LEED credits acquisition	good supply-demand chains are still lacking
cost savings when materials are reused on site	most contractors are still inexperienced

Table 3.1 Benefits and Challenges of Disassembly – adapted from Calkins (2009)

3.2 design for disassembly

The design guidelines for DfD that relate to the facade element level and will be the focus of this research, are illustrated in Figure 3.2. This is a scheme that shows how the guidelines can be divided into material and **connection** principles. The former includes the environmental impact of the materials used, the durability of the components and the end of life potential, and are elaborated in Sections 3.2.1, 3.2.2 and 3.2.3 accordingly. The latter refers to the reversibility of the connections, the ease and the speed of the assembly and disassembly processes, and are analyzed in Sections 3.2.4, 3.2.5, and 3.2.6.

Section 3.2.7 provides an overview of additional strategies that should be taken into account when designing for future disassembly. Prefabrication and independence of building components, stratification according to life cycle and compatibility of dimensioning are briefly described, since they are considered very important and relevant to this research, and omitting them would be erroneous. Section 3.2.8 includes some important considerations to be taken into account during the design, and Sections 3.3 and 3.4 provide an overview of the rating scales and weights. Finally, the summarized strategy will be shown as a whole in Section 3.5.

At this point, it should be mentioned that the Life Cycle Costs were left out of this research, since it has a purely engineering character, and only relates to the principles that directly concern DfD. It may be interesting for a future MSc Thesis or other type of research to delve more into that. This is elaborated in more detail in Chapter 9.2: *Recommendations for future research.*

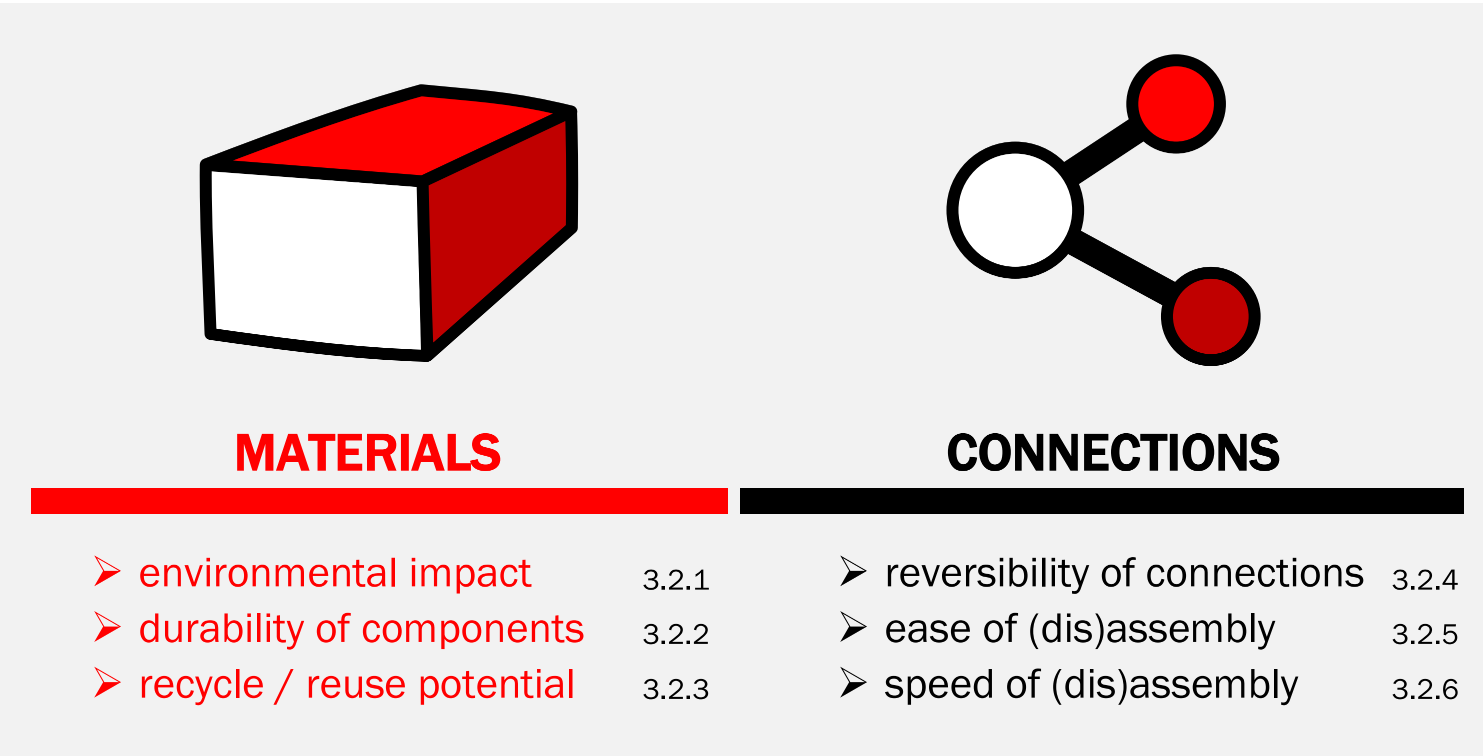


Figure 3.2 The material- and connection-related guidelines (own illustr.)

3.2.1 environmental impact

The design of a building – and more specifically in this case the facade of the building – has a specific impact on the environment throughout the entire life cycle of the materials used. This environmental impact includes the necessary energy for each phase of the life cycle, as well as the toxic substances that are released and the end-of-life treatment. In this case, a cradle-to-gate assessment will be performed, meaning that only impact of the production phase will be assessed.

This impact assessment will take place in Chapter 7 through conducting an environmental product declaration, which is a qualitative technique for determining and evaluating the environmental impacts of construction materials and products, services, and processes through production phase. This section will not provide further information, as everything is elaborated in the corresponding chapter.

3.2.2 durability of the components

Re-use of the building components can take place if the materialization of the construction components allows it physically. Frequent reuse of components is only possible if durable materials are used, in the sense that they last for a long time and that they withstand damage, characteristic of frequent transport and intensive use of construction products. Depending on the future function, other properties of the components will need to be met, such as the aesthetic quality.

Examples of building components with a high resistance to wear that allow for reuse after various assembly and disassembly processes (if the connection method and other external factors allow this) include bricks, ceramic (roof) tiles, steel beams and profiles and wooden planks and beams. In addition, preference should be given to components with low maintenance. For instance, Table 3.2 shows the life expectancy of different kind of materials used in building envelopes.

The lifespan of the various elements should be related to the lifespan of the complete module. All elements and components must have the ability to survive at least one lifespan of their building. In the case where an element has a larger lifespan than the component's, it is advisable to be demountable.

Function	Materials	Expected lifespan
Facade - Inner leaf	concrete, brick, sand-lime brick	100
	timber	75
Facade - Outer leaf	concrete, brick	100
	sand-lime brick	75
	limestone	50
Facade - Cladding	concrete	75
	stony material	40-75
	timber	15-60
	zink, plaster	25
Facade - Insulation	cellulose	30
	phenolic or resol foam, EPS, glass wool, rock wool	75
	cellular glass	100
Sloping Roof - Cladding	ceramic material, slate	75
	copper	100
	zinc, reed	40
Sloping Roof - Insulation	cellulose	20
	flax shives, phenolic or resol foam	30
	EPS, glass wool, rock wool, cellular glass	75
Outer Window	aluminum	75
	softwood	35
	PVC	30
	hardwood	50
Exterior Door	soft wood	25
	hardwood	40

Table 3.2 Life expectancy of façade materials (source: OVAM)

3.2.3 recycle/reuse potential

In today's building practice, building components are often not used throughout their entire technical life within a particular building. By reusing these building components in another building, the production of construction waste and the exploitation of new raw materials are avoided. This also applies to the use of waste products from another sector. Today, construction waste is recycled mainly at material level. This conversion requires a lot of energy and there are only a few materials that can be recycled 100% to an equivalent quality.

Second-hand components, originating from inside or outside the building sector, can be reused in a similar function or in another function, for example wooden train sleepers can be reused as structural elements. It must be ensured that the recycled material / product reaches the quality level for the construction and that its use does not cause any side effects (e.g. substances that are detrimental to health).

As an example, Villa Welpeloo (Figure 3.3) was built 70% from demolition materials and production surpluses in a radius of 15 kilometers around the construction site. The wooden cladding for example consists of cable reels that underwent a thermal treatment to prevent weathering.

Some construction products which are not recyclable are some coated metals, treated timber and some PVC products. Of course non-separable mixed material assemblies and composite products also belong to this category (Calkins, 2009). This is why, when Designing for Disassembly, such products must be avoided.

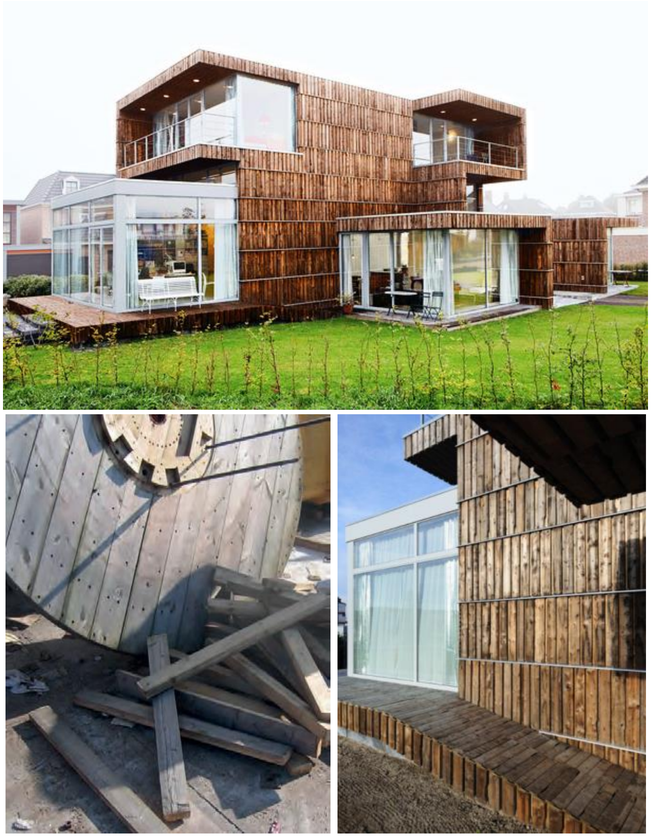


Figure 3.3 Villa Welpeloo wooden cladding

3.2.4 reversibility of connections

The reversibility of the connections between the components determines the feasibility of disassembling components without damaging them. Only then can they be reused and the sorting and recycling process can also be more efficient.

In order to optimize the reuse of building components, priority must be given to reversible connections, such as bolts and screws, but also Velcro or lime mortar. Connections such as gluing and welding make non-destructive disassembly impossible. Figure 3.4 shows some examples of both reversible and irreversible connection types. These are also listed in Table 3.3, together with the advantages and disadvantages of each type of connection.

Reversible connections are often not continuous, so special attention is required for the air and vapor tightness of the connection. For instance, the building of ABT bv in Delft was designed to be completely reversible (Figure 3.5). The façade can be disassembled, as it is mounted by bolts, clamps and hooks. However, in order to guarantee water tightness, it was necessary to add a second skin, which allows for natural cooling at the same time.

Figure 3.4 Bolts and Screws: reversible
Nails, Cement Mortar and Welding: irreversible

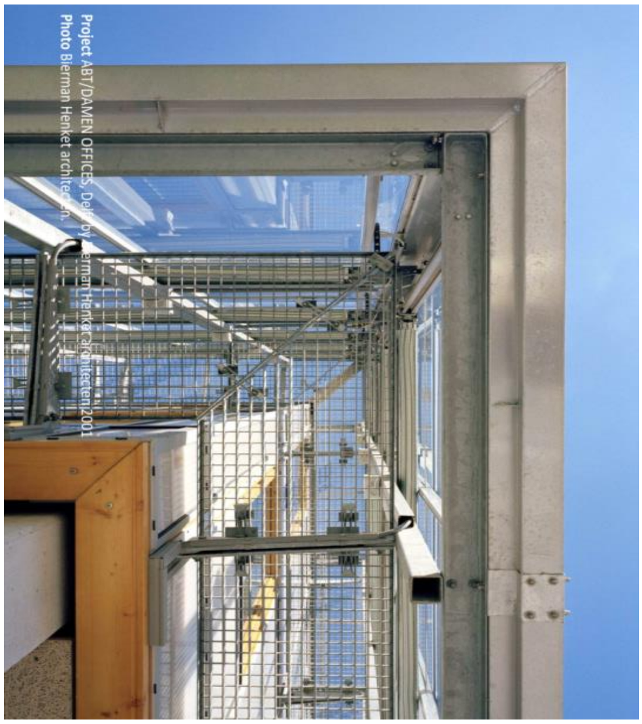


Figure 3.5 ABT office in Delft, a completely reversible building (source: on picture)

Connection Type	Advantages	Disadvantages
screws	easy to remove	screws and holes have limited reuse potential costs are high
bolts	strong reuse more than once	may seize up, complicating removal costs are high
nails	faster construction cheap	hard removal destroys part of the element during removal
mortar	various strengths possible	no reuse, unless clay or lime tough separation of bonded layers
adhesives	variety of strengths	low recycle/reuse potential sometimes they are impossible to separate
rivets	rapid construction	destroys part of the element during removal

Table 3.3 Advantages and Disadvantages of some frequent Connection Types
- adapted from: SEDA (2005)

3.2.5 ease of (dis)assembly

Complex connection techniques that can only be carried out by specialized contractors also call for specialized expertise during dismantling. In addition, the complexity of the assembly and joining techniques also slows down the (dis)assembly process, which results in labor costs being high for the construction and demolition of buildings.

By applying simple, standardized joining techniques, disassembly becomes more efficient. In addition, a certain tolerance between the components is necessary to simplify and accelerate the assembly and dismantling of elements during both the construction phase and the final phase. Finally, preference is given to readable building methods, so that a layman can, for example, see what is bearing and what is not, how one can have access to the techniques, etc.

Screws, bolts and nuts enable simple connections, which can be assembled and disassembled with standard tools, like wrenches and drills (Figure 3.6).

Figure 3.6 Drills, Wrenches and Inbuses

Figure 3.7 shows an example of an adjustable connection that makes the assembly of components much easier. It is actually a 3d illustration of a typical curtain wall anchorage. It can be observed that there are tolerances in all three axis enabling movements of the different components.

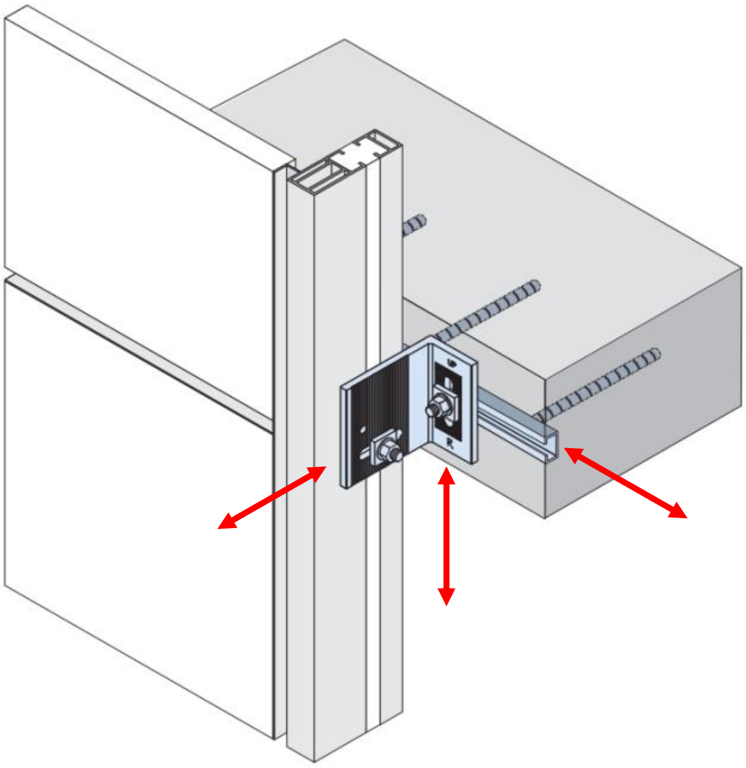


Figure 3.7 Anchor connection of the façade
(adapted from: Halfen)

3.2.6 speed of (dis)assembly

If the construction components can be assembled quickly, then they can also be quickly reclaimed after use, and the chances that the components will be dismantled and recovered during and at the end of life of buildings will increase.

Visual, physical and ergonomically accessible connections increase the ease of assembly and disassembly. For example, if a connection is behind a component and is therefore difficult to access, it will take a long time to remove it. There must also be sufficient space around the connection to maneuver with the necessary tools and remove the component. In addition to the search for fast (dis)assembly techniques, the amount of connections must also be minimized. After all, few connections during the assembly of building elements accelerate the disassembly process. In addition, the choice for one type of connection in a building lowers the complexity of the assembly and disassembly and thus also the time required. This can be further limited by the use of dry connections, such as screws, so that a long drying time, specific to mortar, plaster, etc. is avoided.

Ventilated façade systems avoid labor-intensive and complex masonry and jointing by fast fastening of façade panels against a load-bearing framework. Such façade solutions use large (sub)components that can significantly accelerate the assembly (e.g. large façade panels) and require no additional drying times if dry bonding techniques are used. An example of a ventilated façade (and the air movement in it) is shown in Figure 3.8.

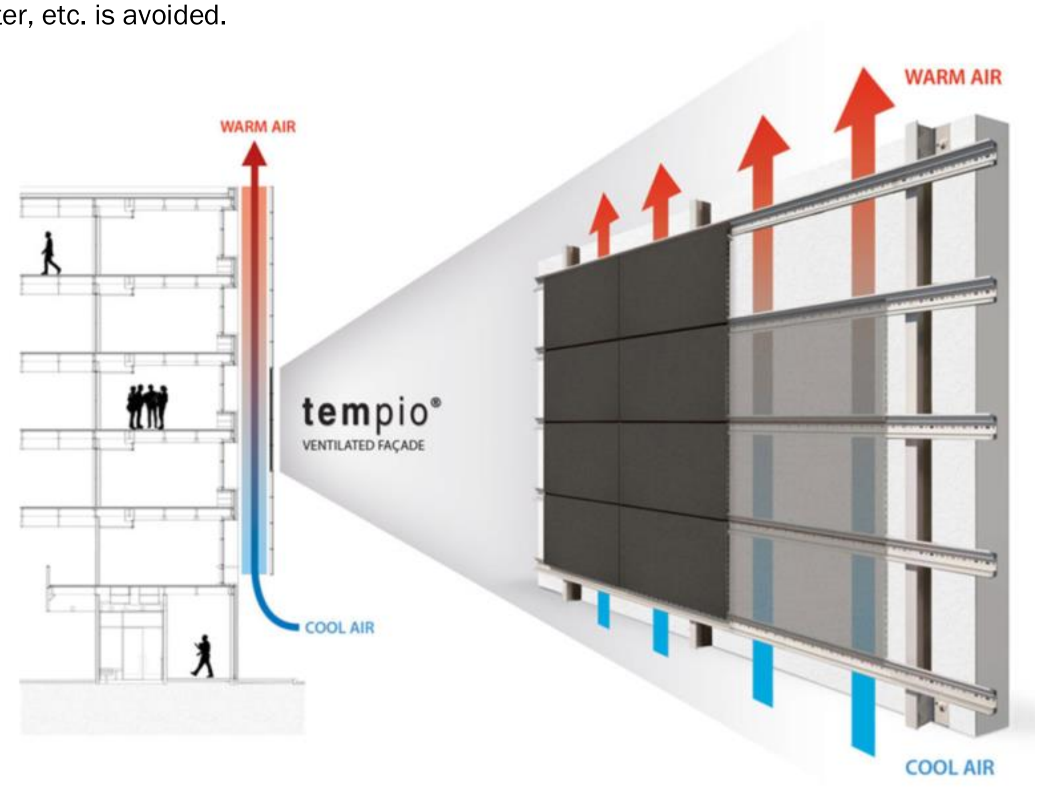


Figure 3.8 Ventilated façade system
(source: tempio®)

3.2.7 additional DfD principles

It should be emphasized again that sections 3.2.1 to 3.2.6 only elaborate the DfD principles on the facade element level. This section will provide a description of other DfD principles relating to the building component level. It should be kept in mind however, that there are also principles relevant on building scale, and even on a district scale that are not described in this research. For further information, one can visit the website of ovam.be, where 24 design guidelines are provided on all the scales.

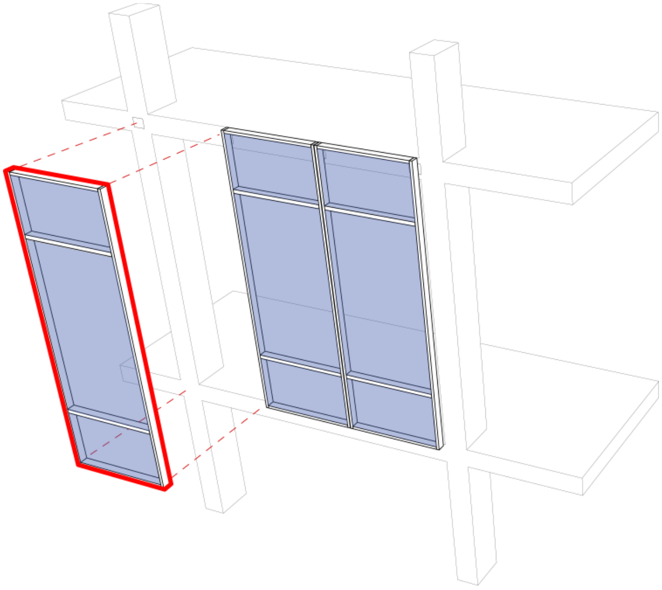


Figure 3.9 Unitized Curtain Wall principle (own illustr.)

3.2.7.1. Prefabrication of building components

When referring to a **unitized** curtain wall system, **prefabrication** of the facade components is the first thing that comes to mind. The assembly of building components prior to the assembly on the construction site has many advantages when it comes to quality control (production in a dry and clean factory), uniformity of building components, reduction of building waste, increasing the construction speed on site and the overall cost reduction of the construction process. In addition, pre-grouping of the components ensures an accelerated disassembly. Last but not least, there is no dependency on the wind and weather. (Tillmann Klein, 2013)

Figure 3.10 Unitized Curtain Wall installation

Facade components are assembled in the factory into larger packages. Their prefabrication can range from prefabrication of a functional layer (e.g. façade cladding) to prefabrication of completely finished building elements (e.g. a complete outer wall with integrated insulation layer and structure). The latter applies to this research project, where the unitized curtain wall (Figures 3.9 and 3.10) comprises of large prefabricated façade elements.

A more detailed scheme is shown in Figure 3.11, where one can observe how the assembly on site can be done with the aid of a railing and 2 laborers. The pre-assembling stages of circularity are illustrated in Figure 3.12. These will be explained in detail in chapter 7, where LCA is performed. This principle will not be compared for the different concepts, as it is valid for all of them. It is however the main principle of a Unitized CW design, and this is why its advantages when it comes to big structures were emphasized.

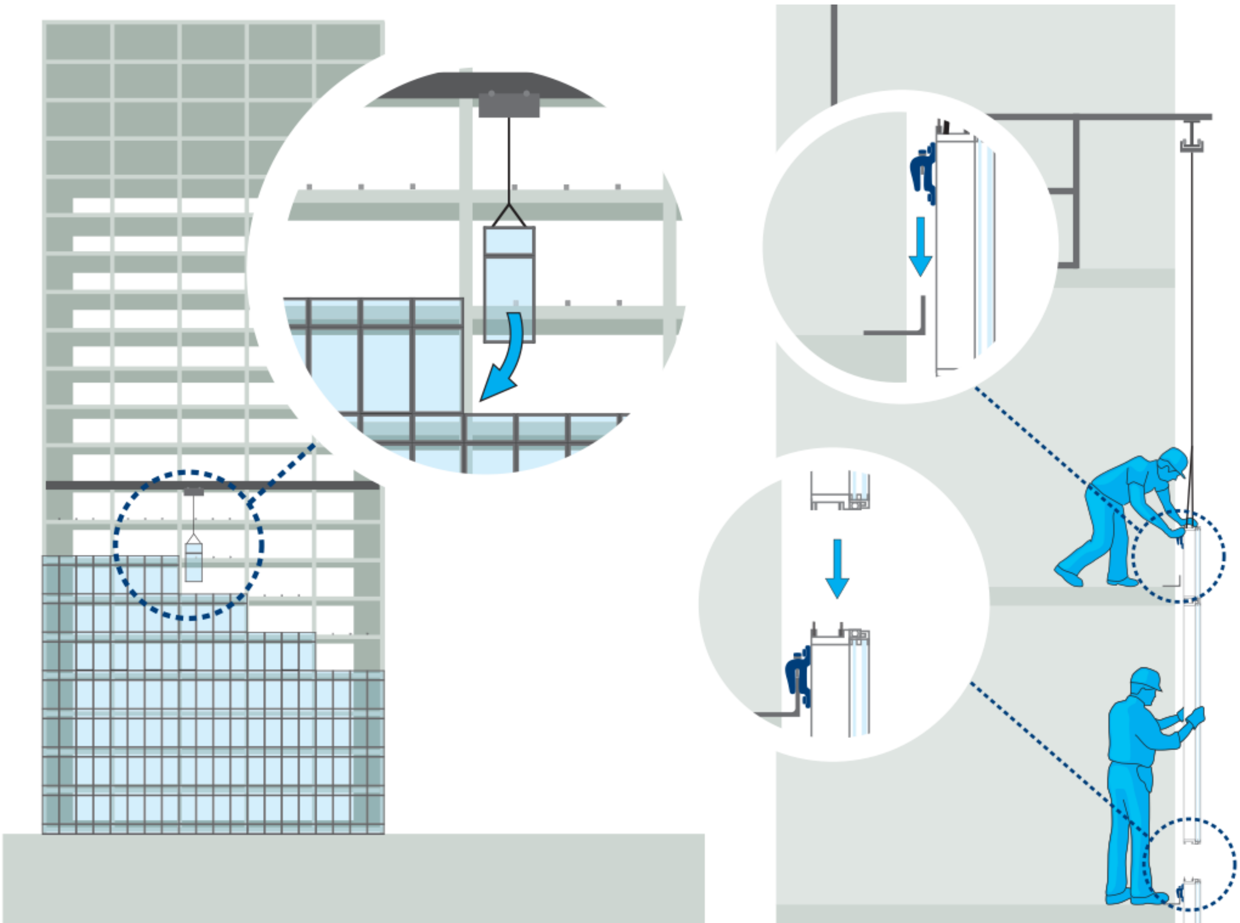


Figure 3.11 Unitized Curtain Wall installation
(source: Reynaers aluminium brochure)

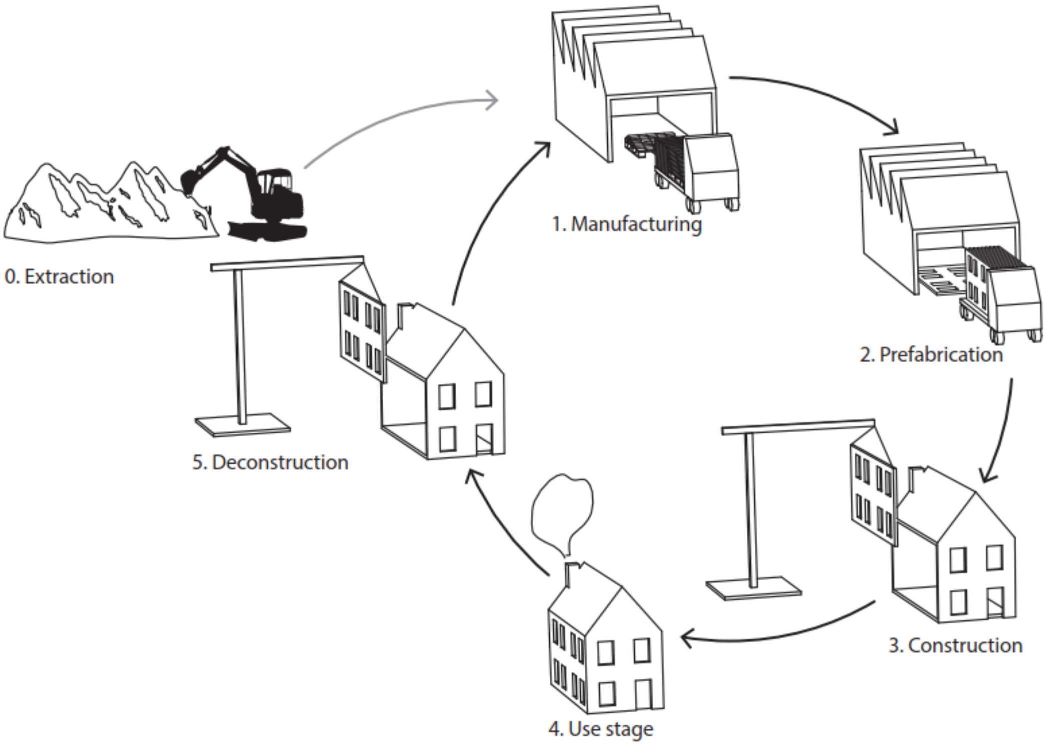


Figure 3.12 Life cycle stages of pre-assembled packages (source: OVAM)

3.2.7.2. Independence of building components

This criterion relates to the mutual relationship between components of a building element. The aim of increasing the independence of components is to simplify the replacement, removal, repair of one or more components in the future without having to remove other components. In addition, the independence of components ensures that disassembly can take place simultaneously in different places, thereby increasing the speed of disassembly.

Foreseeing a parallel instead of a sequential order of disassembly ensures that only certain components of a functional or technical lifetime layer can be removed. This is achieved through an adapted design of a component within the applied assembly.

Figure 3.13 shows how the design of components can contribute to a higher independence, which can increase the ease and feasibility of the dismantling of components.

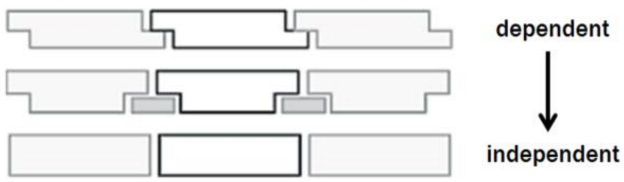


Figure 1.13 Dependence on element geometry

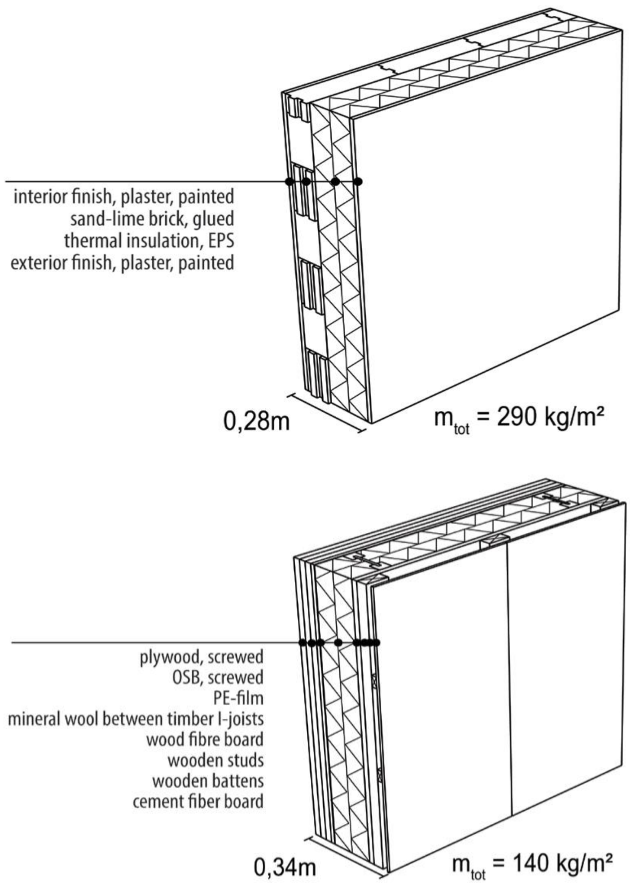
In this research, the facade modules are considered to be independent, and therefore the independency level between the different concepts will not be compared.

5.2.7.3 Stratification according to life cycle

The layering of building elements in physically separated functional and technical lifetime layers allows efficiently to adjust building elements throughout the life cycle of buildings without having to change the entire element composition. This layering allows among other things the performance of each functional layer to correspond with evolving requirements during the life cycle of buildings and simplifies maintenance, repairs and replacements.

The different lifetime layers must be physically separable, with the layers arranged according to the expected functional and technical life cycle of the components. Some components are replaced by new technical requirements, others by new aesthetic trends and others because the performance of the components deteriorates.

Figures 3.14 and 3.15 show an example of detail of a conventional (3.14) and demountable (3.15) external wall. In the first case the different functional and technical layers are not separable, whereas the second detailing has full potential for future separation.



Figures 3.14 - 3.15 Conventional and demountable detailing of external wall (source: OVAM)

This principle will neither be rated nor compared, but is very important especially for curtain walls that use the stick-system. This way selective disassembly and maintenance can occur.

3.2.7.4. Compatibility of dimensioning

By using standardized and compatible components, whose shape and size are coordinated with each other, randomly selected building components can be selected and assembled into a unique product. During the use of a building, the components can be replaced by similar or new compatible components from another manufacturer. In this way the lifespan of the building is extended. In addition, if the technical life of the components has not yet been reached, the replaced components can be repaired, if necessary, or be given a new finish and reused in the same or in another configuration.

A grid can be very helpful for the choice of dimensions and connection points in order to design compatible components. Figure 3.16 shows an example. It is the OS grid which is built up out of 4×4cm squares. The borders of these squares mark the cutting lines, its diagonals mark the assembly points and its enclosed inner circles define interconnecting diameters. Figure 3.17 illustrates shapes and sizes which will enable components to be compatible.

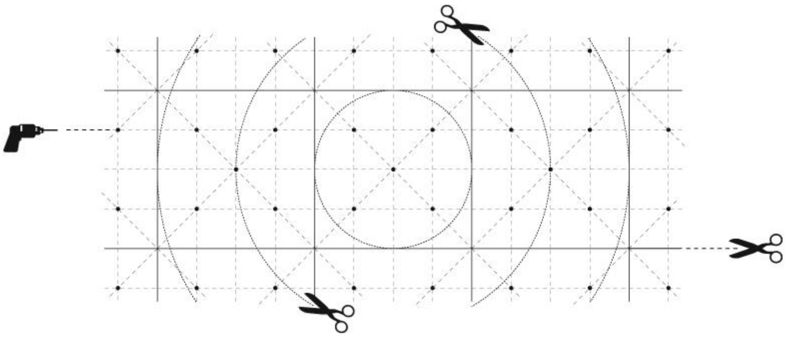


Figure 3.16 The OS grid (source: beta.openstructures.net)

This principle will not be compared later, but it used in the design, by using standard dimensions of module grids and symmetry.

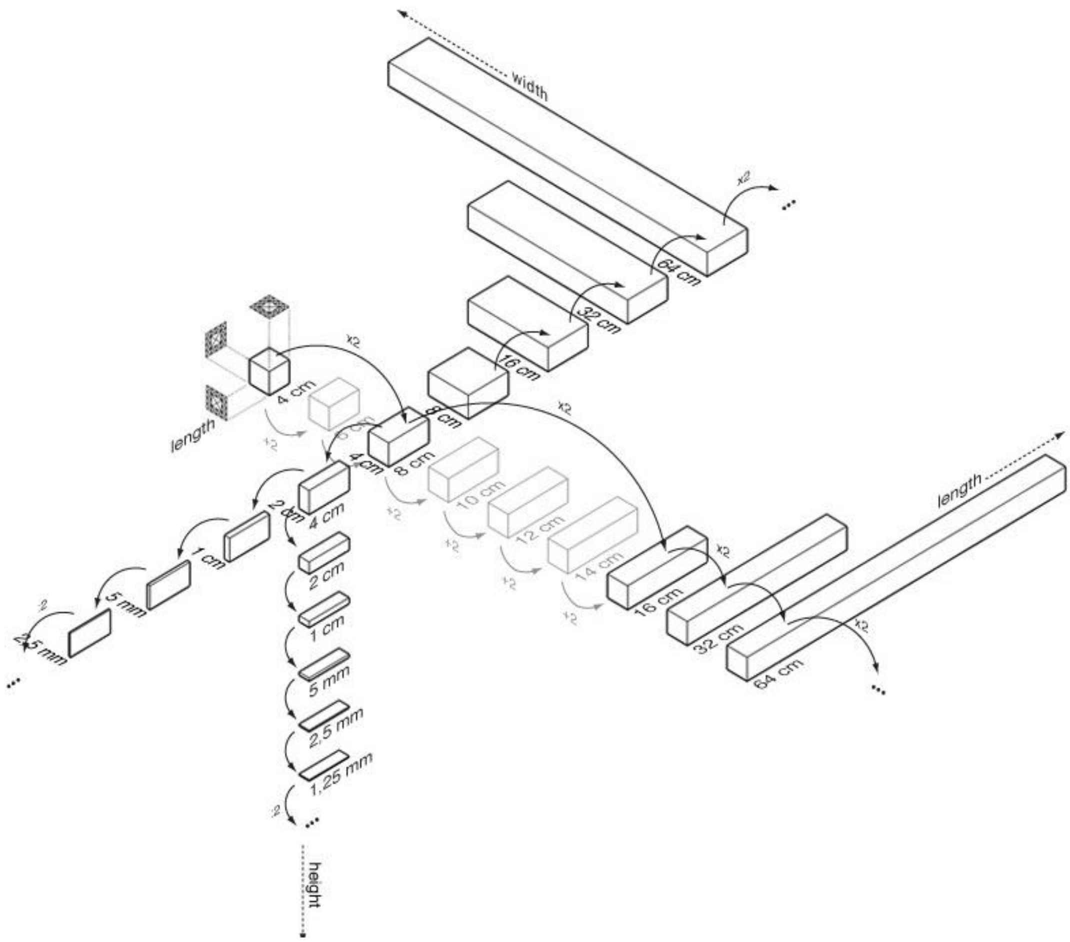


Figure 3.17
Length, Width and Height sequence (source: beta.openstructures.net)

3.2.8 special points of attention

This section provides some special points of attention when designing in a 'circular' way, such as advice on how the design should be made when dealing with non-reversible connection types, and advice on paints and coatings.

3.2.8.1. Non-reversible connections should be made of the same materials

In the case where a permanent connection type should be made, it is preferable that the material of the sub-components are of the same origin. This way they will have maximum potential for future recycling as one piece.

Non-reversible connections can be considered the ones, for which the subcomponents are impossible to be separated after their assembly. For instance, glued and welded connection are considered permanent.

3.2.8.2. Surface treatments should be avoided

When designing for disassembly, paint on timber elements should not be used. Most of the paintings are non-bio-degradable and they contain a high level of VOCs (Volatile Organic Compounds), hence they can be toxic at application. During manufacturing, there is a high amount of hazardous waste and toxic emissions. Nevertheless, it is non-biodegradable and it can be treated as chemical waste. Last but not least, frequent maintenance is required, e.g. re-paint every five years.

As for the metals, an important design rule for future dismantling is to try to avoid the surface coating. This stems from the fact that the recyclability of the materials is reduced, because of additional contaminants.

Source: (http://eco3e.eu/en/base/design-for-dismantling/)

3.2.8.3. Toxic Materials should not be used

Subcomponents that are made of toxic materials may not only prove harmful for the occupants of the building during its life span, but also for the workers that will handle these components after the end of the life; in the disassembly phase.

For example, extruded polystyrene (XPS) which is frequently used for insulation, contains brominated flame retardants that provide fire safety, but are very harmful to the human health when inhaled.

3.2.8.4. Documentation of elements

Being able to keep a clear documentation of all the elements and techniques that were used during the assembly is a key to having an easy and fast disassembly. Developing this 'deconstruction plan' includes (Calking, 2009):

- the 'as-built' drawings, which label the materials and connections
- a full list of all the components in the project
- materials and finishes
- connections and their way of disassembly
- 3D drawings that show the key connections deconstruction method

In the case of a unitized curtain wall, only documentation of one or two modules will suffice (depending on the amount of unique modules). Then knowing the number of the many modules, one can keep clear documentation of the total volumes, weights and costs of materials.

3.3 criteria weights

The DfD strategy with the design guidelines discussed in sections 3.2.1 to 3.2.6 which will be eventually rated for some adaptive facade concepts are shown in the black boxes of Table 3.4, and below each, the criteria, the scale of rating and their weight is provided. For the scale of rating, the minimum and the maximum are shown in Table 3.4, and the individual way of rating is analyzed in more detail in Chapter 8. As for the weight, it can be observed that each criterion has its own weight, and the sum for each disassembly strategy equals 1. The different criteria will be first rated, then multiplied with their specific weights, and a weighted sum will be given to each design guideline. The following section explains how these 6 guidelines will be given a weight factor, which is crucial for a fair final comparison.

Disassembly Criteria	Scale of rating	Weight
1. environmental impact		
overall impact (Life Cycle Assessment)	very high ——— very low	1
2. durability of the components		
life expectancy	1y. ——— 100y.	0.6
maintenance	every 1y. ——— never	0.2
resistance to wear	extremely fragile ——— extremely resistant	0.2
3. recycle/reuse potential		
end-of-life activity	landfill ——— reuse	0.8
side effects when reused/recycled	very toxic ——— 100% safe	0.2
4. reversibility of connections		
reversibility of connections	more non-reversible ——— all con. reversible	1
5. ease of (dis)assembly		
complexity of the conn. techniques	extremely complicated ——— extremely simple	0.5
accessibility of connections	completely obscured ——— completely accessible	0.5
6. speed of (dis)assembly		
amount of connections	∞ ——— 0	0.8
types of connections	≥5 ——— 1	0.2

Table 3.4. Criteria of the 6 DfD strategies, their scale of rating and specific weight

3.4 applying weight factors

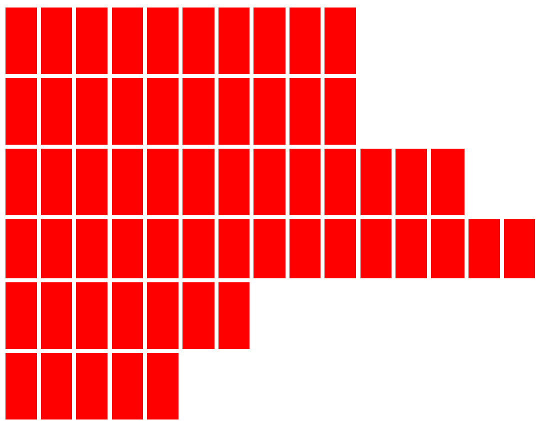
Each design guideline that was discussed has a different amount of importance in the DfD design. This is the reason why weight factors will be used. Comparing the criteria one to another is no easy task. Figure 3.18 shows the evaluation of the 6 criteria for DfD that were described in the previous section. In this scheme, a scale of 1 to 3 was used; from 1 being *less important* up to 3 being *more important*. 2 stands for *almost equally important*.

The process of this evaluation is quite simple and accurate. Each criterion (in the rows) is compared to the rest criteria (in columns), and if it is considered more important, a rating of 3 is given. If, on the other hand, it is considered less important, a rating of 1 is given. This process is done for all criteria, and in the end it results in a summed weight.

It can be easily observed that reversibility of the connections appears to be the most crucial criterion when Designing for Disassembly of facades, and the potential for reuse or recycling stands in the second place. What also stands out is the poor ranking of the 'speed of (dis)assembly' criterion, which appears to score the poorest in comparison to the rest.

However, it should be emphasized that this poor weight rating does not make it a useless criterion. This is also the reason why the number 1 is given to indicate less importance, rather than 0.

		MATERIALS			CONNECTIONS			
		environmental impact	durability of components	recycle/reuse potential	reversibility	ease of (dis)assembly	speed of (dis)assembly	weight
MATERIALS	environmental impact		2	1	1	3	3	10
	durability of components	2		1	1	3	3	10
	recycle/reuse potential	3	3		1	3	3	13
CONNECTIONS	reversibility	3	3	3		3	3	15
	ease of (dis)assembly	1	1	1	1		3	7
	speed of (dis)assembly	1	1	1	1	1		5



1: the assessed criterion is of less importance than the one compared to

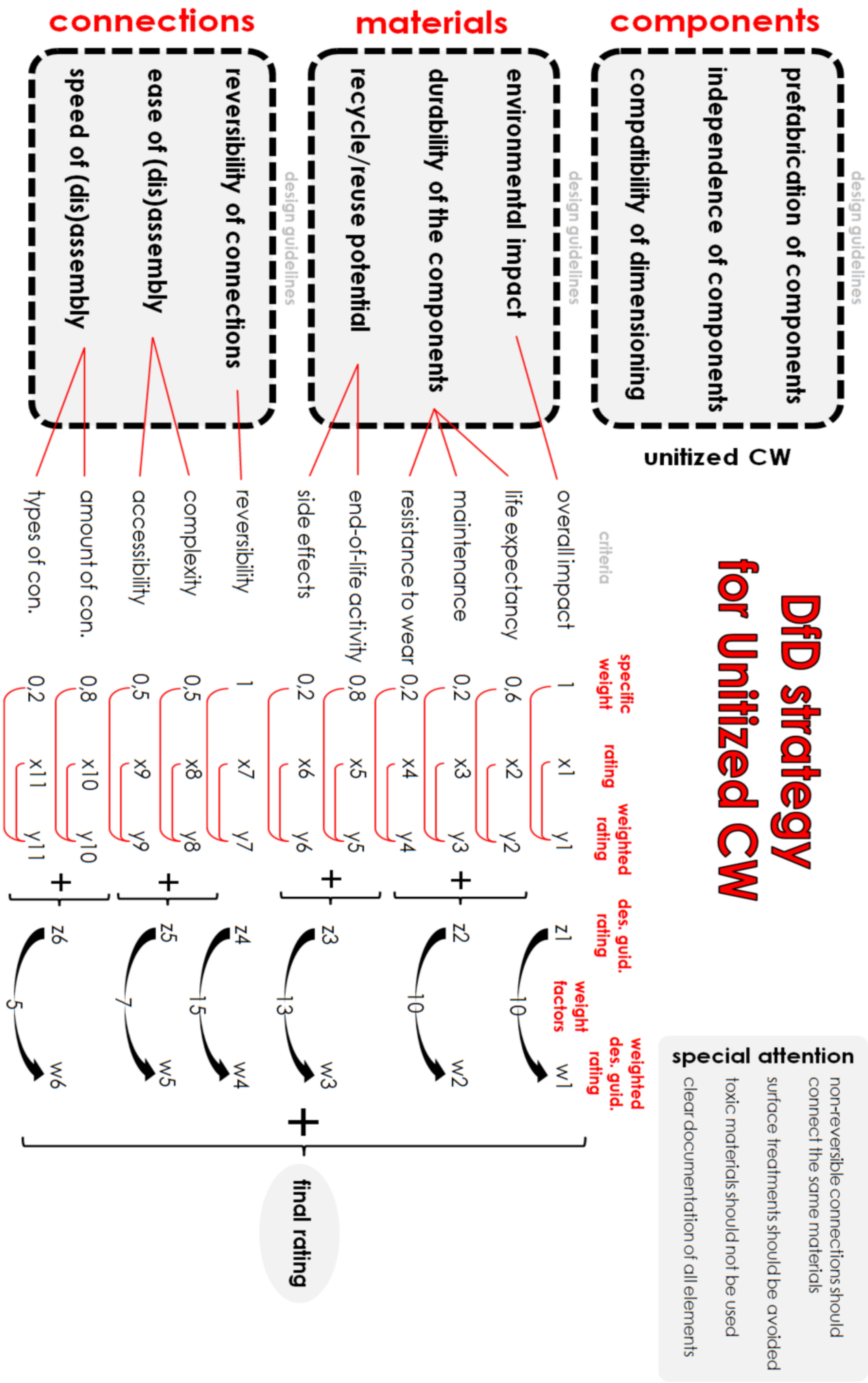
2: the assessed criterion is of about equal importance to the one compared

3: the assessed criterion is of more importance than the one compared to

Figure 3.18 Comparing the weight factors of the design guidelines (own illustr.)

3.5 the DfD strategy summarized

The summary of the whole strategy framework that was formed in this research is provided in the next scheme:



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4 ADAPTIVE BUILDING ENVELOPES

image source:
i.pinimg.com/originals

4.1 introduction and definitions

Nowadays there is a very high demand for efficiency in the building envelope due to the increasing requirements for energy use and comfort level of buildings. Having the role of the interior climate regulator, façades are highly responsible for the overall performance of a building. Climate Adaptive Building Skins (CABS) adjust in a dynamic way to the environmental changes and enable much higher level of performance in comparison to static constructions. The concept of such 'smart' building skins is not new. In fact it has already been applied many times, as it exists since the 1980s. But as years go by, more and more possibilities for the implementation of intelligent façade systems emerge.

In general, 'Climate Adaptive Building Skins' is only one of the different terms used in literature. The following are some of the other terms that can be found in the literature: dynamic, kinetic, responsive, smart, etc. Although these expressions have a somewhat different meaning, they are often used interchangeably. Figure 4.1 illustrates a number of similar terms used in literature, and their size is an approximate indicator for their frequency.

If we were to define CABS, we could say that it refers to a building envelope which 'has the ability to repeatedly and reversibly change some of its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance' (Loonen, 2013). A more detailed explanation will be provided in the following sections.

In the following section, the concept of biomimicry will be introduced, together with 3 realized examples of biomimetic buildings. Their sustainable outcomes are provided in a collective table in the end of Section 4.2. The scales of adaptation will be then mentioned, together with the physics related. Section 4.4 includes all the research that was done on daylight, heat gain and solar energy production for office buildings. In the end of this Chapter (Section 4.5), the 4 adaptive concepts will be introduced, together with their properties and a case study building for each.

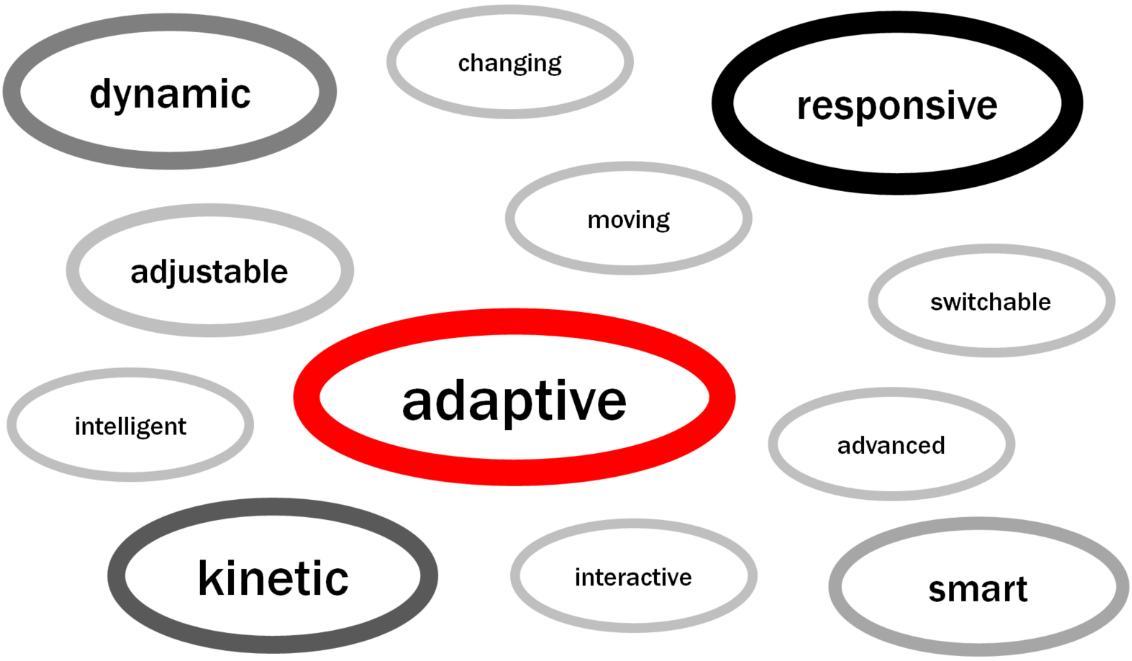


Figure 4.1 Different terms used in literature for what is usually called 'Adaptive' facade (as created by the author)

4.2 sources of inspiration & biomimicry

At this point, a famous quote from Leonardo da Vinci (Figure 4.2) needs to be stressed. He said:

'Although human ingenuity makes various inventions, it will never discover inventions more beautiful, appropriate and more direct than in Nature, because in Her, nothing is lacking and nothing is superfluous.'

Nature is one of the most prominent inspiration sources for CABS. Generally, no one can argue that adaptability is a term that goes together with nature. This is where the concept of **biomimicry** (a word taken from the Greek words: *bios* meaning life; *mimesis* meaning imitation) comes to link nature's time-tested designs to building envelope conception. The way people sweat and shiver has frequently been used as metaphor to connect the concept of the building envelope to a living membrane. This is why many concepts of CABS imitate a plant's growth/rotation as a response to an environmental stimulus. The aforementioned is called tropism. When a change occurs in response to light, the adaptation is called phototropism, while when it occurs in response to the sun, it is called heliotropism. Both of these have been successfully converted into CABS projects.

Three notable case studies of biomimetic buildings will be elaborated in this section; namely the CH2 in Melbourne, the Esplanade Theater in Singapore and the Water Cube in Beijing.

❖ The Council House 2 (CH2), Melbourne

This is a 10-storey building built in 2006 with an extremely innovative design which emulates the bark of a tree. In order to reach its sustainability objectives, the building is linked to its external environment and the living organisms that surround it. This results in a holistic response to the environment. (Radwan, 2016).

The entire building uses a biomimetic approach in many ways. Striking example is how the west facade imitates the *epidermis* of a tree thus moderating the external environment with the adaptive sun louvers (Figure 4.3), while the north and south (Figure 4.4) facades being inspired by the tree's *bronchi*, through exterior wind pipes and air ducts. As for the eastern side, it emulates the skin of a tree (the bark), by acting in a protective and filtering way in terms of light and air.

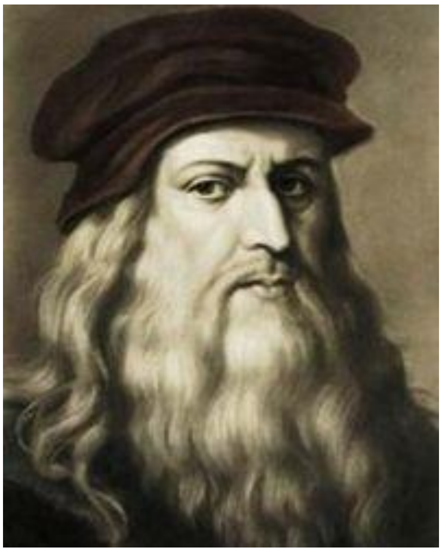


Figure 4.2 Leonardo da Vinci (source: onthisday.com)

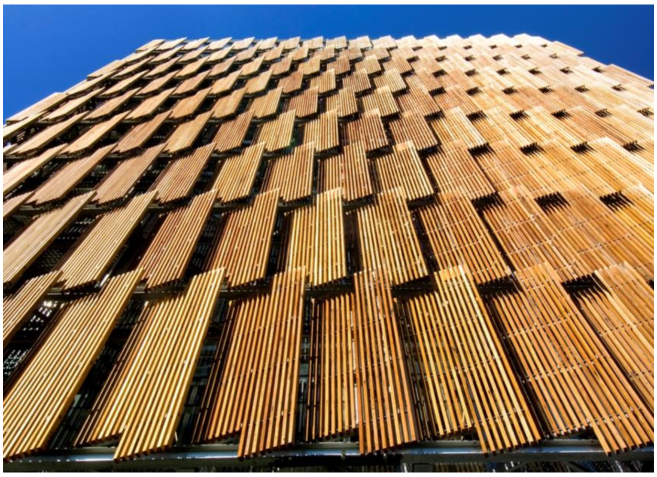


Figure 4.3 The west facade of the CH2 (source: archdaily.com)

Figure 4.4 The south facade of the CH2 (source: urbanthriving.com)

❖ The Esplanade Theater, Singapore

This 2-storey building was completed in 2007 (shown in Figure 4.5), the design of which aimed at a building that is modern but at the same time responds to its environment and culture. The building skin mimics a tropical fruit called the durian plant, shown in Figure 4.7. Just as the durian plant uses its exterior spikes to protect its inner content (its seeds), the theater uses its sun shades to protect its visitors from direct sunlight (Figure 4.6).

According to DP Architects, in order to enable nice views and counteract the strong equatorial sunlight at the same time, these triangular sun shades were deemed to be the most promising option. Due to the strongest sunlight being on the east and west sides of the building, the longest sun shades were located on these facades. The north and south sides on the other hand were designed with much smaller aluminum 'spikes'. The aerial photograph provided in Figure 4.5 shows this size variation of the shades.

Figure 4.5 The Esplanade Theater
(source: dpa.com.sg)

Figure 4.6 The inner view of the Esplanade facade
(source: dpa.com.sg)

Figure 4.7 The durian fruit
(source: ctvnews.ca)

❖ The Water Cube, Beijing

The National Aquatics Center, mostly known as the 'Water Cube', is a sporting venue that was built for the 2008 Olympics in China (Figure 4.8) and contains 5 swimming pools (Figure 4.9) and a restaurant. The inspiration of the building's form was derived by the natural formation of soap bubbles, as shown in Figure 4.10. Although appearing random and organic, the unique geometry of the structure was deemed to be buildable and highly repetitive, thus simplifying things.

As far as the building skin is concerned, its ability to divide spaces into equal cells and to cover minimal surface area of the facade are definitely two pros. But what made it special is its ability to absorb solar energy, thus achieving energy efficiency. Ethyl tetrofluoroethylene (ETFE) was the material choice for the façade, which has a weight of just 1% the weight of glass while at the same time being a better thermal insulator. It was calculated that around 20% of the solar energy would be trapped and then used for heating. (source: www.arup.com)

Figure 4.8 The Water Cube
(source: commons.wikimedia.org)

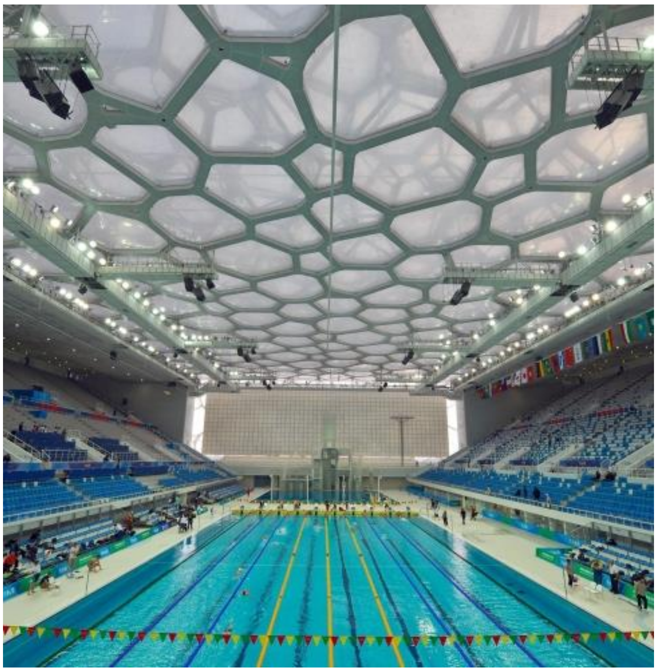


Figure 4.9 The inner impression of the Water Cube
(source: www.scmp.com)

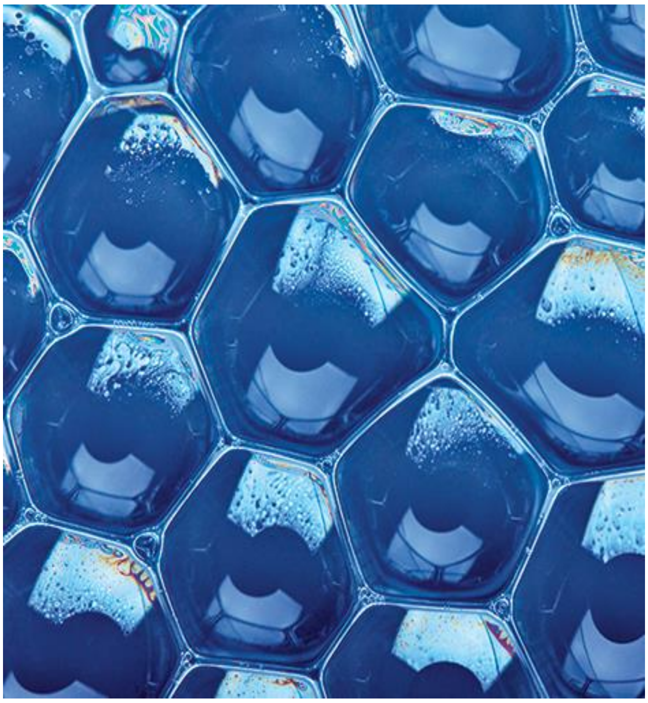


Figure 4.10 The soap bubble pattern
(source: www.nautil.us)

At this point, a collective table is formed, containing all the benefits obtained due to each of the three aforementioned biomimetic building skin designs. It can be derived from Table 4.1 that biomimicry in buildings provides a substantial improvement on energy performance and comfort, aside from other benefits, such as the prestige of an impressive and innovative building, which can attract tourists for example. The table also indicates a large variety of benefits among the different buildings discussed.

CASE STUDY		Outcome due to Building Skin design
	The Council House 2 Melbourne	• Greenhouse gas emissions are reduced • Air is filtered 100% • Natural lighting and ventilation savings up to 65% • Maximum natural ventilation • Natural environment is involved • Shading aids visual comfort • Adjustable shutters that respond to the sun position regulate heating and cooling
	The Esplanade Theater Singapore	• Comfort for users • Maximum view to the outside • Protection against heat by blocking direct sunlight • Natural lighting • Lowered HVAC levels • Desired airflow and temperature thanks to CFD
	The Water Cube Beijing	• Energy consumption was reduced up to 30% • Artificial lighting costs reduced by 55% • Energy savings by ETFE selection • 20% of solar energy is trapped and used for heating

Table 4.1 Benefits of each biomimetic case study building

4.3 scales of adaptation and physics

The adaptation of the building envelope to the environmental change can have a big range, as far as time is concerned. Some concepts have façades that may change their form every second, while others can have a seasonal adaptation which may be barely noticeable. It is safe to say that there are the following time scales:

- **Seasonal Adaptation**: This application is the most elegant of all due to the substantial performance benefits that arise from the high variation in environmental conditions in different seasons, especially in high latitudes.
- **Diurnal Adaptation**: CABS of this type can take full advantage of the 24h fixed pattern and it is most frequent when occupants are present.
- **Hourly Adaptation**: This includes CABS tracking the movement of the sun or a temperature change, and adjusting accordingly in an hourly basis.
- **Minute Adaptation**: This applies to all the adaptive facades that aim at optimizing daylight versus heat gain for energy savings and enhanced user comfort.
- **Second Adaptation**: Wind speed and direction apply to this category, where changes have a very short time frame.

Moreover, the adaptation is either based on a change of properties or behaviour in the macro-scale or in the micro-scale, but also combinations are possible.

Macro scale adaptation refers mostly to what is usually called kinetic facades. This means that a certain movement takes place, either by the facade components, or by the building as a whole. Different kinds of motion in projects have been realised, the most common of which are: sliding, rotating and folding. It is however not just the mechanical motions that can be dynamic, but also fluid movements and other flowing media. A very well-known example is the Phase Change Materials.

On the other hand, **Micro scale** adaptation takes place when the thermophysical or optical properties of facade elements change. A classic application concerns the light-transmitting properties of a material, like the switchable windows that adjust their properties to change their transparency levels.

As regards the physical parameters that are related, there are four main domains, namely thermal, optical, air-flow and electrical, as already shortly discussed in Chapter 1. These 4 domains are illustrated as ellipses in Figure 4.11. By overlapping, the aforementioned parameters create 15 different possible combinations, also called multi-physical overlaps (Loonen, 2013). Of course, there are also some other domains, such as moisture and sound, but in this research the focus will be on the thermal, optical and electrical domains, shown in a red outline in Figure 4.11. The overlap is distinguished by the letter O in the following figure.

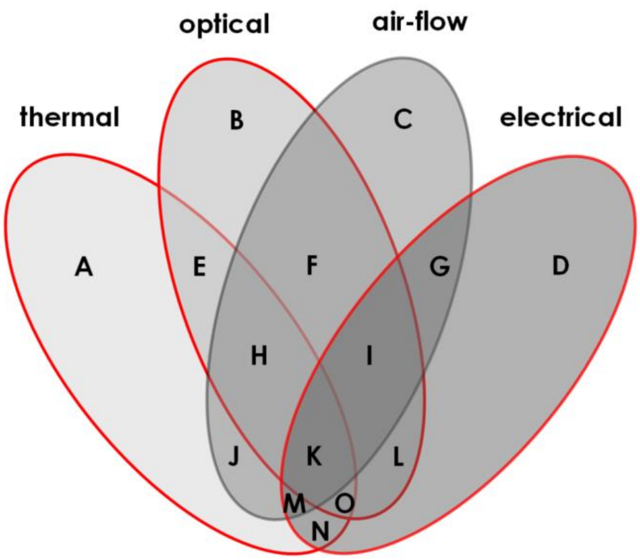


Figure 4.11 Classification of relevant physics
(adapted from: Loonen 2013)

It is also of crucial importance to mention the two different types of control of CABS; namely extrinsic and intrinsic. The **extrinsic** controlled CABS take advantage of feedback, and can adjust when necessary by using sensors, processors and actuators. These extrinsic controlled CABS are the subject of the thesis. The **intrinsic** controlled CABS on the other hand, rely on the fact that the adaptive capacity is an inherent feature of the subsystems comprising the building shell.

4.4 daylight, heat gain and energy production

In light of the physics that are relevant to the adaptive concepts of this research, as presented in the previous section, a more detailed overview will be given of what optical, thermal and electrical properties concern when designing an adaptive building envelope. These can be also named as daylight, heat gain and energy production of facades respectively.

4.4.1 Daylight

Daylight in architecture is the controlled admission of natural light, i.e. direct sunlight and diffuse skylight, into a building in order to reduce artificial lighting and to save energy. Lighting can be considered to be one of the most crucial factors that affect the interior space of an office building and helps create a visually stimulating and productive environment for anyone who works there. The way that the space is felt and perceived by its occupants is highly affected by the quality of that space's lighting. But apart from providing a more pleasant working environment, an accurate strategy for daylight can also significantly reduce the costs for electricity and heating/cooling, and should therefore be considered of paramount importance in the Zero Energy Design of buildings.

4.4.1.1 Daylight Availability

The amount of natural light available depends on both the latitude of the building site and the obstructions surrounding the building. In addition to these two, the climate also affects the daylight available. For instance, the prevailing climate conditions together with the sunshine probability and the ambient temperatures are distinct for a particular climate. A sun path analysis is necessary in order to determine the daily and seasonal arc-shaped path, which the sun follows as the earth rotates and orbits the sun. The length of daytime that we experience is affected by the sun path, which also has an effect on the amount of daylight received, for a certain season and latitude. An example of a sun path polar chart is given in Figure 4.12, which refers to any location at the latitude of Rotterdam, and Figures 4.13 and 4.14 show the seasonal difference on the sun angle from a northern mid-latitude. At this point it should be mentioned that since the winter daylight arrives at a low angle, it may be desirable to absorb this 'free' heating energy provided by the mild winter daylight.

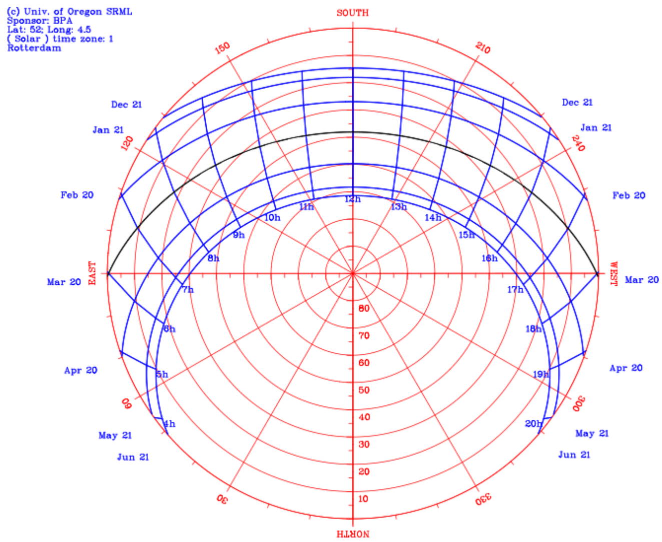


Figure 4.12 Sun path at the latitude of Rotterdam (source: www.wikiwand.com/en/Sun_path)

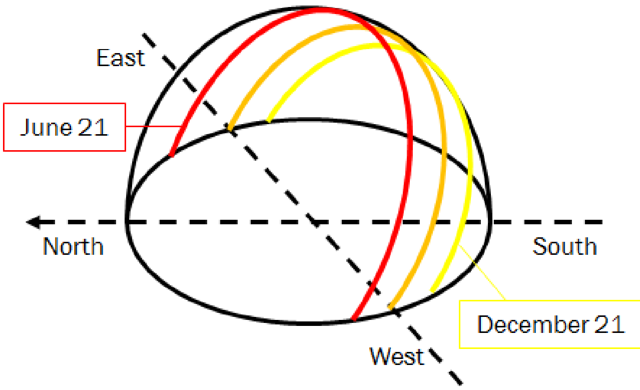


Figure 4.13 Sun's seasonal declination differences *(source: author)*

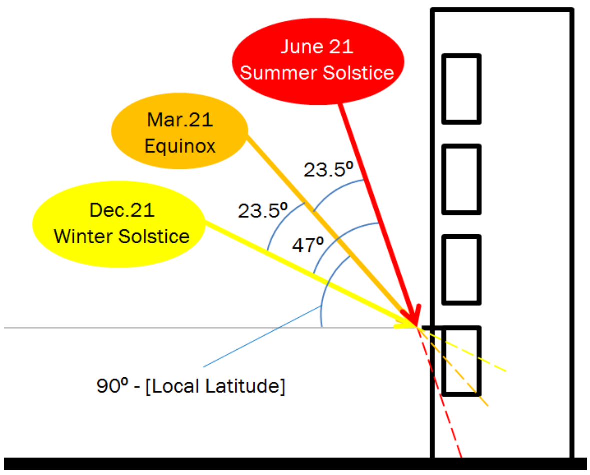


Figure 4.14 Winter daylight has 47 degrees angle difference compared to Summer daylight (own illustr.)

When it comes to high latitudes, summer and winter conditions are distinct. The daylight levels during winter are low, and therefore designers aim at maximizing the sunlight intake. The opposite is true for low latitudes, where daylight levels are high through the whole year, and thus main strategy is to restrict sunlight entering in order to prevent overheating.

4.4.1.2 Building Orientation & Obstructions

Availability of daylight is not only dependent on the latitude but also on the orientation that a building has; each orientation calls for different design solutions for façades. The design of a North-facing façade can therefore differ to a great extent when compared to the South-facing, due to the difference in sunlight.

As regards the construction site, it is common that the surrounding buildings and/or vegetation may obstruct the daylight to some extent (Figure 4.15). Therefore, the daylight potential of each façade is strongly affected by the obstructions in the construction site. When a façade is heavily obstructed, then an improvement on the distribution of light should take place via daylight-redirecting systems, such as laser-cut panels, anidolic elements, etc.

4.4.1.3 Building Form

The building form can both affect solar radiation intake and wind exposure. Depending on the shape in which the architect will choose to design the building, the amount of daylight able to enter the building can be quite different. Some examples of plan shapes for an effective distribution and use of daylight are shown in Figure 4.16. It should be noted that including an atrium can effectively cut the occupant's maximum distance to daylight in half, thus improving working conditions and the amount of natural light inside the building.

It is worth mentioning that the more compact forms (Figure 4.17) that minimize the surface area exposed to volume ratio can be ideal for extreme climates, as they gain less heat at daytime and lose less heat during the night. This comes in contrast to the efficiency for daylight design, as described in the previous paragraph. Thus the right balance must be found.

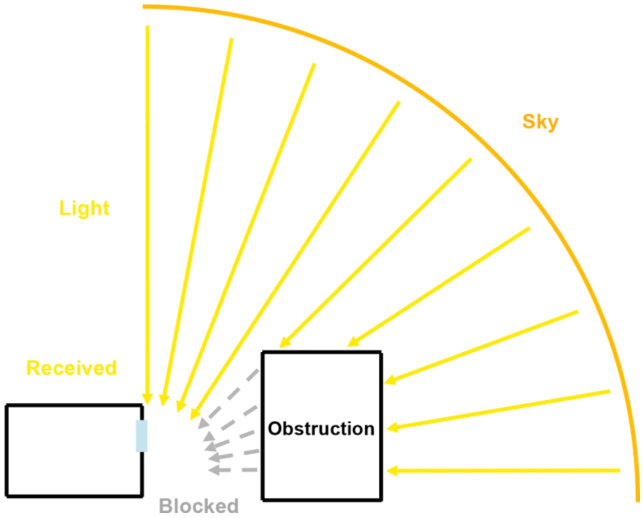


Figure 4.15 Obstruction of daylight (source: http://people.bath.ac.uk)

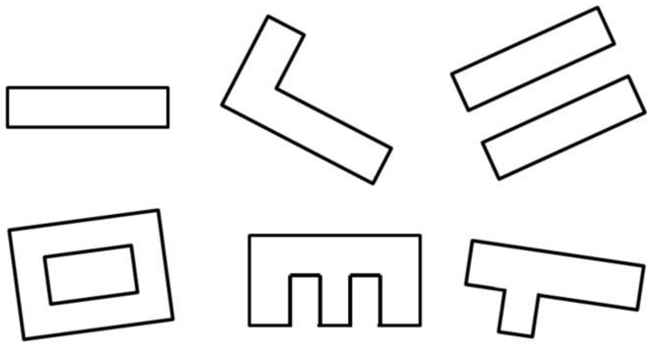


Figure 4.16 Plan shapes for more daylight distribution (own illustr.)

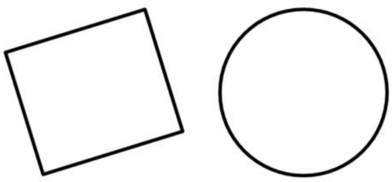


Figure 4.17 Plan shapes for less heat exchange (own illustr.)

4.4.2 Heat Gain

The heat balance of a building is highly influenced by the indoor and outdoor heat exchange that takes place every second on the facade layers. This influence of the building envelope on the energy balance of the whole building is illustrated in Figure 4.18. It is the task of the heating and cooling systems to provide the building with a comfortable indoor climate.

The building envelope is, as already mentioned, the physical separator between interior and exterior. Therefore it is the medium, via which heat gain and heat loss take place by either conduction, convection or radiation. Of course, almost always a combination of the three aforementioned heat transfer principles takes place. In the end, the total U-value of the construction is used that expresses the heat transportation. However, for the solar heat gain, the g-value is used in order to express the total amount of solar energy that enters the construction.

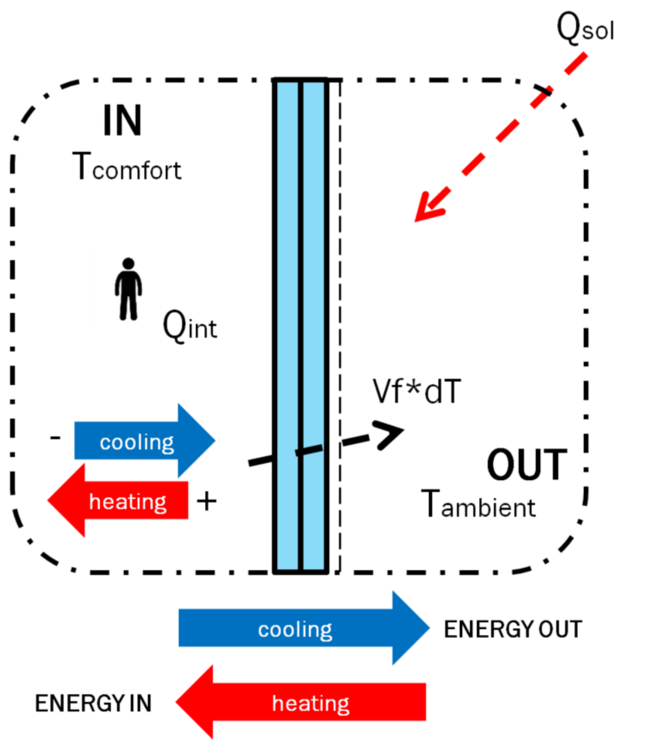


Figure 4.18 Heat exchange through the building envelope (own illustration)

4.4.3 Energy Production

As far as solar energy production is concerned, it is achieved through Building Integrated Photovoltaics (BIPV). There are various technologies nowadays, like Monocrystalline, Polycrystalline and Thin film, with different amounts of efficiencies (Figure 4.19).

There are some solar energy variables, like the azimuth angle, the tilt angle and the sun path. The latter was discussed in Section 4.4.1.1. As for the former two, a short description will be provided here.

The photovoltaic system orientation should be based on the **azimuth angle**, which is the compass direction where daylight comes from. Both the horizontal direction of the sunlight and the reference plane (either South or North) determine the azimuth angle, as shown in Figure 4.20A. The sun faces the south directly at solar noon in the northern hemisphere, while the opposite is true for the southern hemisphere. Throughout the day, there is a variation in the azimuth angle.

The tilt angle, or inclination, is basically the angle of the elevation of the sun (Figure 4.20B). In other words, it is the angle between the height of the sun and the horizontal. This angle is equal to 0 degrees at sunrise and equal to 90 degrees during noon.

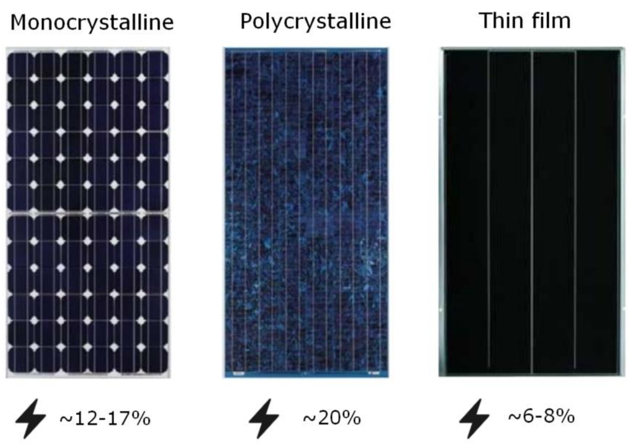


Figure 4.19 BIPV Technologies and their efficiencies (own illustration)

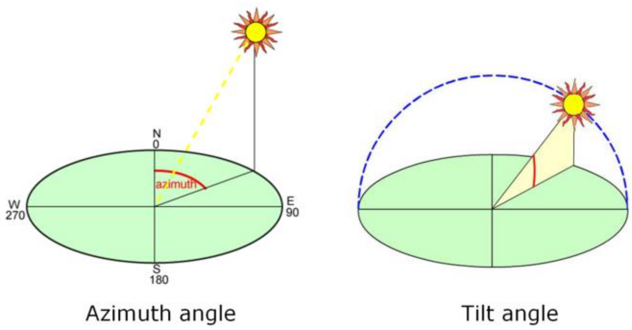


Figure 4.20 A) Azimuth angle B) Tilt angle (source: Invisible Photovoltaics, 2015)

As mentioned, there is an obvious variation of the tilt angle during the daytime. It is dependent however on the time of the year and the latitude of the specific location of the application. The scheme on Figure 4.21 shows the dependency between efficiency and azimuth and tilt angle.

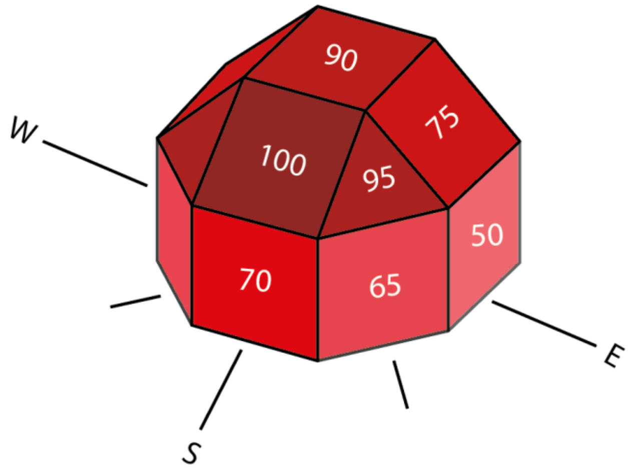


Figure 4.21. Efficiency – Orientation Cube (own illustration)

4.4.3.1 BIPV applications

Integration on the building envelope can usually take place on one of the following 3 different places:

A. **Cladding** (no transparency – good efficiency)
B. **Glazing** (good transparency – bad efficiency)
C. **Shading** (transparency depends on the technology used – highest efficiency, especially when shading is adjustable)

These are illustrated in Figure 4.22, where a realized example building is shown for each different case, and the two most important properties (transparency and efficiency) are rated by using a colour; green being the top performance indicator and red the worst. If a quick conclusion could be drawn from this diagram, this would be that the adjustable application on the exterior solar shading system of the third case appears to perform best in terms of efficiency, while also providing some transparency, while for the other two buildings, only one of the two properties is .

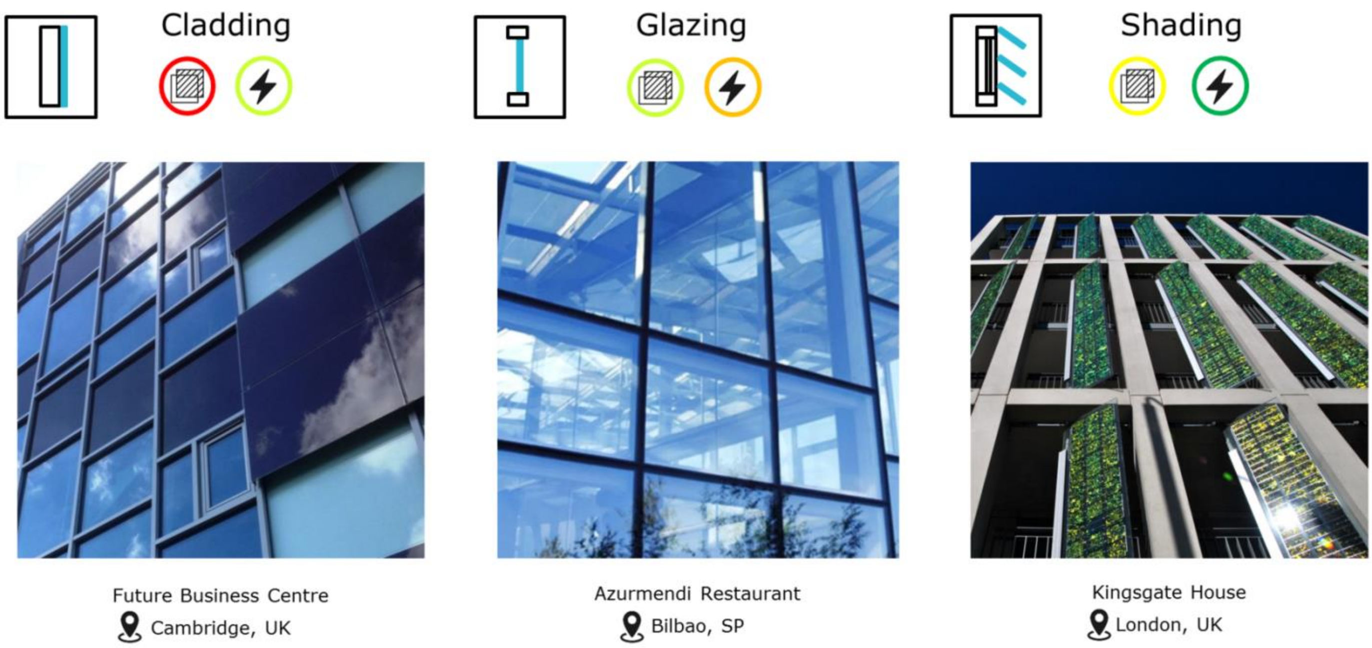


Figure 4.22 Comparison of 3 different BIPV applications (own illustration)

4.5 the 4 adaptive concepts

Trying to come up with a new design of a successful adaptive facade is no easy task. This research focusses on applying existing concepts of adjustable exterior shading into the circular and unitized facade design. This is why 4 adaptive designs will be discussed, the energy performance of which will not be the focus of this thesis. This section provides a short description of the basic principles behind each of the 4 concepts, together with a case study building, where such a facade was implemented in the past.

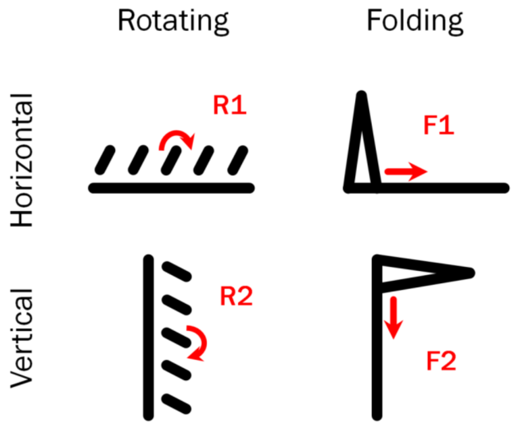


Figure 4.23 The 4 adaptive concepts (own illustr.)

As shown at the right part of the page in the scheme of Figure 4.23, there is a rotating and a folding concept both in horizontal and vertical direction each, comprising a total of 4 modular design ideas. These imply movement of the solar shading devices on the exterior of the construction. So for example A1 is the concept of vertical fins rotating through the vertical axis for a horizontal adaptation, while A2 stands for horizontal fins rotating vertically. More detailed explanation will be provided further on in this section, and an elaborate indication of the different subcomponents is given in Chapter 5.

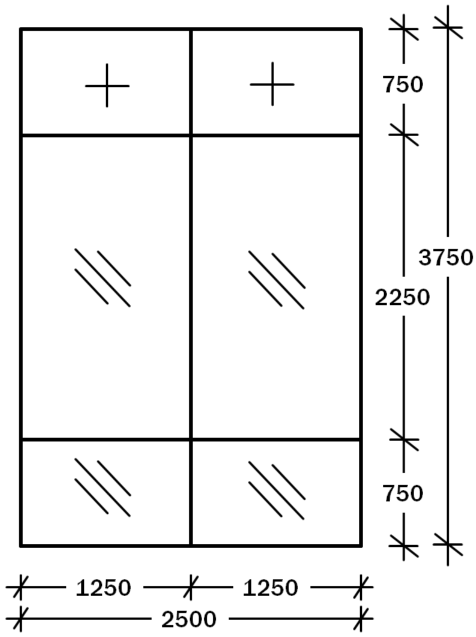


Figure 4.24 The typical module dimensions (own illustr.)

The application of the 4 designs was done on the CCN building in Brussels, where the office grid has the dimensions as presented in Figure 4.25. The dimensions of each module were also taken based on the building design of the CCN and are shown in Figure 4.24. It can be observed that the top panels are indicated with a cross, which means they are 'closed', in order to hide the floor level and the services, while the rest of the panels are 'open', meaning they are glazed. These are the ones that primarily need to be shaded on the exterior.

The research entails a comparison between 4 different concepts for 2 different Curtain Wall materials each, comprising a total of 8 adaptive concepts. Since this is a comparative study, the exact dimensions may not seem of primary importance but using the same scheme for all concepts will give a good estimation for the comparison, as described in Chapter 7, in which the Life Cycle Assessment is performed.

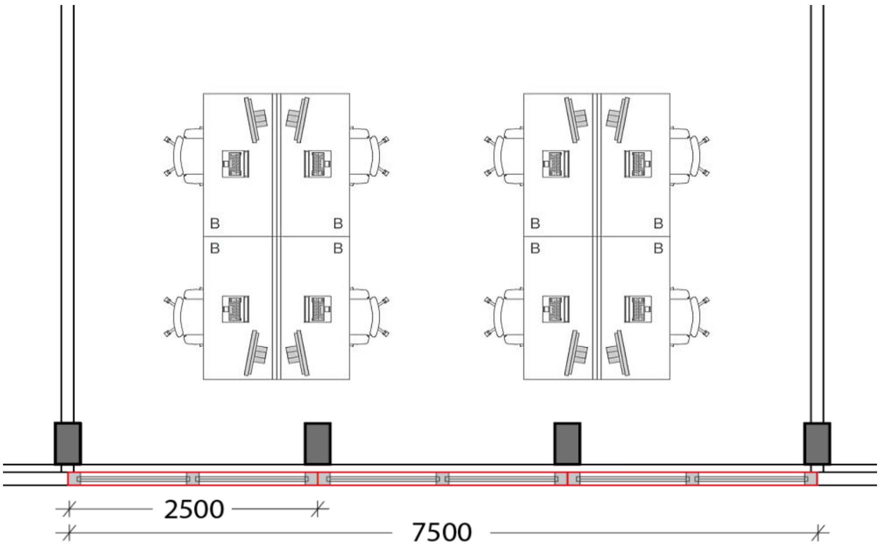


Figure 4.25 The office grid dimensions

ADAPTIVE CONCEPT R1 – Vertical Rotating Fins

Description of the system mechanism:

This first adaptive concept is based on the rotation of the vertical fins (also called louvers), which adapt to the sun angle, depending on the time of the day and the season of the year (see Section 4.4.1.1 Daylight Availability). This can result in an adequate blocking of the direct sunlight, which is usually not desirable during summer, due to the overheating it may cause inside the office. This can decrease the energy used for cooling the building (Figure 4.27). At the same time energy production can be achieved through the BIPV applied on the shading, especially when the sun angle is low (usually in **east** and **west** for the 'hot' period) in order to have a better angle and therefore a better efficiency.

On the other hand, winter sun may be welcome to enter the building, because of the 'free' heating it can provide (Figure 4.27). This way, the energy and costs used for heating can be significantly reduced, especially in cold but sunny days. As far as energy production is concerned, this is much lower during winter compared to summer, because when sun is present, it is much smarter to let it enter the building instead of stopping it with the PV fins. It is also due to the fact that daylight during winter is weaker compared to the strong summer sun.

As far as the hourly adaptation is concerned, the position of the sun each time of the day defines the angle which the blinds have. This is depicted through the examples in Figures 4.28 and 4.29, where the sun needs to be blocked during summer but it can be allowed to enter and provide a constant heating during the winter months. It should be emphasized however, that sometimes direct sunlight in office buildings is undesirable no matter what the season is, because it causes glare.

Figure 4.26 shows a 3D impression of the adaptive concept R1, with the vertical fins rotating through the vertical axis. In this figure, the basic elements of the module are indicated. As already mentioned, no dimensions are shown in the figures since the structural and energy performance are considered to be redundant.

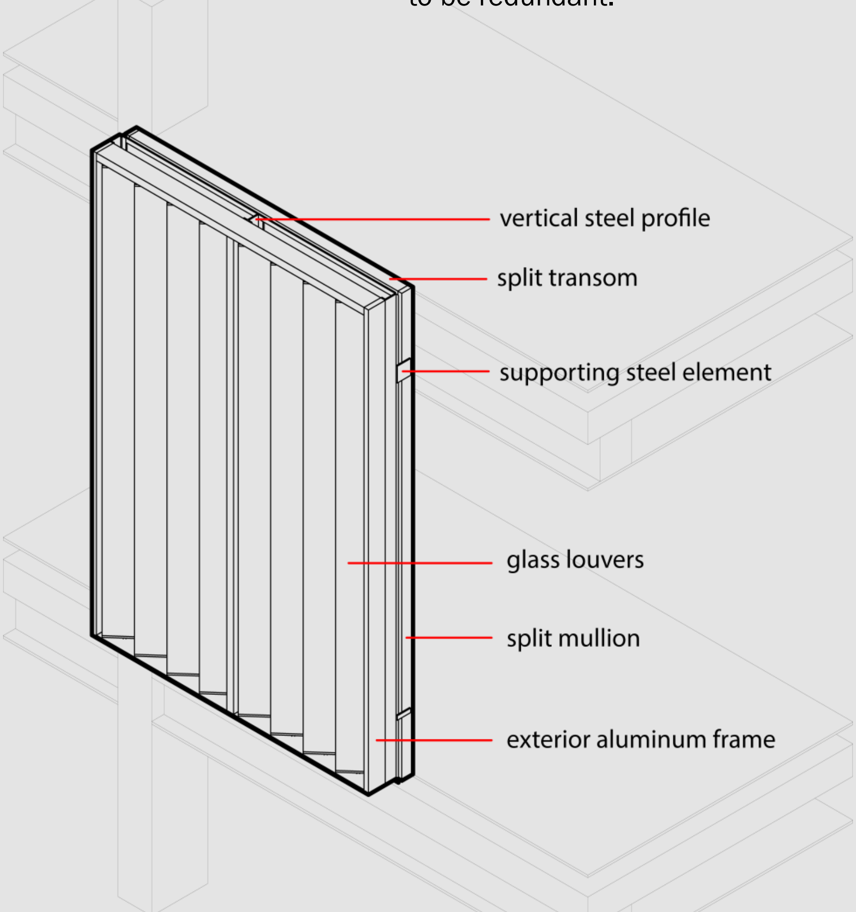


Figure 4.26 Concept R1 (own illustration)

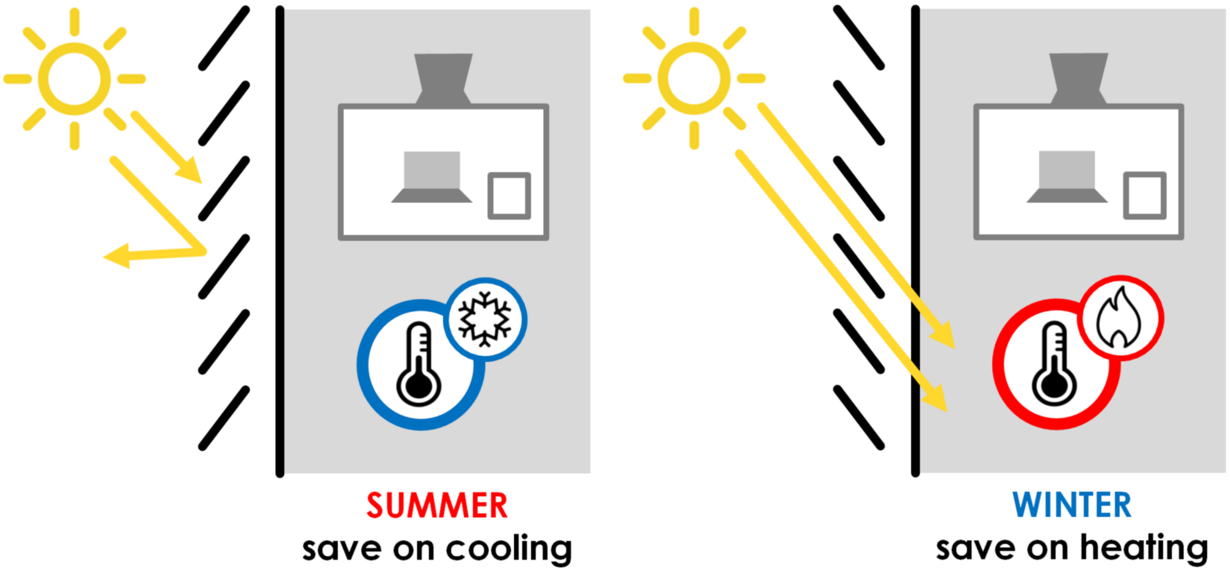


Figure 4.27 Seasonal Adaptation of the Adaptive Concept R1 (own illustration)

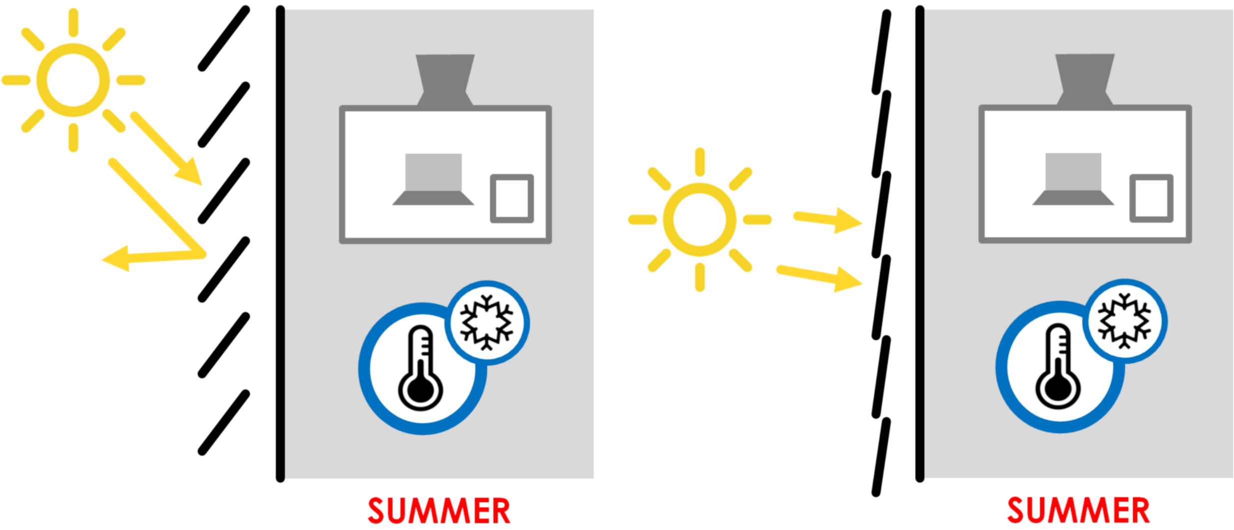


Figure 4.28 Hourly Adaptation of the Adaptive Concept R1 during Summer (own illustration)

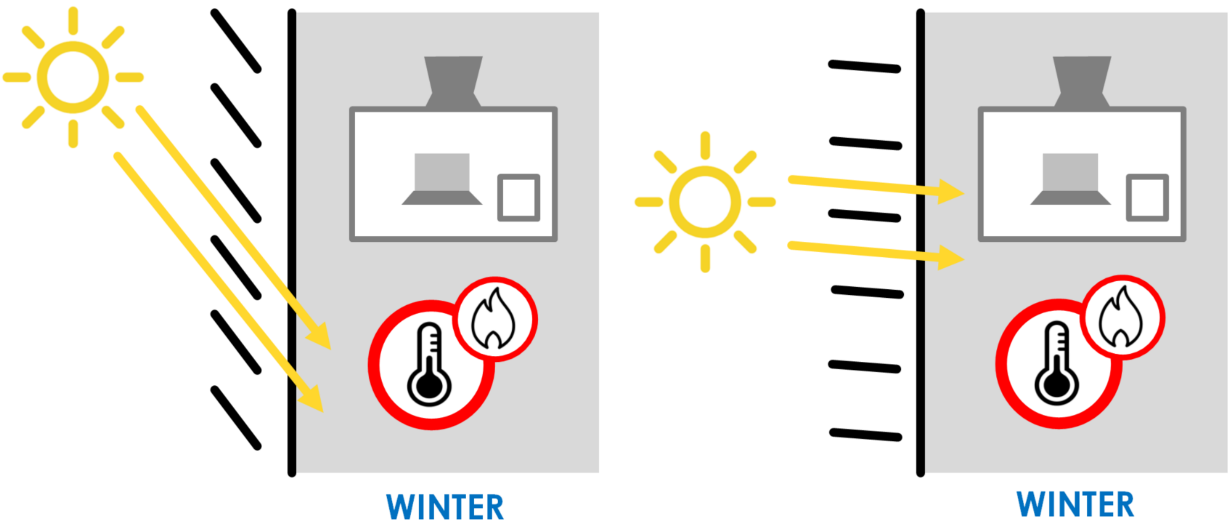


Figure 4.29 Hourly Adaptation of the Adaptive Concept R1 during Winter (own illustration)

The SwissTech Convention Center's location is in the northern part of the École Polytechnique Fédérale de Lausanne (EPFL) and it's a relatively new building (2014) for the campus which includes housing, retails and service areas and a hotel. The expressive identity of this building makes it unique. Its aluminium roof creates a strong contrast with the light glass facade, as shown in Figure 4.30.

Figure 4.30 The SwissTech Convention Centre (source: www.richterdahlrocha.com)

The PV installation on the west facade of the building (Figure 4.31) was realized with the financial support of a local electricity provider resulting in 200 m² of photovoltaic area, a total of 355 panels. Panels of different height were produced in order to fit the roof inclination, and a total of 65 columns of coloured photovoltaics were installed, thus meeting the aesthetic ambitions and energy demands of the designers.

Figure 4.31 The SwissTech Convention Centre facade (source: www.richterdahlrocha.com)

The architects had set a light transmission target, and it was successfully met, thanks to the coloured and transparent panels. Arranging the colours in an ingenious way, artist C. Bolle shaped a special dynamic on the facade, while at the same time giving a very smooth tone of colours inside the hall, as it can be observed in Figure 4.32.

But most importantly, the 2 aims were eventually achieved:

- passive prevention of the entrance hall from overheating due to direct sunlight
- active production of renewable energy from daylight

The PV modules which were applied, had multi-colored dye-sensitized solar cells (Grätzel cells), and the energy produced is 2000 kWh/year.

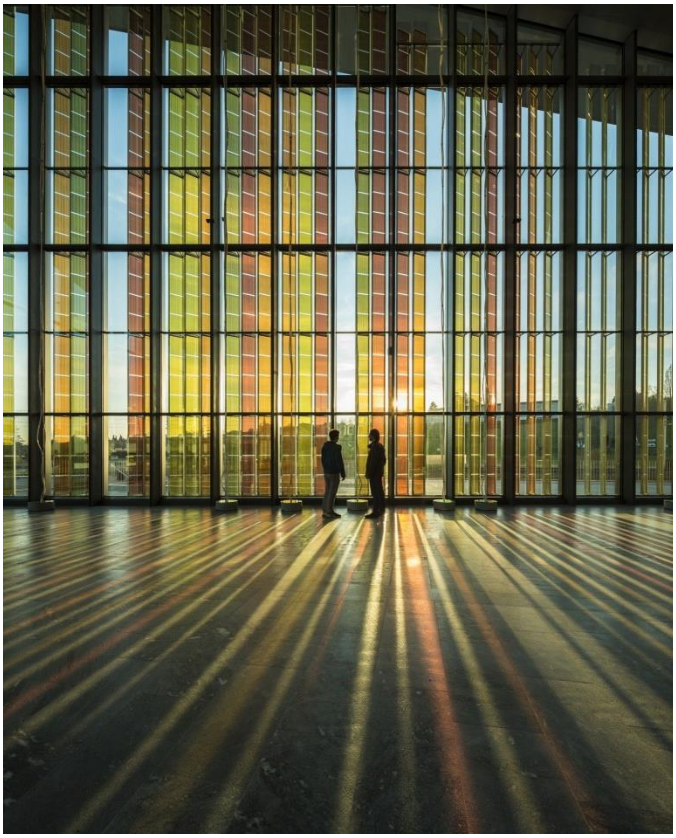


Figure 4.32 The SwissTech Convention Centre as seen from the inside (source: ArchDaily)

ADAPTIVE CONCEPT R2 – Horizontal Rotating Fins

Description of the system mechanism:

This second adaptive concept is based on the rotation of the horizontal louvers, which adapt to the sun angle, just like the previous concept, depending on the time of the day and the season of the year. This, again, rotates – but on the horizontal axis now - to block part or all of the direct sunlight, which is undesirable during a hot summer, due to the overheating that may be caused inside the office. This, of course, decreases the energy used for cooling and at the same time energy production can be achieved through the photovoltaics applied on the shading, especially when the sun angle is high This occurs mainly in the **south** orientation for the 'hot' period. When winter comes, sun is more welcome to enter the building, due to the 'free' heating it can provide. Just like the previous concept A1, the energy and costs used for heating can be significantly reduced, especially in cold but sunny days. Figure 4.34 illustrates this seasonal adaptation.

As far as energy production is concerned, this may be significantly lower during winter compared to summer, because when sun is present, it is much smarter to let it enter the building instead of stopping it with the PV fins. It is also due to the fact that daylight during winter is weaker compared to the strong summer sun. It is worth mentioning that sometimes direct daylight may not be desirable due to the glare it may cause, especially in offices where people may work close to the facade.

As regards the hourly adaptation, the blinds track the sun position throughout the day. This is depicted through the examples in Figures 4.34 and 4.35, where the sun needs to be blocked during summer but it can be allowed to enter and provide a constant heating during the winter months. It should be emphasized however, that sometimes direct sunlight in office buildings is undesirable no matter what the season is, because it causes glare.

Figure 4.33 shows the adaptive concept R2, with the vertical fins rotating through the horizontal axis. This figure illustrates the basic elements of the module. Again, no dimensions are provided due to the lack of exact structural analysis of the exterior shading system.

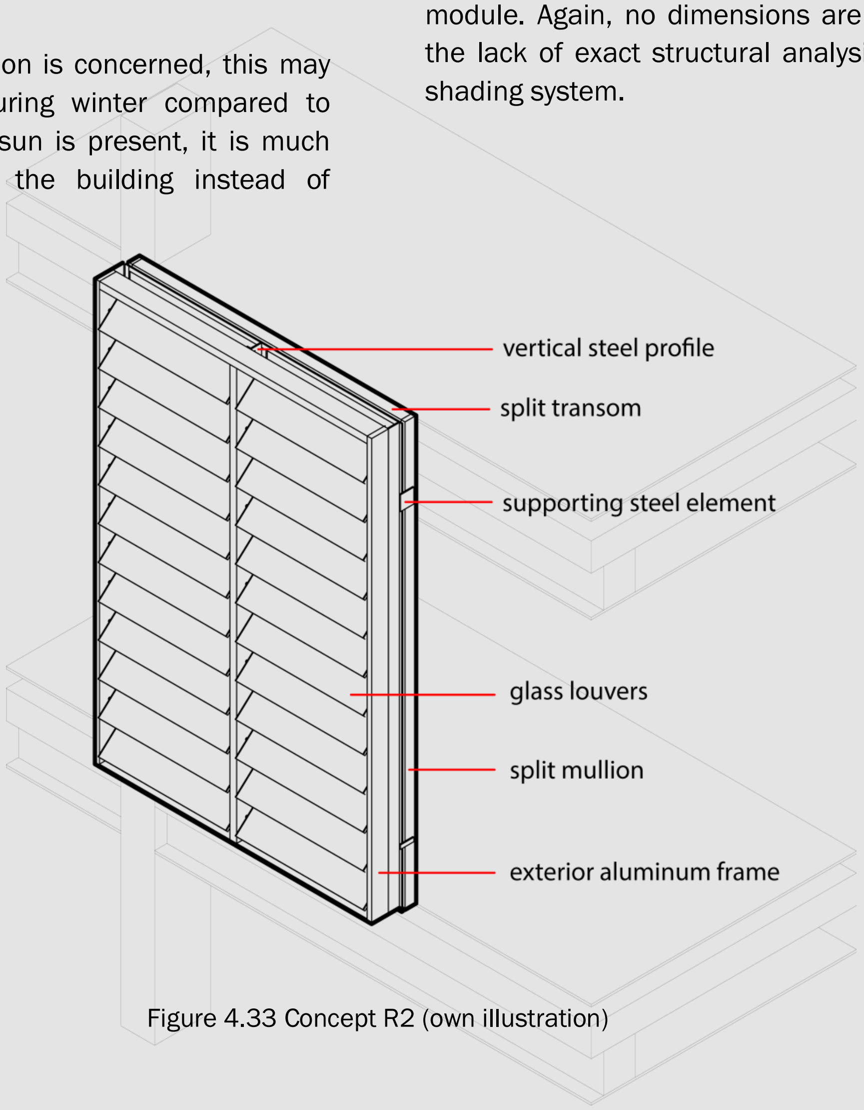


Figure 4.33 Concept R2 (own illustration)

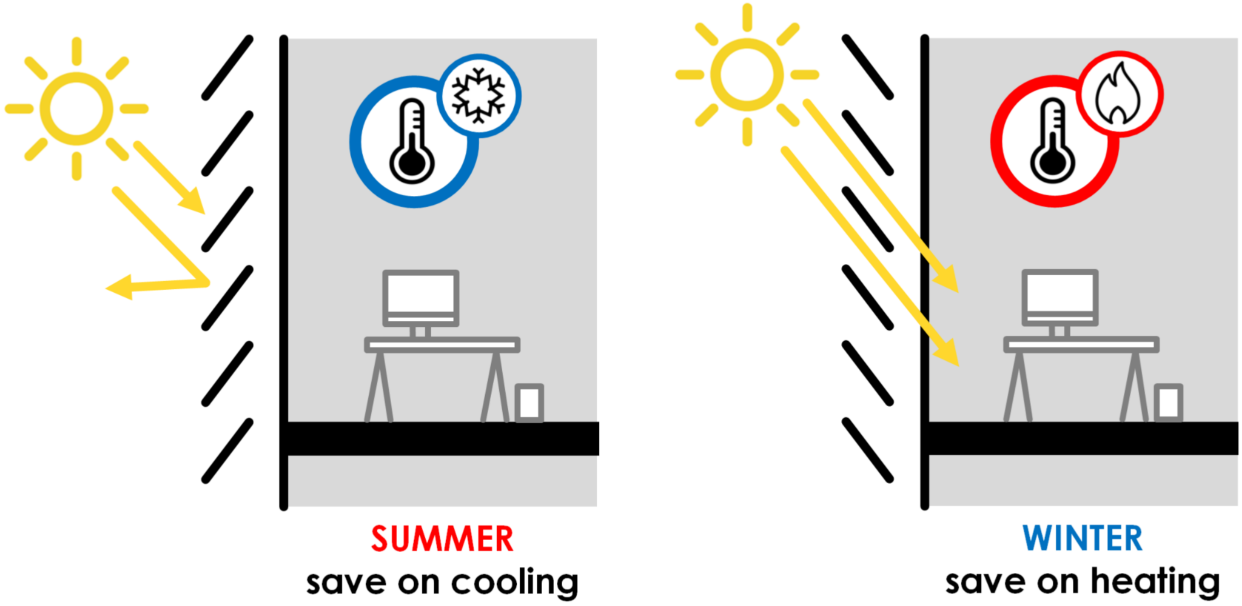


Figure 4.34 Seasonal Adaptation of the Adaptive Concept R2 (own illustration)

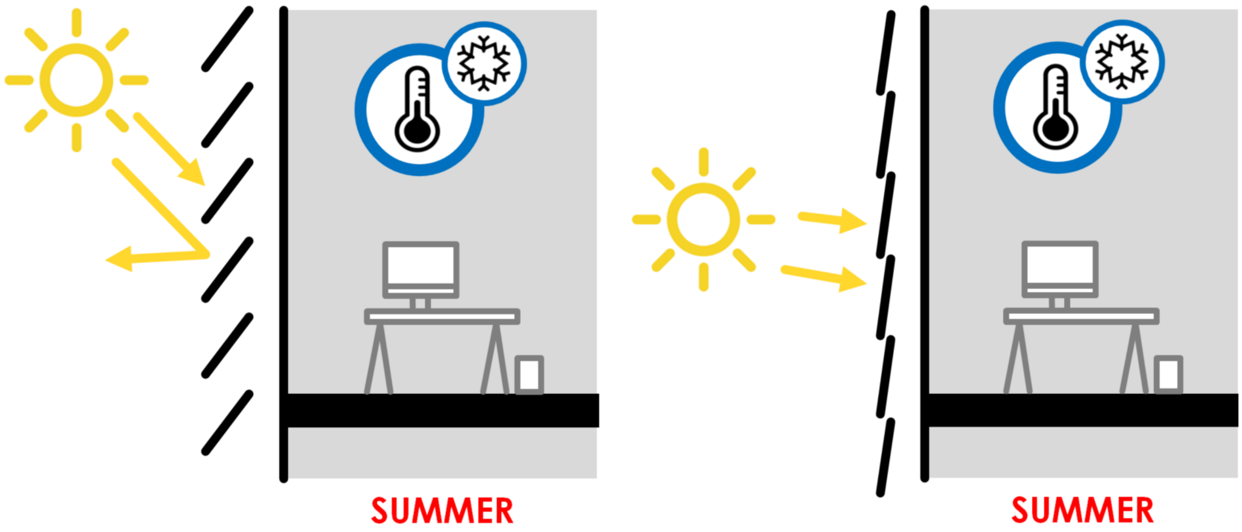


Figure 4.35 Hourly Adaptation of the Adaptive Concept R2 during Summer (own illustration)

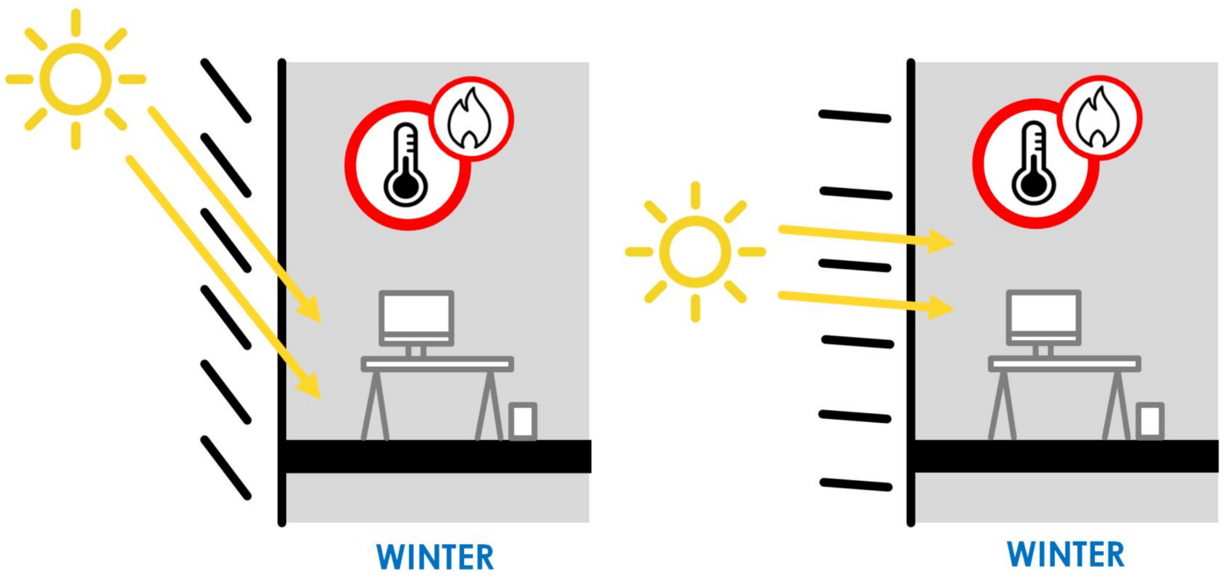


Figure 4.36 Hourly Adaptation of the Adaptive Concept R2 during Winter (own illustration)

This building was designed as a demonstration of what the new 'Green' technologies are for buildings and how they can be applied in practice. Decreasing energy consumption was not the only goal of the building design, as it also focused at embodied energy of materials and many different emissions (CO2, SO2, NO, methane, etc.). A good view of the BRE building 16 is shown in Figure 4.37.

Figure 4.37 BRE Building 16
(source: fcbstudios.com)

In order to optimize solar control, an exterior shading system with louvers was used, which allows maximum daylight with minimum glare. These louvers, shown up-close in Figure 4.38, are coated with a translucent ceramic material which filters the direct sunlight while a big part is reflected. The louvers move depending on the sun position (hourly and seasonal adaptation) and can be controlled through an automated system which can also become remote if necessary. The orientation, in which the louvers were designed, enables minimum view obstruction in either seated or standing position.

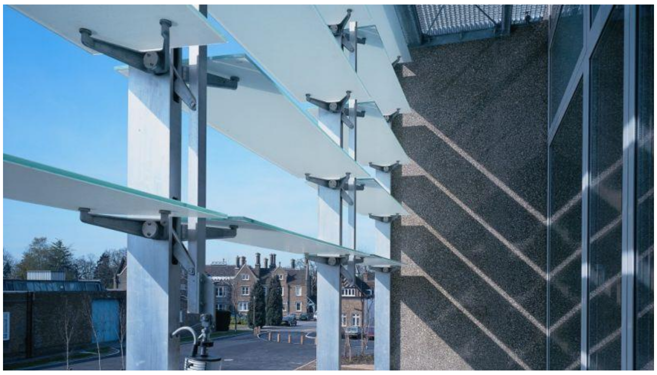


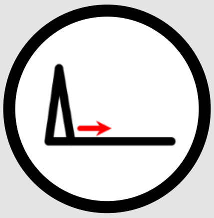
Figure 4.38 The shading system of the BRE Building 16
(source: www.coltinfo.co.uk)

When direct sunshine is bearable, the louvers can take an angled position to act as 'light shelves'. This means that they reflect sunlight onto the ceiling of the office, thus reducing the artificial lighting necessary to provide a bright office space, especially further inside from the facade (Figure 4.39).

Figure 4.39 The inner impression of the BRE Building 16
(source: www.feildenclegg.com)

As far as the lighting and electrical systems are concerned, the building uses TL5 fluorescent light that is more energy efficient than the normal tube, and just one fifth of the mercury is used. A bright workplace was eventually the result of the high amount of diffuse light that was reflected by the ceiling, providing 300lux. All these systems are powered by the building integrated photovoltaics (BIPV), which are applied on the facade of the building. The computer installed in the building can control the power, and inform the occupants how much of the power is used in relation to the total consumption.

ADAPTIVE CONCEPT F1 – Horizontally Folding Panels



Description of the system mechanism:

When referring to a foldable technique for exterior shading systems, there should always be a steady fixed point, a hinged connection and a sliding part that combine altogether in order to adapt to the sun angle, like the previous two concepts, depending on the time of the day and the season of the year. As can be seen in Figure 4.40 the panels fold horizontally in the same direction for all modules, and should be carefully placed to the facade that gets sunlight mainly from an angle throughout the day, in order to avoid being closed most of the time thus hindering the view from inside the office. This is why the southern direction would not seem appropriate for such a design, whereas **east** and **west** appear to be much more suitable for this application.

The system works in a somewhat similar way to the rotating fins concepts, in the sense that it adapts to the position of the sun in order to either block or allow daylight to enter the building. So, again, overheating may occur in case the daylight enters during a hot summer day, and that's why the shutters should unfold to block the sun to prevent such a situation. This also results in a reduced energy consumption because of less need for cooling (Figure 4.41). At the same time, photovoltaics integrated in the shading system can produce significant amounts of energy by adapting to achieve a good angle to the sun throughout the day. In the cold months, sun can enter the building to provide the necessary and 'free' heating, thus decreasing the need for extra heating and contributing to the overall decrease of the energy consumption.

As far as the hourly adaptation is concerned, the position of the sun each time of the day defines the angle which the foldable shutters have. This is depicted through the examples in Figures 4.42 and 4.43, where the sun needs to be blocked during summer but it can be allowed to enter and provide a constant heating during the winter months.

As far as energy production is concerned, it can be considered to be much lower during winter compared to summer, due to the fact that sun presence means folding to allow it to enter the construction, rather than being blocked. It is also due to the fact that daylight during winter is weaker compared to the strong summer sun. Figure 4.40 illustrates the adaptive concept B1, with the vertical panels folding and sliding in the horizontal axis. This figure indicates the basic elements of the module.

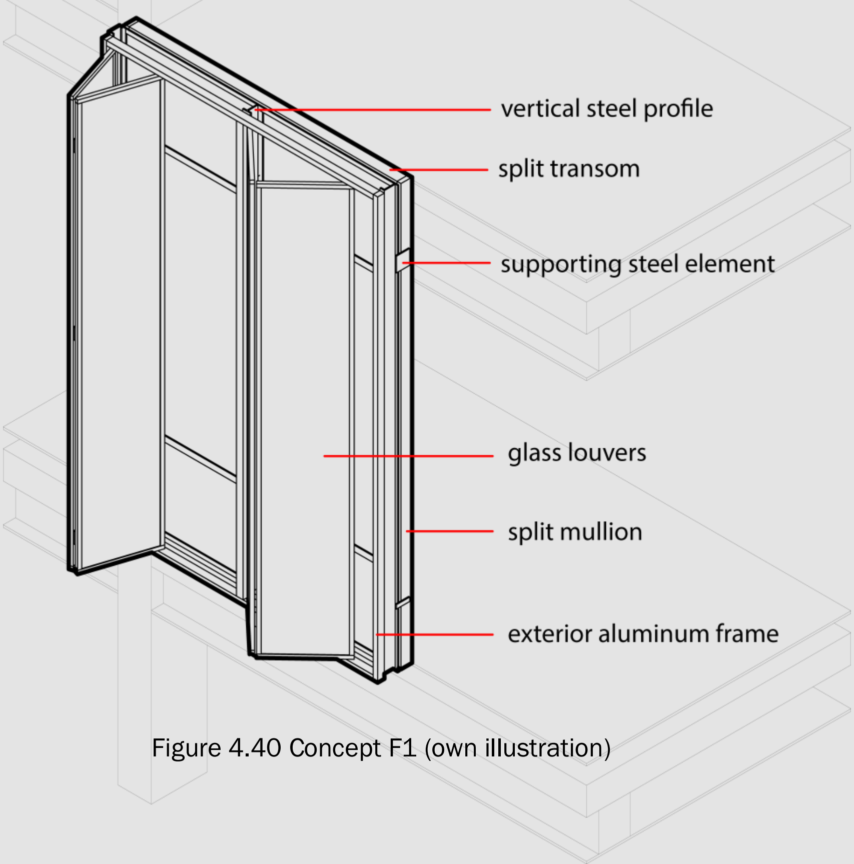


Figure 4.40 Concept F1 (own illustration)

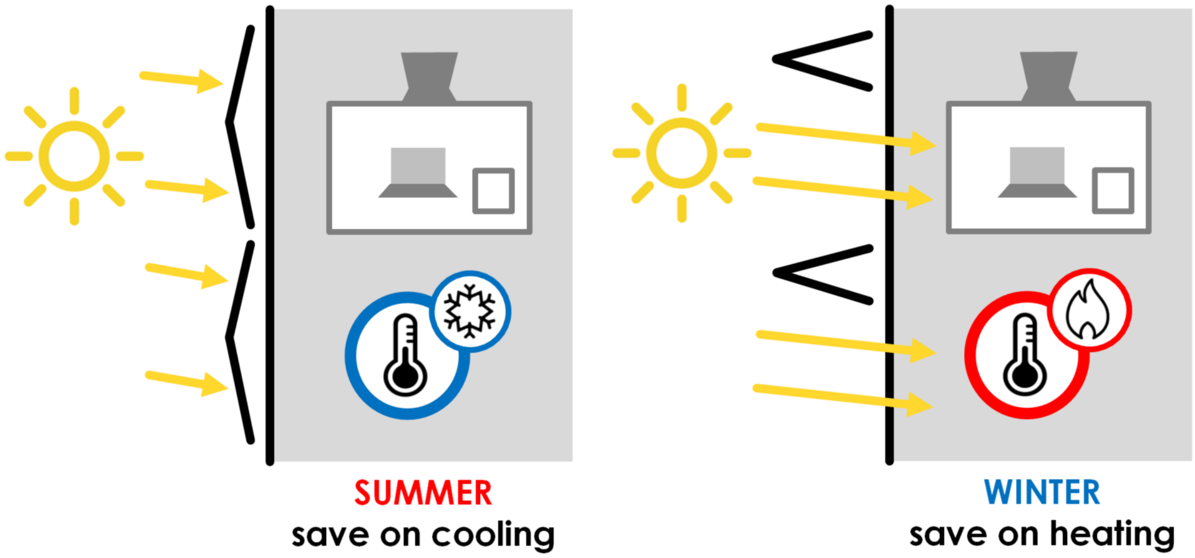


Figure 4.41 Seasonal Adaptation of the Adaptive Concept F1 (own illustration)

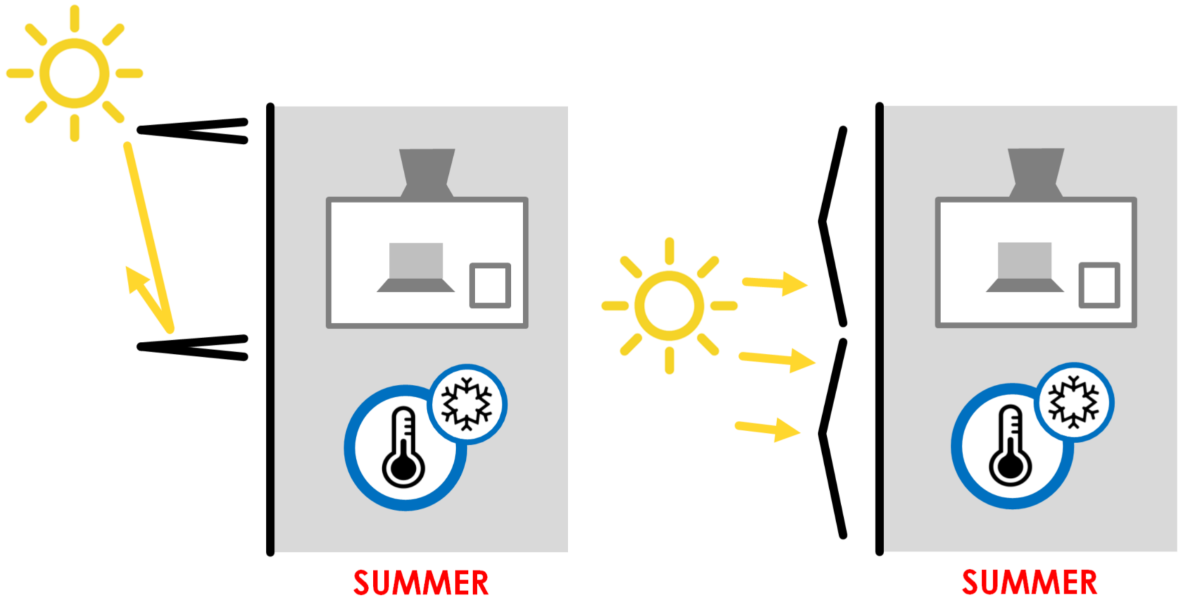


Figure 4.42 Hourly Adaptation of the Adaptive Concept F1 during Summer (own illustration)

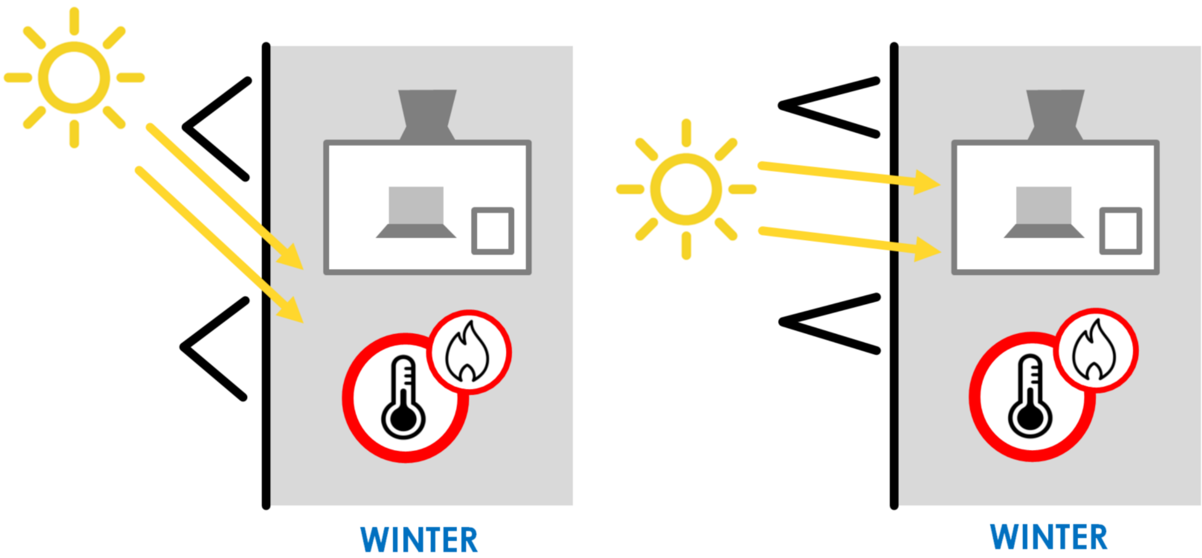


Figure 4.43 Hourly Adaptation of the Adaptive Concept F1 during Winter (own illustration)

The 45.000 m2 building for the UN (United Nations) in Copenhagen is a very sustainable design which is shaped like an 8-pointed star, as shown in the aerial photograph in Figure 4.44. This specific shape expresses the UN's essential values and authority. A lot of environmental strategies were applied in this building, with the folding solar shading being the most remarkable. Other than that, seawater was used for cooling the building and 14.000 solar panels were installed on the roof to produce energy. Eventually, the UN City was awarded platinum certification in the LEED scale – the highest grade possible.

Figure 4.44 The UN building, shaped like a star (source: www.nordhavnen.dk)

The bright facade (shown in Figure 4.45) stands out and creates a luminous contrast to the water that surrounds it (Figure 4.46). The fully glazed curtain wall is covered by an envelope which consists of 1400 shutters – approximately 3.4 m tall and 1.5 m wide – made of white perforated aluminum. These shutters shield the interior from daylight by being in constant motion throughout the day, remotely controlled by the office occupants through their computers. They can also dim the lights and close the shades when nobody uses a certain space via the computerized integrated building management system on their electronic calendars. This way, this dynamic movement of the shading transforms the UN building into a living organism.

Figure 4.45 The facade of the UN building (source: un.dk)

As far as the roof is concerned, animal-based materials compose a white reflective membrane that covers the whole roof of the building, thus decreasing the accumulation of heat. In addition, the 14.000 solar panels located in the roof produce energy of approximately 300.000 kWh/year. This makes the building almost independent, thus not relying so much on using power from the local grid.

Figure 4.46 The UN building in the evening (copyright: ADAM MØRK)

ADAPTIVE CONCEPT F2 – Vertically Folding Panels

Description of the system mechanism:

The vertically folding concept moves just like the previous concept, depending on the time of the day and the season of the year. As can be seen in Figure 4.47 the panels fold vertically and should be carefully placed to the facade that gets sunlight a high angle for the most of the day, in order to avoid being closed most of the time thus hindering the view from inside the office. This is why the **south** is the most appropriate orientation for such a design (because it receives most of the daylight at relatively high angles especially in the summer), whereas east and west appear to be less suitable for this application.

Overheating may occur in case the daylight enters during a hot summer day, and that's why the shutters should unfold to block the sun to prevent such a situation. This results, of course, in a reduced energy consumption because of less need for cooling. At the same time, photovoltaics integrated in the shading system can produce significant amounts of energy by adapting to achieve the best possible angle in relation to the sun throughout the day. During the cold months, sun can enter the building to provide the necessary and 'free' heating, thus decreasing the need for extra heating and contributing to the overall decrease of the energy consumption.

The hourly adaptation can be seen in Figures 4.49 and 4.50, where the sun needs to be blocked during summer but it can be allowed to enter and provide a constant heating during the winter months.

As far as energy production is concerned, it can be considered to be much lower during winter compared to summer, due to the fact that sun presence means folding to allow it to enter the construction, rather than being blocked. It is also due to the fact that daylight during winter is weaker compared to the strong summer sun. It is should be mentioned that direct daylight may be undesirable due to the glare it usually causes, especially in offices where people may work next to the facade. Figure 4.47 illustrates the adaptive concept B2, with the horizontal panels that fold at the horizontal axis. This figure indicates the basic elements of the module.

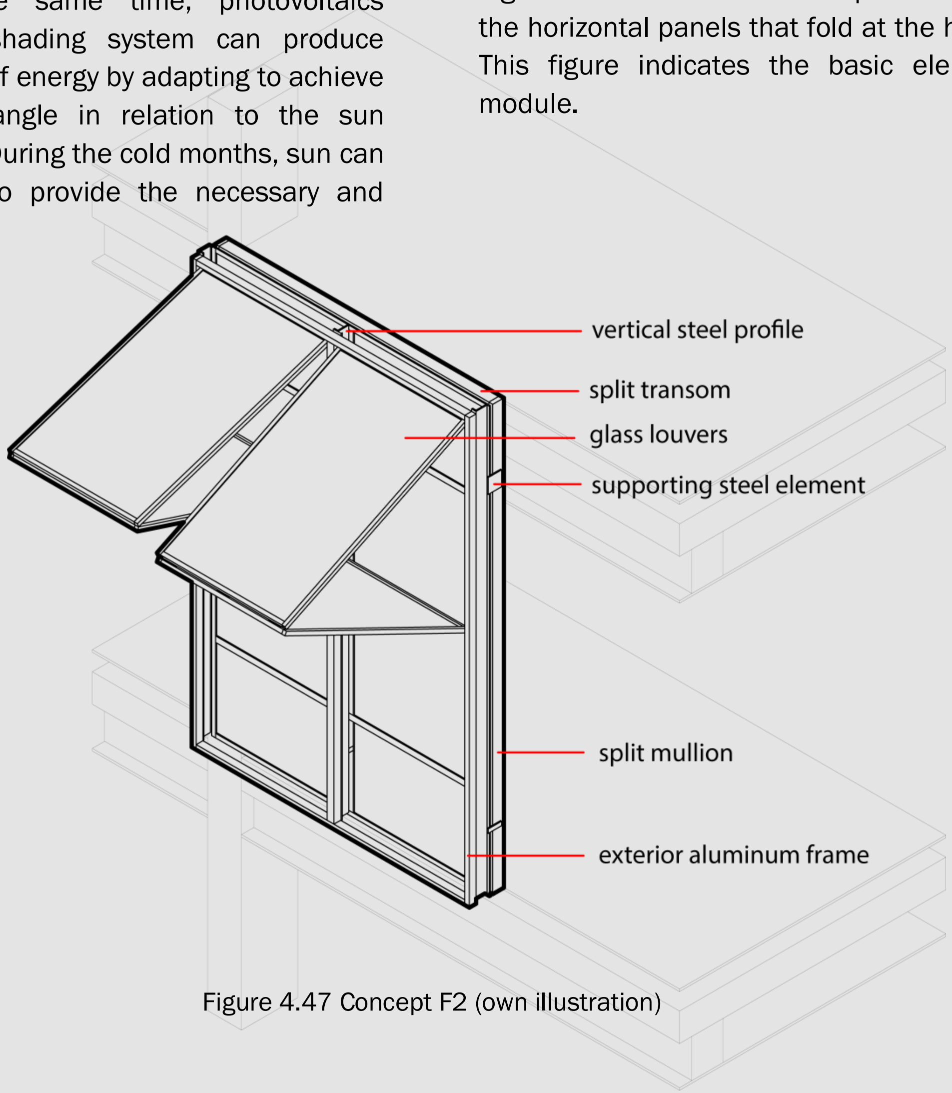


Figure 4.47 Concept F2 (own illustration)

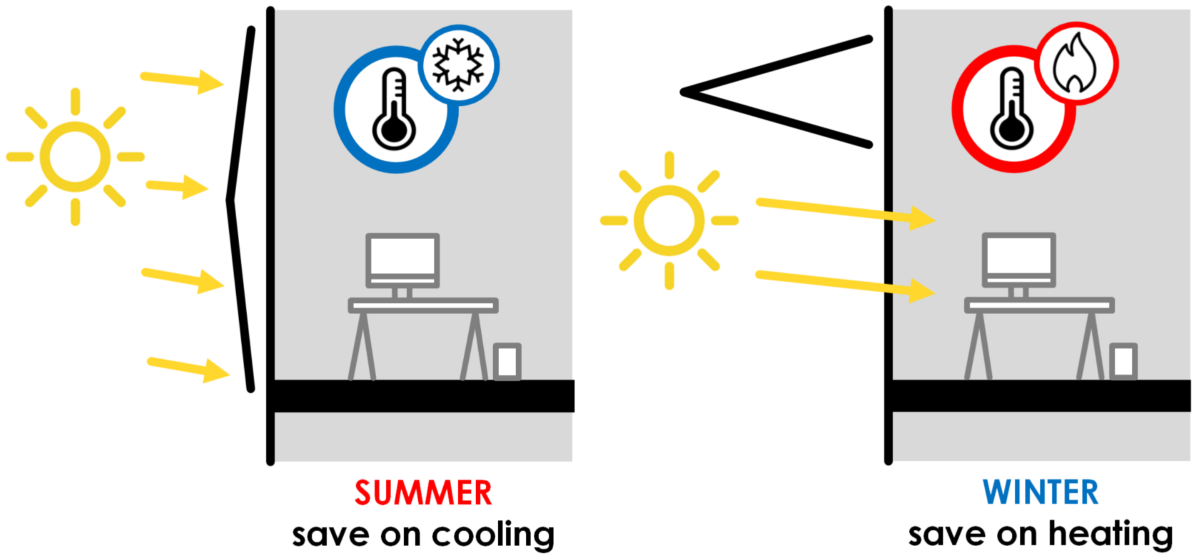


Figure 4.48 Seasonal Adaptation of the Adaptive Concept F2 (own illustration)

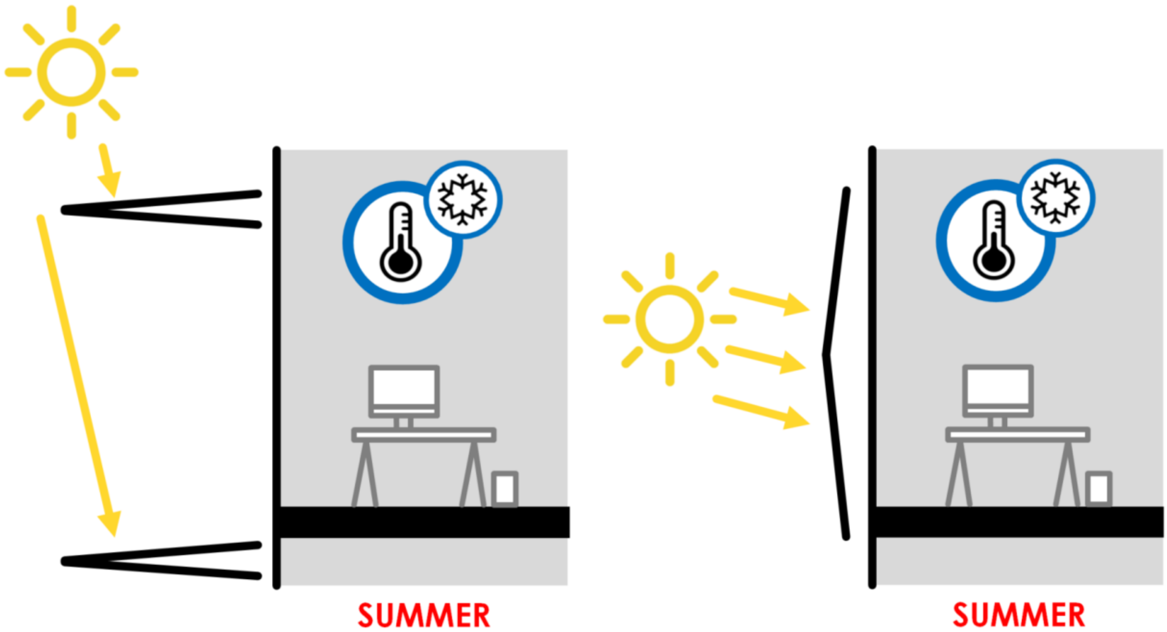


Figure 4.49 Hourly Adaptation of the Adaptive Concept F2 during Summer (own illustration)

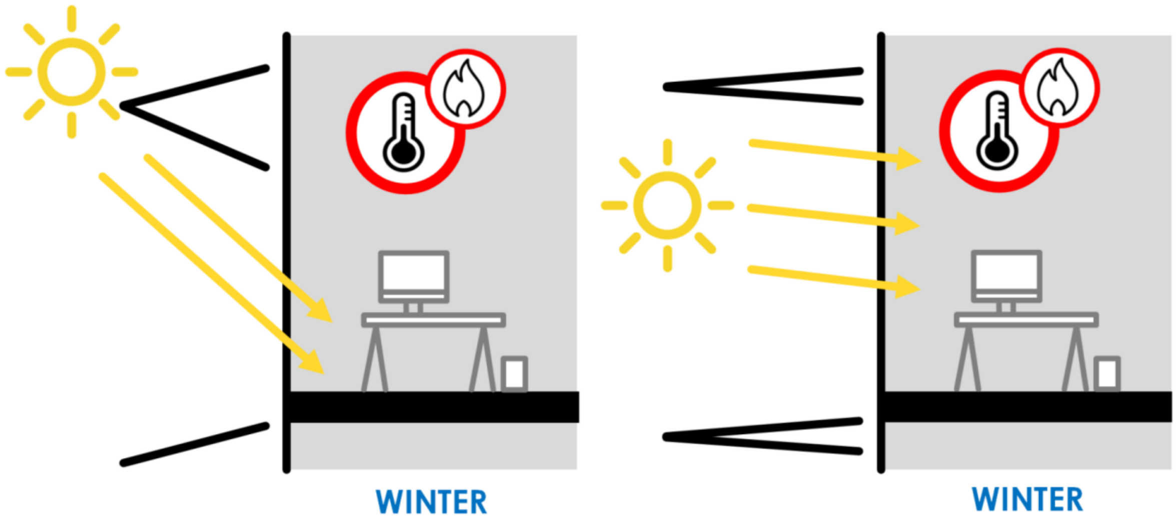


Figure 4.50 Hourly Adaptation of the Adaptive Concept F2 during Winter (own illustration)

This showroom and office building was completed in 2007 in a small village, on the southern side of Austria named Bad Gleichenberg. The client desired a break of pattern in order to really make a statement. The ability of the shading system for automatic adaptation and the individual movement of each panel make this building unique. The big amount of shape compositions give an endless set of patterns on the exterior, as can be seen in Figure 4.51. Weather conditions and preference of occupants can shape the exterior appeal of the building, which can be a reason for shape change itself.

The material used for the shutters is perforated aluminum (clearly shown in Figure 4.52) and an electric motor powers every single moving panel, thus posing this facade a bit expensive but easily maintainable. Moreover, installation of the facade system was quite easy due to the modularity of the panels.

As far as sustainability is concerned, the weight of the aluminum panels is low, which meant lower embodied energy. However, movement against gravity forces increases energy consumption making it less efficient power-wise. Last but not least, the aluminum has an increased resistance to weather conditions, meaning high durability, and when demolished, it can be recycled.

Figure 4.51 The Kiefer Showroom facade patterns (source: Kiefer technic)

Figure 4.52 The Kiefer Showroom exterior shutters (source: www.architonic.com)

4.6 references

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5

SUBCOMPONENTS AND MATERIALS

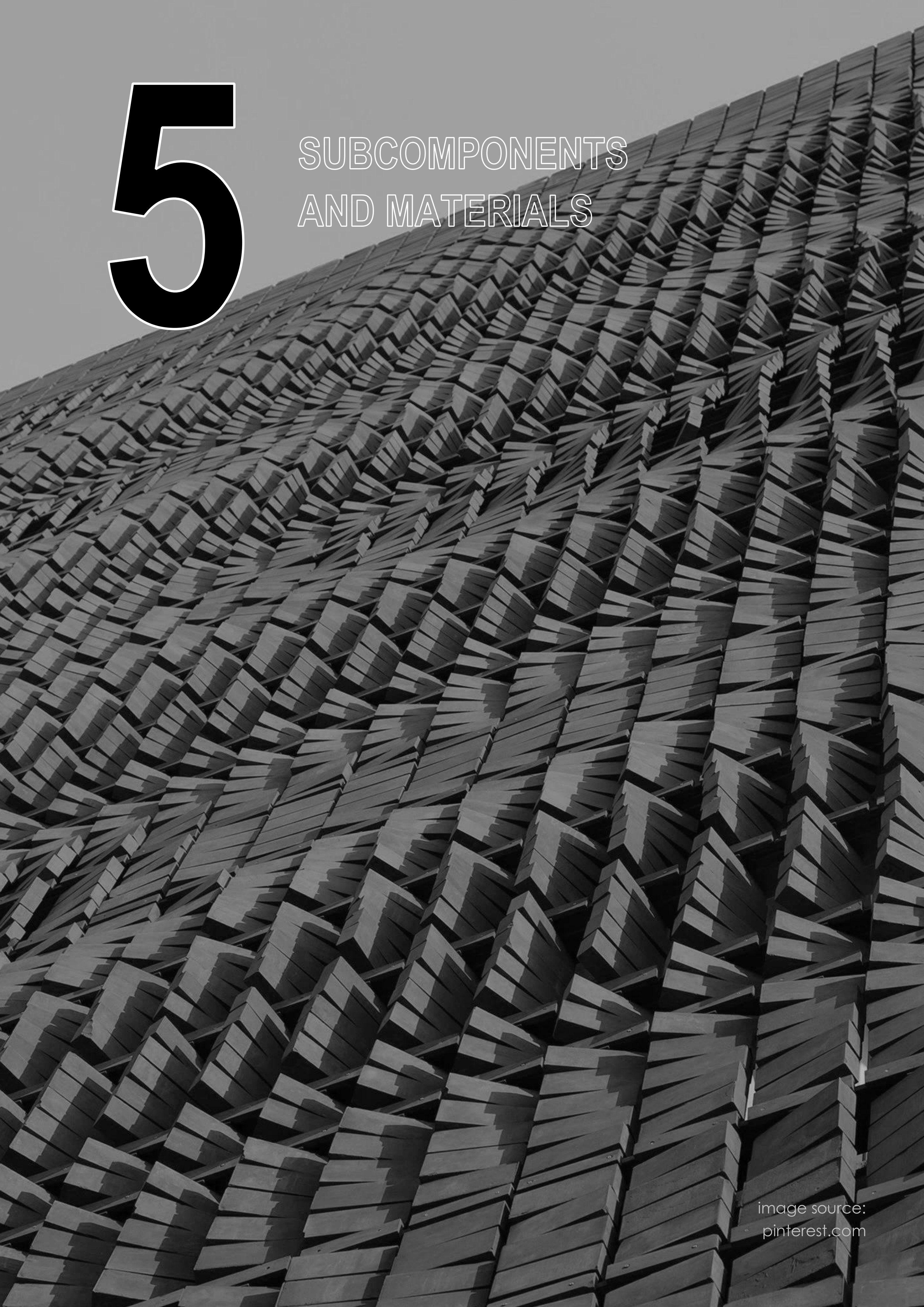


image source: pinterest.com

5.1 introduction

In this chapter, an overview of all the elements that are involved in a Unitized Curtain Wall system will be presented, with an emphasis on their assembling techniques and their disassembly potential. In order to do this, it was deemed necessary to split the component (i.e. whole unitized module of the facade) into 3 different subcomponents, as illustrated in Figure 5.1; namely support structure, infill materials and solar shading system, underlined in red in each case. Each subcomponent can be divided into certain elements, which are shown in the red box between the subcomponent name and the illustration.

Section 5.2 focusses on the anchor connection – between mullion and structure – and on the mullions and transoms. Two different materials for mullion and transom profiles are examined in this research: aluminum and timber. Section 5.3 provides an overview of the infill materials, with their layers and elements: the glazing, cladding, and insulation types. As for the last section 5.4, it is about the solar shading system that is used in each case, and provides exploded views of its assembly and disassembly including all the different elements.

The number of transoms/mullions used in each prefabricated module may also influence the thickness of the mullion/transom profiles and the glass. The same applies to the height and width of the openings. For this thesis, everything is based on the dimensions and grids of the case study building, which comply with the typical office grids, since it would not be reasonable to cover all the possible design scenarios.

This chapter will also be a starting point for the Environmental Product Declaration performed in Chapter 7, as the material differences will be pointed out.

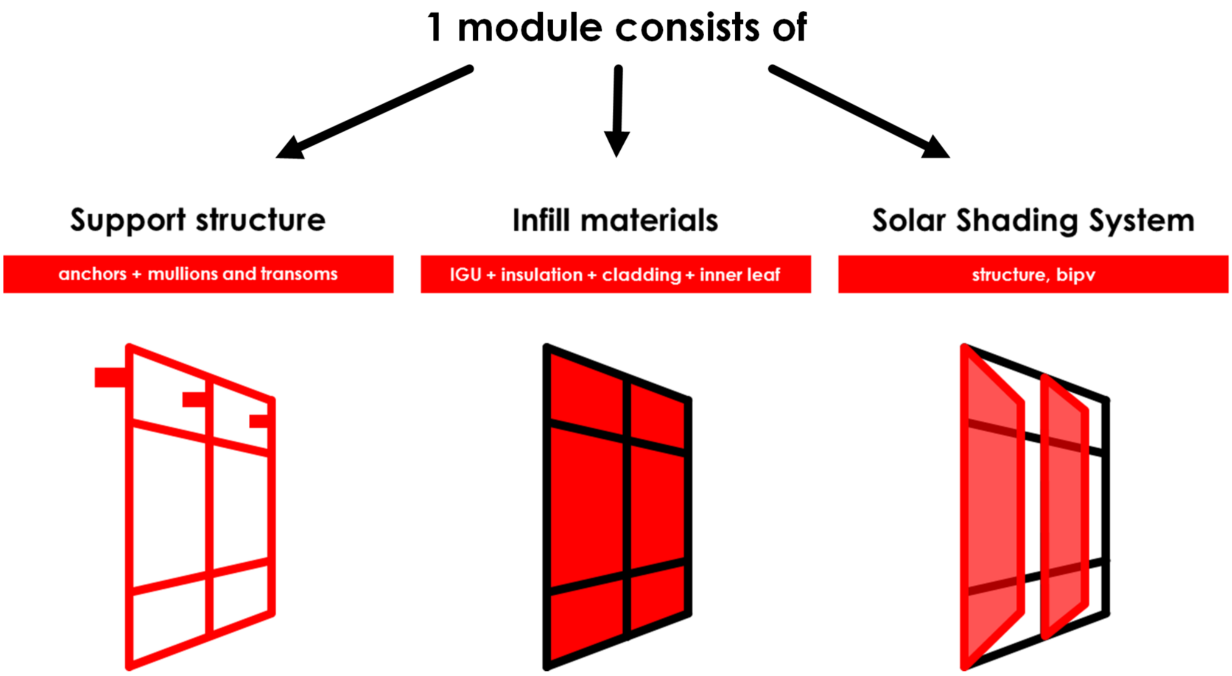


Figure 5.1 The 3 subcomponents (own illustr.)

5.2 support structure

This section is about the elements and connections used for the support structure, namely the **anchors**, the **mullions** and the **transoms**. A brief introduction will be given for each, and then the focus will be on the materials used in each case, their connection types and disassembly method.

5.2.1. ANCHORS

5.2.1.1 General information

One of the most crucial parts of a curtain wall (either unitized or stick-system) is the connection of the facade elements to the main structure of the building. A **quick installation** is desirable, without compromising **safety** at any point. For the former, easily adjustable connections are needed by using 'slotted holes' that provide tolerances. For the latter, damage on the reinforcement of the concrete needs to be avoided. It should be kept in mind that the system should be galvanized in order to have protection again corrosion.

Figure 5.2 Anchor on the **side** of a concrete slab

5.2.1.2 Elements

It should be emphasized that not all anchors have the same form – this depends on the producer. Nor are they attached to the same material in all projects. Two types of anchors are the most usual, which get attached to concrete slabs or beams. They will be briefly analyzed in this section.

The anchor usually gets mounted either on the **side** of the concrete slab (Figure 5.2), or on **top** of it (Figure 5.3). In both cases, Figures 5.4 and 5.5 show that it consists of:

- the **channel** (which comes with rebars that are anchored in the concrete slab)
- the **brackets** (which connect the channels with the mullions)
- the **T-bolts** (which are used instead of welding)

Figure 5.3 Anchor on the **top** of a concrete slab

The concrete slab and the mullions are also depicted in both Figures 5.4 and 5.5. A detailed explanation of the mullions is given in the next section.

As for the **anchor channel**:

- When mounted on concrete, no welding is needed. Only a torque wrench is necessary for assembly and disassembly.

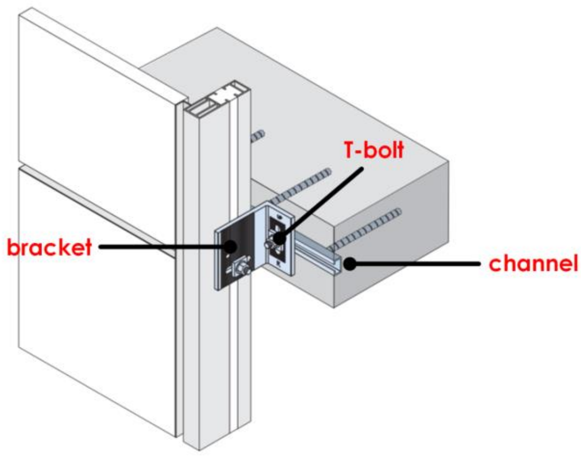


Figure 5.4 Side-supporting anchor (source: Halfen)

- When mounted on steel, welding is necessary. It has been mentioned above that welding does not comply to DfD. When connecting two steel elements however, welding is not so much against the principles of DfD, as they can be then disassembled and recycled at one piece. In this case, the anchor is the connecting point between the facade and the structure, and it is thus better to be demountable in order to provide flexibility for future use.

It is necessary to emphasize at this point that timber mullions may call for a different (and more innovative) anchor solution. Everything that was mentioned in this section mainly applies to aluminum mullions, which are the most commonly used ones. Later in this study however, the same anchor will also be used for timber mullions, in order to provide a fair comparison among the 8 concepts.

5.2.1.3 Layout Fixation

In order to know what the suitable connection for the anchor will be, the most important consideration is to distinguish what kind of **layout fixation** there should be. This refers to the anchoring onto the building's structure, which can take place in various ways. It can span one or two floors, and either hang from the top or stand on the bottom. These are all shown in Figure 5.6, and are:

- One-level hanging (Layout 1G)
- Two-level hanging (Layout 2G)
- One-level bearing (Layout 1-0)
- Two-level bearing (Layout 2-0)

In the case of buildings with exterior solar shading, that also use the unitized principles, using 1G or 1-0 may prove much more beneficial, since the facade modules are not as lightweight as in the case of a simple glazed CW assembled on site. In the study of this thesis, 1G will be used, since modules hanging on each floor is the most usual way of structure attachment and is the most suitable for double skin concepts, with exterior shading, due to increased weight.

Next, knowing the forces of the connection between anchor and mullion is important. This will enable the designer to choose the right **slotted holes** for the occasion. In this specific case, all three directions have forces; dead weight on the vertical and wind forces on the horizontal directions.

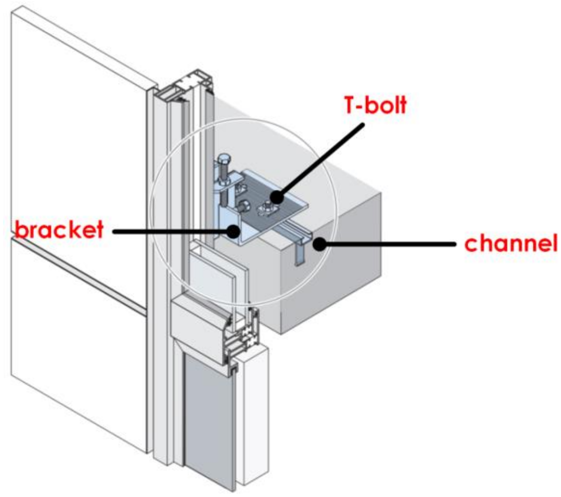


Figure 5.5 Top-supporting anchor (source: Halfen)

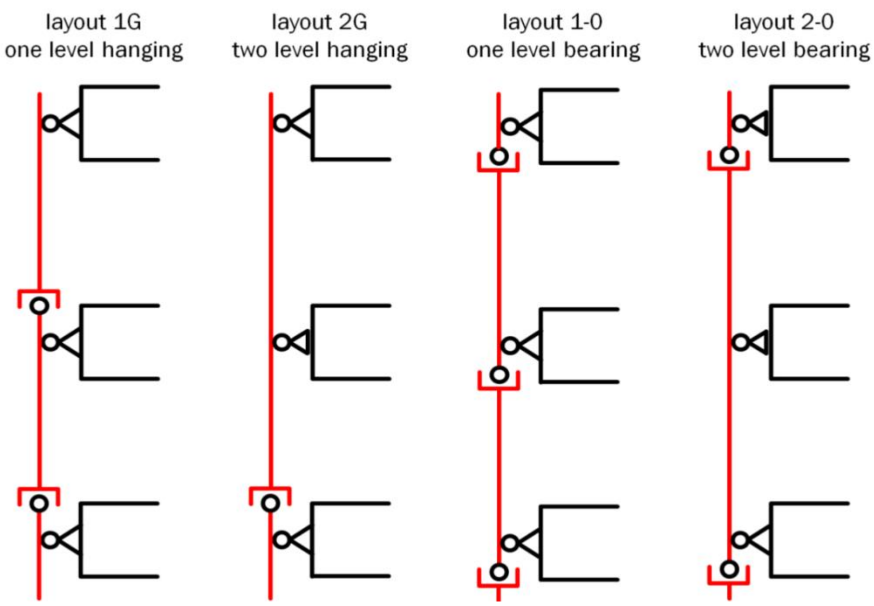


Figure 5.6 Main layouts of curtain wall fixation (own illustr.)

5.2.1.4 Materials

All the separate elements are put on Table 5.1 that also lists the materials used. Apparently, channels, brackets and T-bolts are all made of steel. Figure 5.7 is subtracted from the brochure of Halfen, and gives a very clear and realistic indication of the separate steel elements in either side- or top-based anchors.

ELEMENT	MATERIAL
channel	steel
brackets	steel
T-bolts	steel

Table 5.1 Materials used in anchors

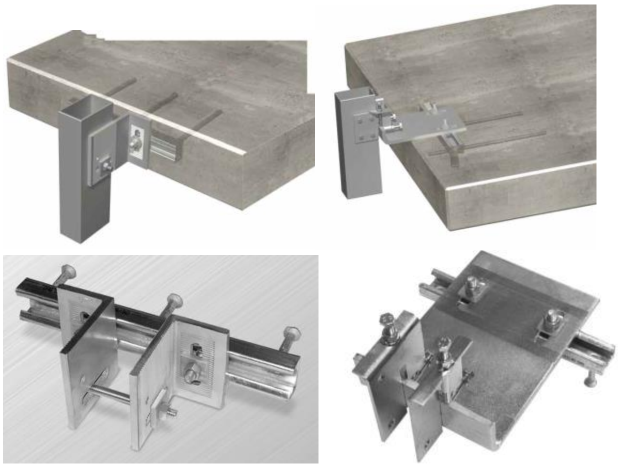


Figure 5.7 Materials used in anchors (source: Halfen)

5.2.1.5 Assembly

As far as the assembly sequence is concerned, this is illustrated in Table 5.2. It is emphasized that not all elements of the anchor are installed at once. The channels are put in place before even the concrete floor gets formed. After the floor formation, the brackets are put in place, and T-bolts are used to attach them to the channel.

The unitized CW modules are then brought into the construction site and installed. Each module takes its place with the aid of the crane, and T-bolts are again used to 'hang' the mullions in the exact place. Any adjustments can be made with the aid of the slotted holes, as already mentioned in the end of section 5.2.1.3. A 3-dimensional detailed illustration is provided in Figure 5.8, which shows how the various parts of the anchor are connected.

ELEMENT	ASSEMBLY PRIORITY
channel	1
concrete slab formation	
brackets	2
T-bolts	3

Table 5.2 Assembly sequence of anchor elements

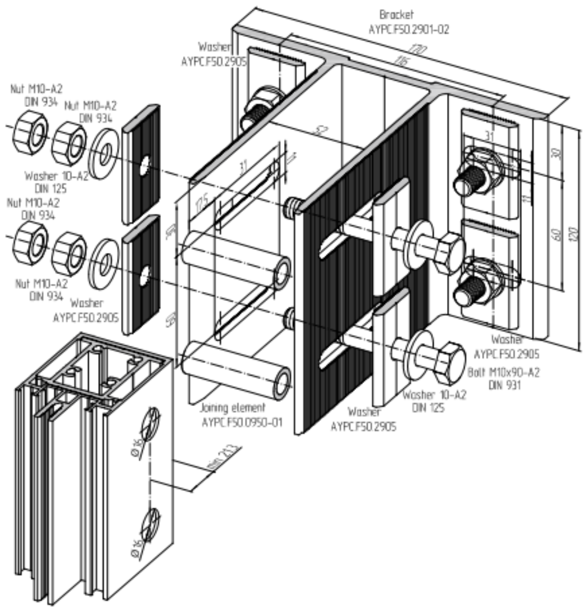


Figure 5.8 Assembly of the different anchor parts (source: ALUTECH ALT F50)

5.2.1.6 Disassembly

When the curtain wall reaches its lifespan, it should be either maintained or completely changed. In any case, the existing unitized modules will have to be removed, either temporarily or permanently.

At the time of the disassembly, the T-bolts holding the facade will first have to be loosened and eventually removed. The facade panels are taken away with a crane, and then the brackets can take their turn through unscrewing the T-bolts of the channels. All of these actions are summarized in Table 5.3.

ELEMENT	DISASSEMBLY PRIORITY
T-bolts	1
CW module taken away	
T-bolts	2
brackets	3

Table 5.3 Disassembly sequence of anchor elements

5.2.2 MULLIONS and TRANSOMS

5.2.2.1 General Information

In this section, the mullions and transoms that are used in unitized curtain wall will be explained in detail. They are the elements of the facade responsible of resisting the forces taken by the glass (e.g. wind) and then transferred to them. The mullions are vertical primary elements, while the transoms are horizontal secondary elements.

Figure 5.9 shows a scheme of the facade module, where the mullions and transoms are grouped. So, according to the numbers given:

- 1 refers to the main mullion
- 2 refers to the main transom
- 3 refers to the secondary mullion
- 4 refers to the secondary transom

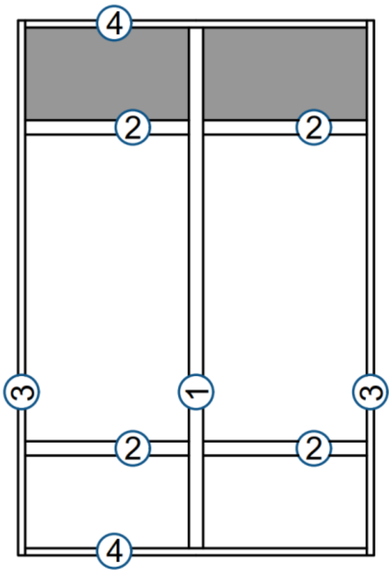


Figure 5.9 Module with grouped mullions and transoms (own illustration)

5.2.2.2 Materials

As for the materials, aluminum curtain walls are the most common, due to being lightweight, durable and relatively inexpensive. A 3-dimensional impression of the section of a typical aluminum mullion is shown in Figure 5.10. However, aluminum is not a very sustainable material, since it requires a huge amount of embodied energy for its production and it's hard to recycle. This is why the aluminum curtain wall will be compared to a timber one. Timber is a very sustainable material and a 'warm' material that improves interior aesthetics, and this is why the client may prefer it.

Figure 5.10 Aluminum mullion section (source: Schüco Façade FW 50+.HI)

Timber curtain walls are being built more and more often nowadays. Usually the inner part of the mullion is made of timber, while the rest are similar to the aluminum curtain wall (Figure 5.11). This will be explained in the next section. There are also other types of curtain walls, such as steel supported ones, but since they are rarely used in modular systems, they will not be addressed in this thesis.

Figure 5.11 Timber mullion and transom section (source: www.scandinaviantimber.com)

Moreover, structural glazing (with the use of silicone) is not mentioned in this thesis, since it hampers reversibility of the glass panels. Thus, only curtain walls with cover caps are described.

In the following section, a full list with all materials used in each element of the CW mullions and transoms will be provided, as also indicated by some construction details.

5.2.2.3 Elements

In the aluminum detail of Figure 5.12 each element used is identified and indicated with its name. It can be observed therefore, that a curtain wall consists of:

- **mullions and transoms** that provide stiffness
- **glass panels and thermal breaks** (isolators) that insulate thermally and have acoustic properties
- **external gaskets** to provide water-tightness
- **internal gaskets** to provide air-tightness
- **pressure plates**
- **tapping screws**
- **cover caps** (can be customized) for aesthetics

The IGU (insulating glazing unit) is described in the next section, and will not be further discussed. All the other elements mentioned above are grouped according to their material type and shown in table 5.4. A more detailed and clear illustration of all the profiles used in curtain walls is provided in the next page, in Figure 5.14.

Aluminum Curtain Wall	
ELEMENT	**MATERIAL**
mullion/transom	aluminum
pressure plate	aluminum
cover cap	aluminum
glazing gaskets	plastic (EPDM)
rebate gaskets	plastic (EPDM)
thermal break	plastic (e.g. ABS)
tapping screws	steel

Table 5.4 Materials used in aluminum curtain walls

For timber, the profiles used are the same, apart from the mullion that is usually made out of Glued Laminated (Glulam) timber or laminated veneer lumber, and some additional screws that bind the glazing to the mullion itself. These differences can be observed when comparing Table 5.4 to Table 5.5, but also when comparing the details in Figures 5.12 and 5.13.

It is worth mentioning that there are lots of design and material choices for the cover cap. For instance, timber caps can be screwed on the exterior. It is the most wise choice, however, to use aluminum ones, especially in countries with a temperate climate, where moisture levels are high. This way, the frequency at which a module needs to be maintained is reduced.

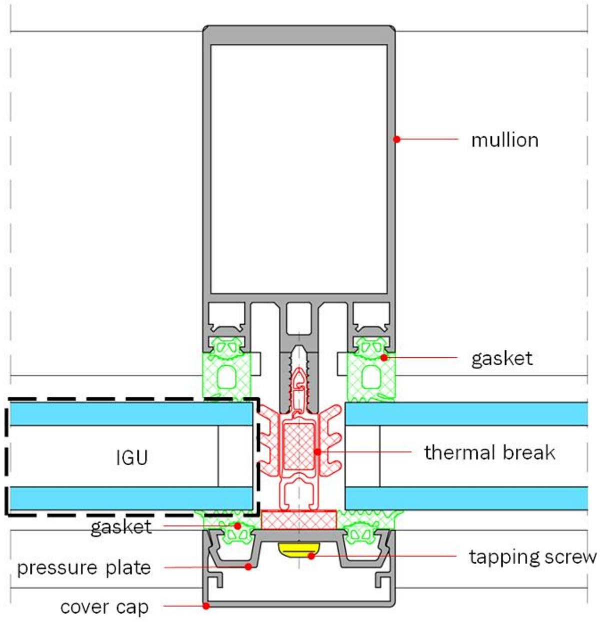


Figure 5.12 Aluminum mullion detail

Timber Curtain Wall	
ELEMENT	**MATERIAL**
mullion/transom	timber
pressure plate	aluminum
cover cap	aluminum
glazing gaskets	plastic (EPDM)
rebate gaskets	plastic (EPDM)
thermal break	plastic (e.g. ABS)
tapping screws	steel

Table 5.5 Materials used in timber curtain walls

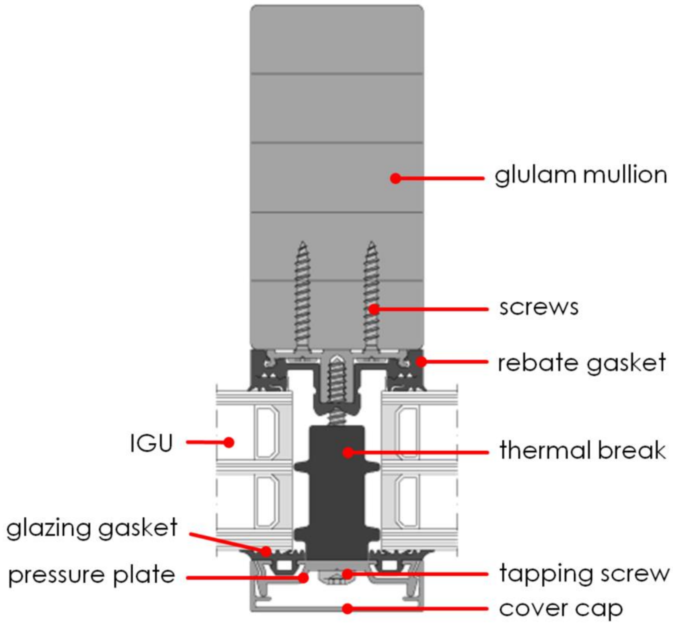


Figure 5.13 Timber mullion detail
(adapted from: RAICO)

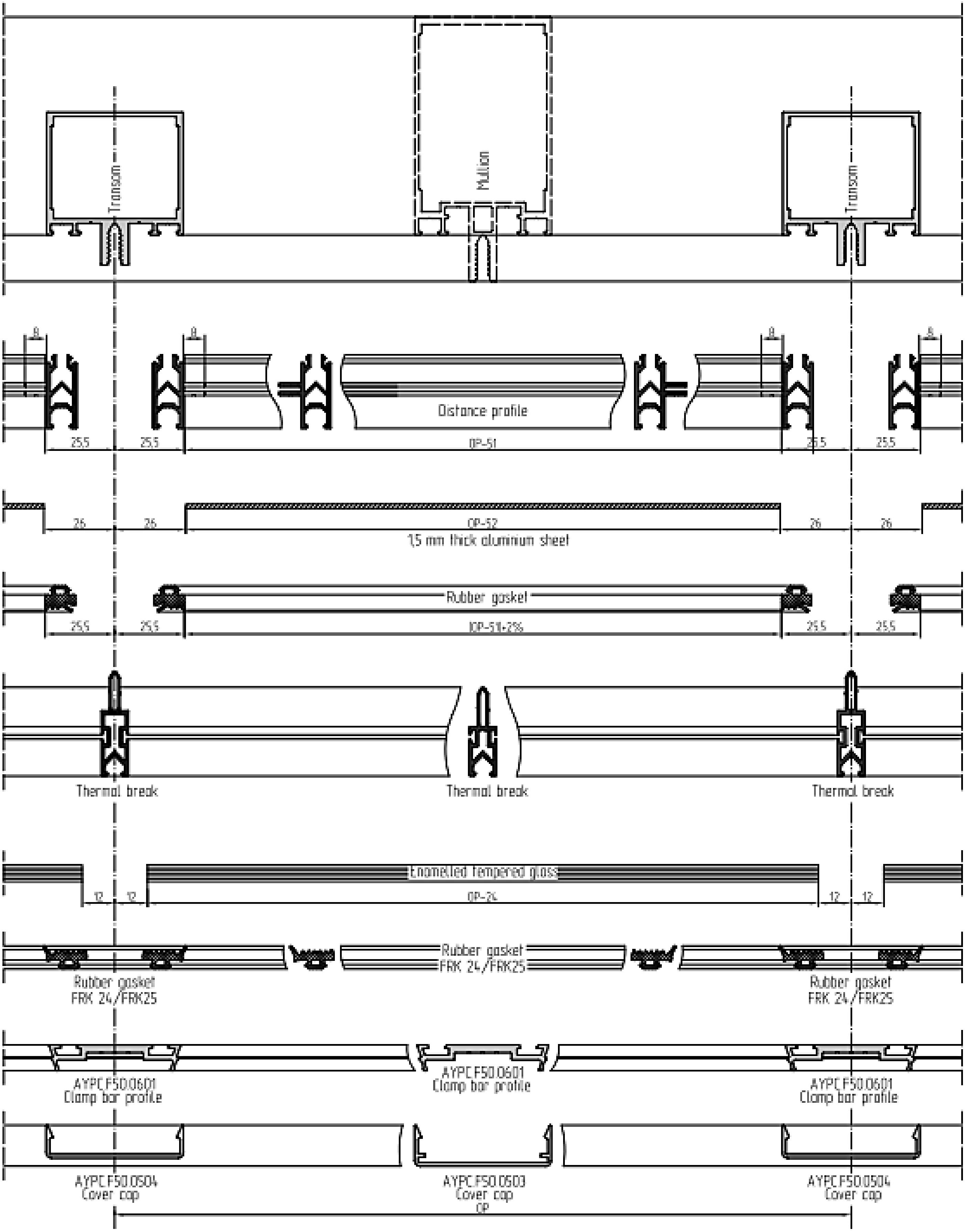


Figure 5.14 Indication of profiles used in aluminum curtain walls
(source: ALUTECH ALT F50)

As far as the **split mullions** are concerned, when looking at the 3d impressions (Figures 5.15 and 5.16) and details (Figure 5.17), one can easily observe one main differences:

- The profiles are split
- The coupling gaskets (additional rubber gaskets which aim at binding the two split parts)
- The front weather seal gasket
- The insulating foam that should be inserted in between the 2 split cover caps
- The connectors

Of course, the extruded mullion and transom profiles (and therefore the plastic shapes) depend on the producer. So the exact shape of a mullion or transom may show slight variations from producer to producer. Table 5.6 summarizes the elements used in a split mullion and sorts them according to the material. Connectors are not included due to not being extruded elements.

Split Aluminum Curtain Wall	
ELEMENT	**MATERIAL**
split profile	aluminum
pressure plate	aluminum
cover cap	aluminum
glazing gaskets	plastic (EPDM)
rebate gaskets	plastic (EPDM)
rainscreen gasket	plastic (EPDM)
coupling gasket	plastic (EPDM)
front weather seal gasket	plastic (EPDM)
thermal break	plastic (e.g. ABS)
insulating foam	polyurethane

Table 5.6 Materials used in split aluminum curtain walls

The split profile detail and table for timber curtain walls are not included, due to the lack of resources and standardized solutions for this specific case. It is, however, considered that it can be detailed in a similar way to aluminum.

Figure 5.15 Aluminum Curtain Wall – split mullions (source: Schüco Façade USC 65)

Figure 5.16 Timber Curtain Wall – split profiles (source: unavailable)

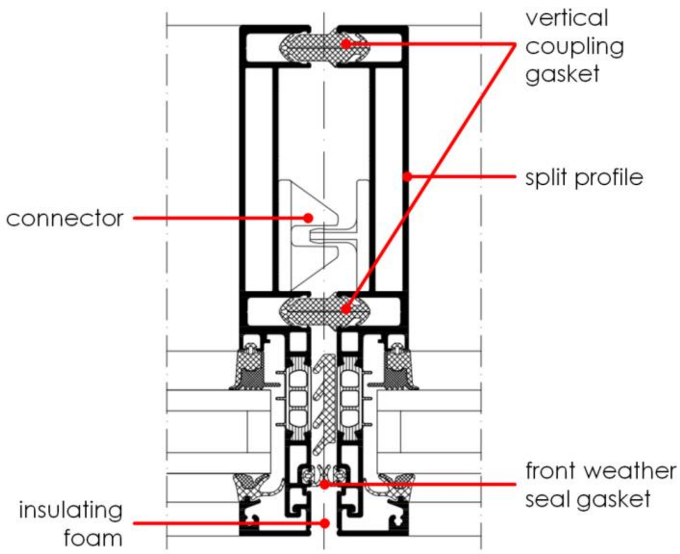


Figure 5.17 Split mullion detail (adapted from: Schucco)

5.2.2.4 Assembly

Figure 5.20 on the next page illustrates the steps of assembling an aluminum mullion. The first step is putting the thermal break on the mullion, and the final one is covering the exterior side with the cover cap. This exploded view also shows how the connection mullion-transom can be done. Figure 5.18 is extracted from RAICO brochure and shows the steps to mount the transom to the mullion on timber curtain walls.

5.2.2.5 Disassembly

In order to successfully recover the materials or components without being damaged, a careful disassembly is necessary. For that, disconnection of the fasteners should take place in the reverse order of its assembly. For instance, disassembly steps of Figure 5.20 are of the opposite order to assembly.

Demounting of the modules is done with the aid of hand tools, such as hand drills, ripping bars, end nips, etc. depending on the connection type. Table 5.7 lists various connection types and their consequent disassembly tasks to be performed (Gupta, 2004). Ease of removal definitely affects the overall productivity, and this is why it is one of the main connection-related design guidelines that will be rated. Another one is the speed of demounting a connection, which may be dependent on the laborer experience, but also on the task. For example, glued connections take much more time than bolted ones.

Figure 5.18 Assembly of the mullion-transom connection (adapted from: RAICO)

Type of Connection	Task for Disassembly
mate	remove
lock	move
bundler	shear cut
spring	deform/pull
screw	unscrew (drill)
lock washer	deform/pull
cotter pin	pull
snap fit	deform, pry out/pull
press fit	pull/pry out
shrink fit	pull
rivet	pry out/drill
fold	deform
glue	peel/pry out/break

Table 5.7 Types of Connections and Tasks for Disassembly (adaoted from Gupta, 2004)

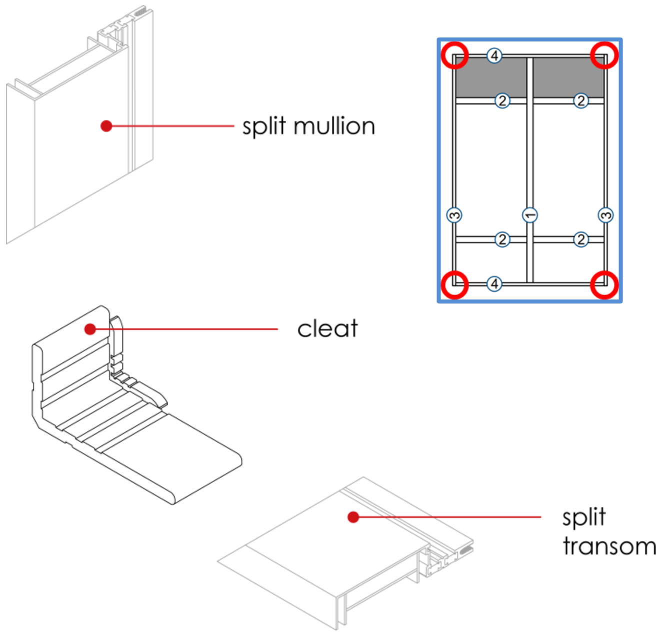
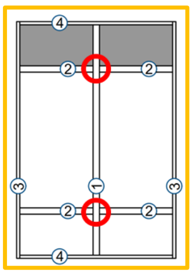


Figure 5.19 Isometric exploded view of the split mullion - split transom connection (own ill.)



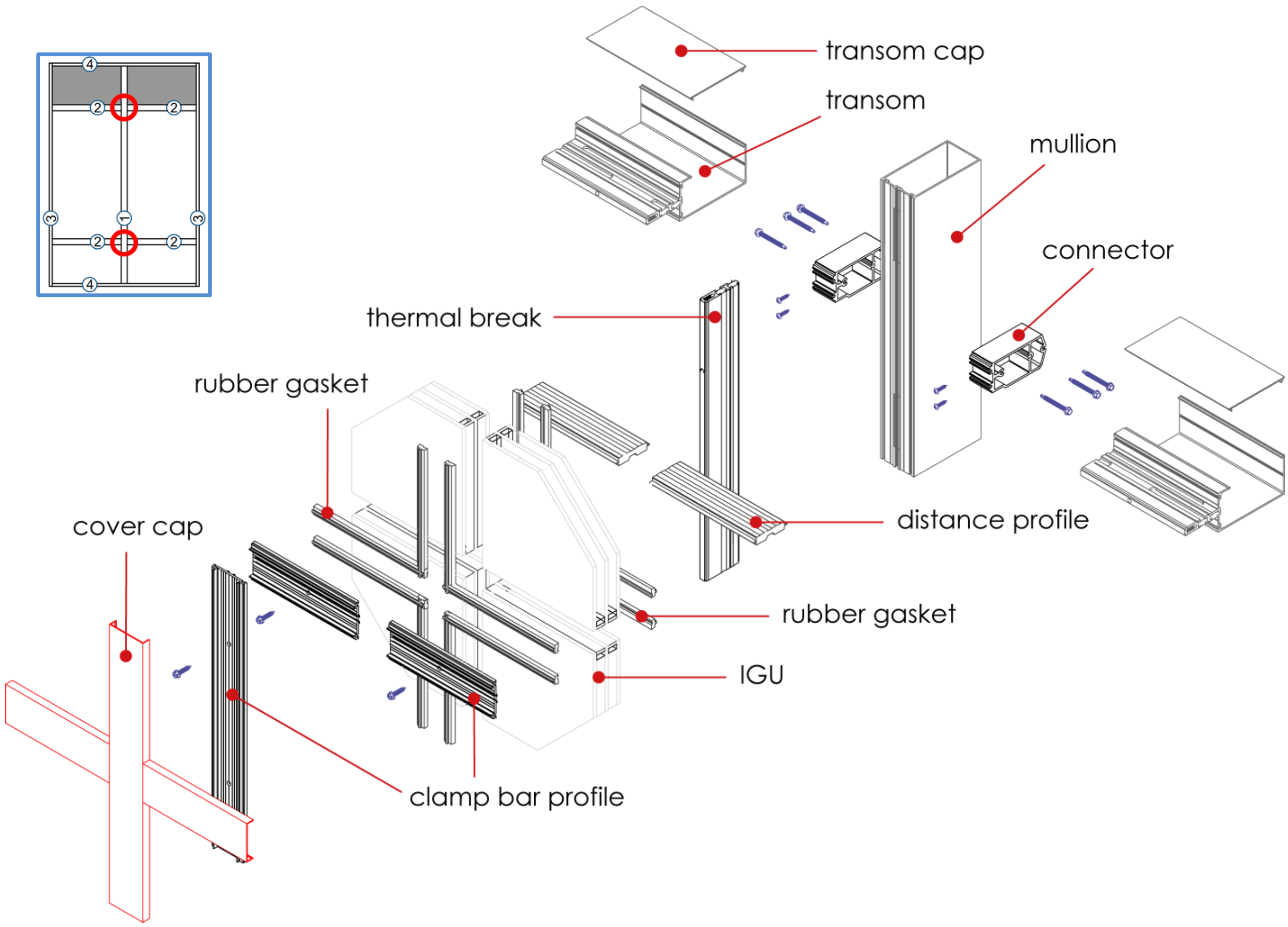


Figure 5.20 Isometric exploded view of the mullion-transom connection (own ill.)

5.3 infill components

This section provides a quick overview on the components that are used to provide transparency and on the ones that insulate the building; namely the insulating glass unit (IGU), the spandrel glass and the insulation panels. Figure 5.21 illustrates in one graph all the infill components that will be described in this section. A brief introduction will be given for each, and then the focus will be on the materials used and the connection types.

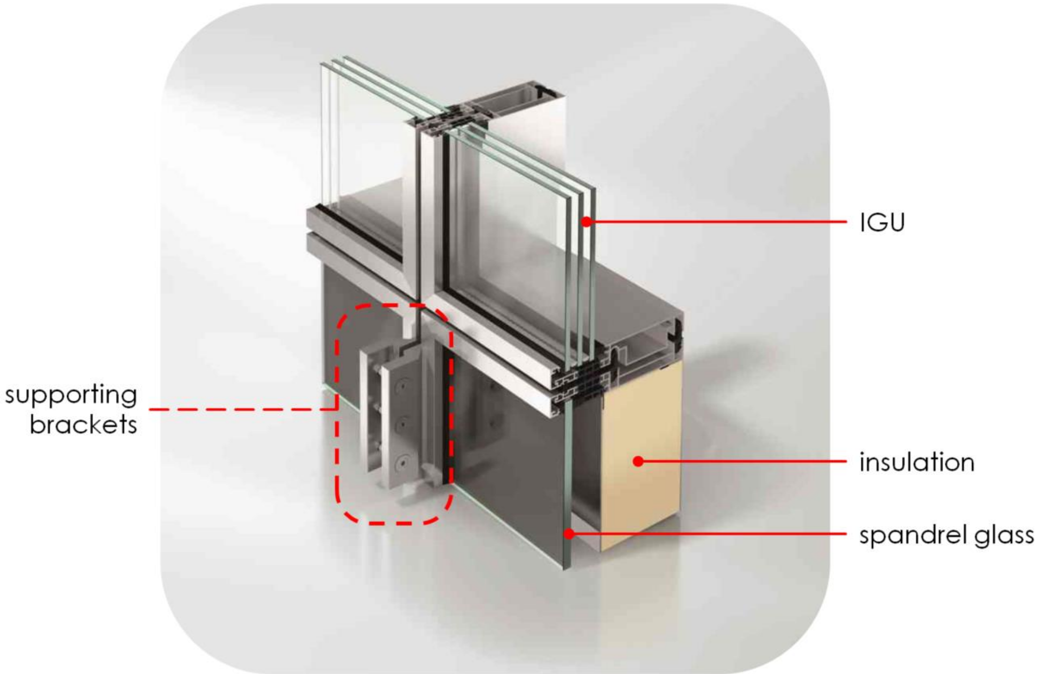


Figure 5.21 Infill materials overview

5.3.1. INSULATING GLASS UNIT (IGU)

An insulated glass unit aims at better thermal performance levels by using the layering technique. It usually consists of two or three layers of glass, on which a coating may be used. The edges of this IGU are usually made out of various elements:

- Spacer: It is used to hold the 2 glass panes together, providing a fixed gap at the same time. Being made out of aluminum, it is also used as a bed for the desiccant. The spacer is usually available in widths of 6mm, 12mm or 15mm, depending on the requirements of the gap.
- Desiccant: It is a drying agent and aims at absorbing the humidity inside the IGU. Silica and zeolites are most commonly used for this.
- Sealants: Their purpose is to seal the space, in order to avoid having the gas in the cavity escape. The main sealant is usually Butyl, sealing the spacer and the glass airtight. The secondary sealant is made of Silicone or Polysulphide, and it provides structural integrity to the unit.
- Cavity: The inert gas that fills the cavity should be insulating (not vacuum). In general, argon or krypton are used so that heat conduction is decreased.

Figure 5.22 shows all the aforementioned sub-components of the IGU unit and a realistic picture of an IGU section is shown in Figure 5.23. Nowadays, triple glazing is becoming more and more of a standard, having a high insulation value. The construction of an insulated glass unit is integral, which means it is not demountable after it is assembled. In the unfortunate case where a glass pane breaks, the whole IGU will have to be taken out and replaced.

This thesis mainly focusses on the connections between structural elements of curtain walls, and therefore longer research on IGU was considered redundant.

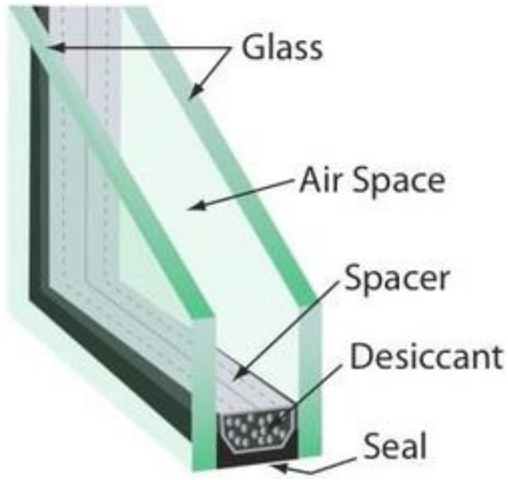


Figure 5.22 The various elements of an IGU (source: www.premierglassfl.com)

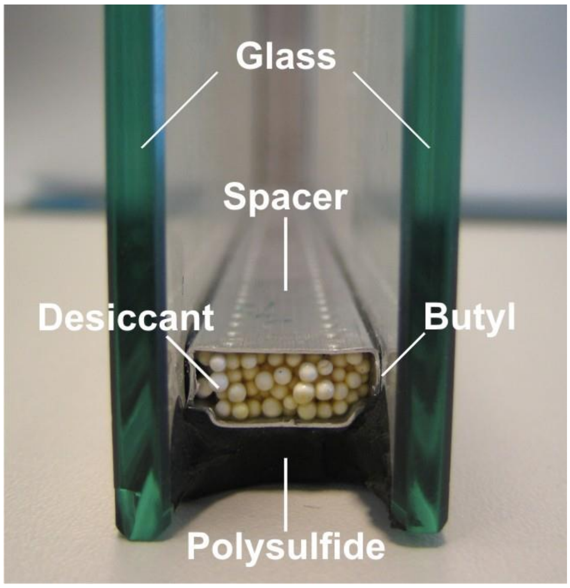


Figure 5.23 Actual section of IGU (source: Miller Glass)

5.3.2. SPANDREL GLASS

The main use of the spandrel glass is to hide some parts of the structure from being visible outside, such as the area between the floor and the false ceiling. Opacity is one of the characteristics of a spandrel glass, where the aesthetic purposes highly influence the color and amount of opacity. In order to avoid breakage from thermal stress, spandrel glass panels need to be heat-treated.

At this point, more research on spandrel glass is considered superfluous, since this thesis only focusses on the disassembly of these elements. In this case, simple removal of the panel is required. This occurs through first removing the cover caps of mullion and transoms, unscrewing the screws, removing the pressure plate and taking the spandrel glass out with the rubber gaskets.

5.3.3 INSULATION

Buildings can be insulated through various different insulation materials, which can take many different forms. These materials can be categorized into organic, inorganic and fossil organic, as presented in Figure 5.25.

When designing curtain walls, sandwich panels are most commonly used for insulating panels. In the case of this research, they are located behind the spandrel glass. The mostly used insulation materials for sandwich panels are Polyurethane, Polystyrene, Phenolic Foam and Rockwool. These are all shown in Figure 5.24, which combines pictures of all the aforementioned materials, found in the AssanPanel brochure.

As already mentioned for the previous section on the spandrel glass, but now for this section, going into more detail on insulation materials is considered to be out of scope of the current research. In the design part, all concepts have the same insulation material. Therefore, it will not be taken into account in the calculations and final comparison.

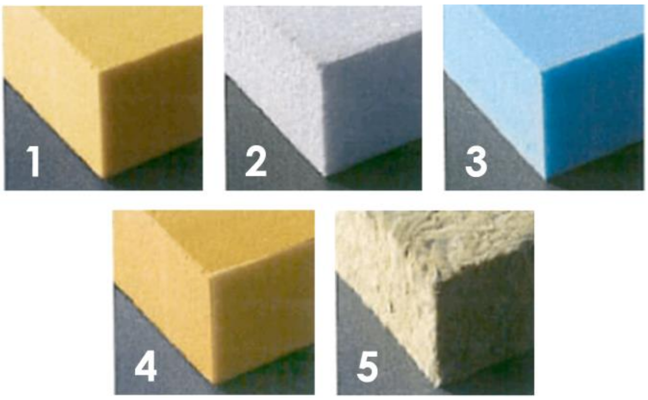


Figure 5.24. Most common insulation materials used in sandwich panels (adapted from: AssanPanel brochure)

1. PUR / PIR (Polyurethane)
2. EPS (Expanded Polystyrene)
3. XPS (Extruded Polystyrene)
4. Phenolic
5. Rockwool

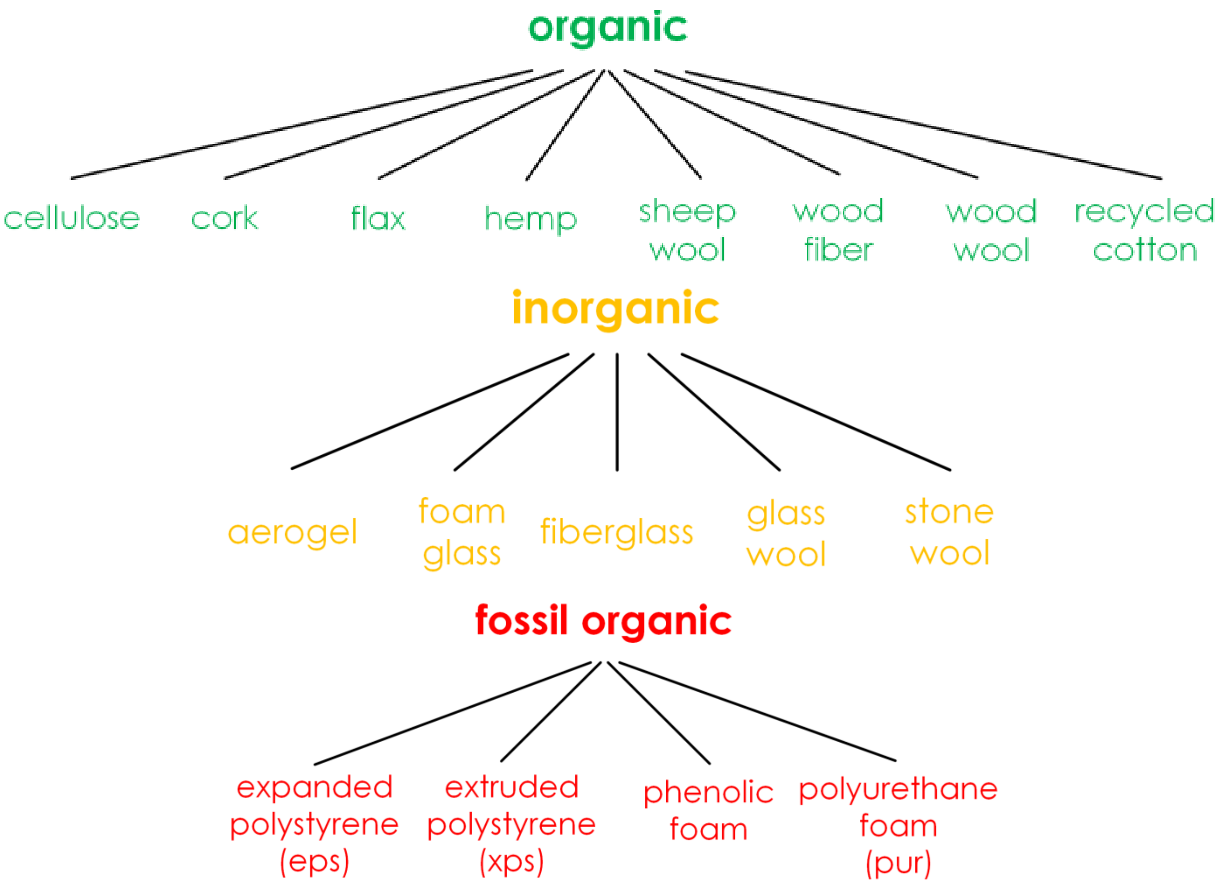


Figure 5.25 Insulation types and some commercial products for each

5.4 shading system

The shading system consists of **the frame**, meaning the structure that holds the louvers or panels for each module type, and **the adjustable shading**, which includes the glass louvers/panels, the motors, the glass fittings and the connections. The whole shading system, which can also be considered as a 2nd skin in the facade, is prefabricated in the factory, and then assembled on site, as will be explained in this section.

5.4.1 General Information

In order to have a good overview of the different parts of the facade, Figure 5.27 (in the next page) provides an exploded isometric of the R1 module. Outlined with red are the prefabricated parts (1 and 7), and in between the connection technique is illustrated. This is done with the use of steel profiles (5) that transfer the loads through the steel plates (3) onto the anchors via bolts (2). In order to achieve a smooth connection and avoid corrosion between the steel profiles and the aluminum hollow sections, rubber profiles (6) are put, and the connection is done again with bolts (4). Figures 5.28 – 5.30 show the typical connection techniques used in the prefabricated modules.

Figure 5.26 illustrates a scheme of the shading module, where the horizontal and vertical aluminum profiles are grouped. So, according to the numbers:

- 5 refers to the main vertical hollow section
- 6 refers to the half vertical hollow section
- 7 refers to the horizontal hollow section

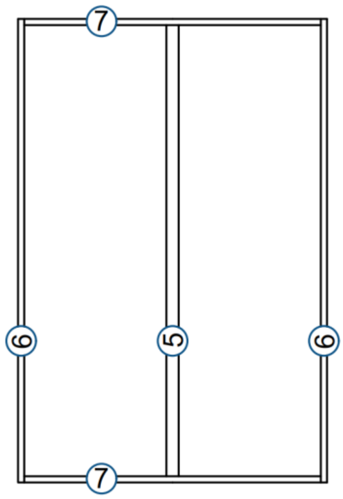


Figure 5.26 Module with grouped aluminum hollow sections (own illustration)

5.4.2 Elements and Materials

As described in the previous section, Table 5.8 is formed that includes the elements and materials that bind the two prefabricated parts. As for the materials used in the prefabricated shading frame, they are listed in Table 5.9. Note that the motors are not included, because their selection is highly dependent on the manufacturer chosen.

ELEMENT	MATERIAL
steel plates	steel
bolts	steel
T and L profiles	steel
rubber profile	rubber

Table 5.8 Materials used to bind the two modules

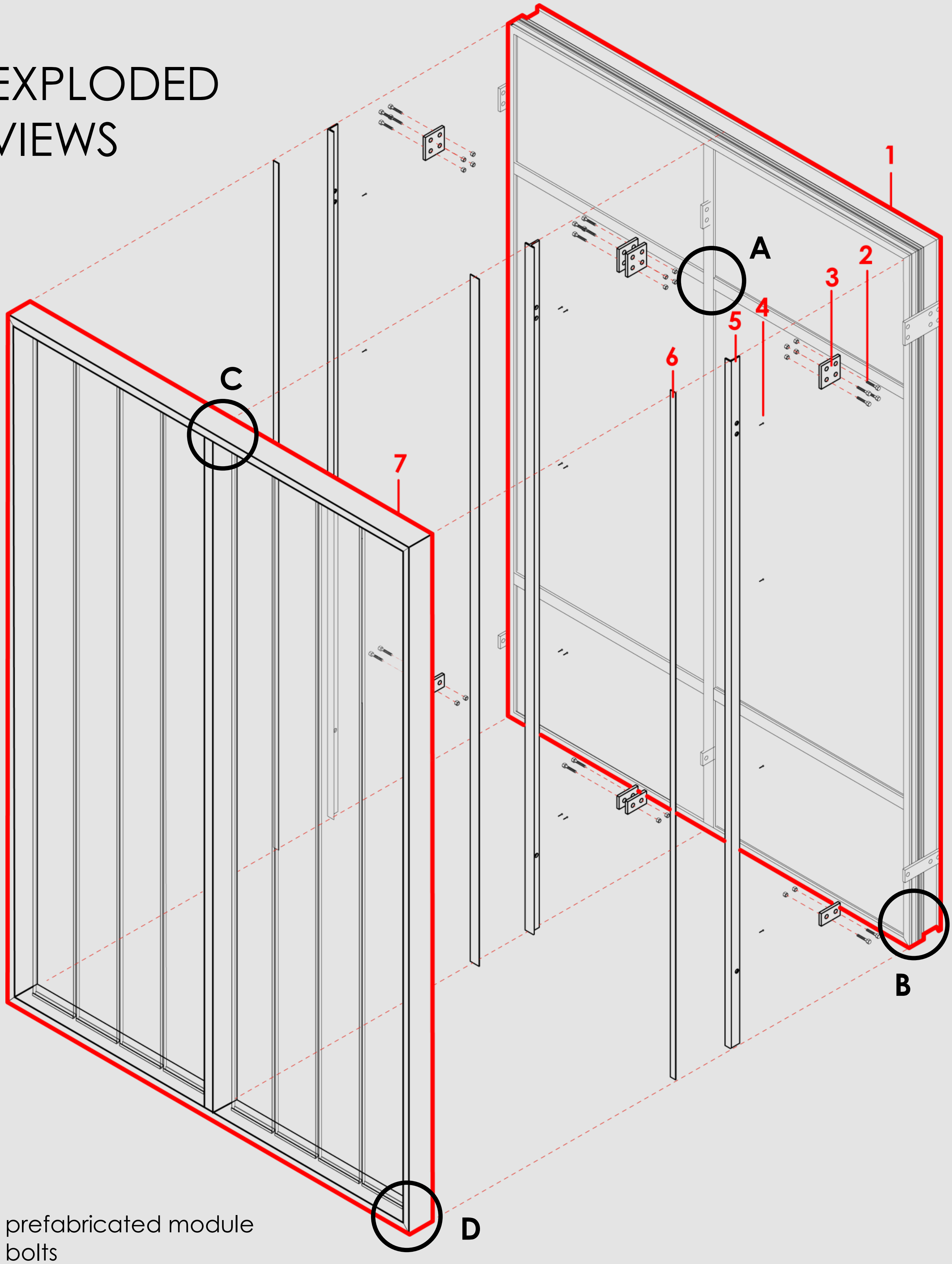
ELEMENT	MATERIAL
hor. sections	aluminum
vert. sections	aluminum
connector	aluminum
cleat	rubber
screws	steel
panels	laminated PV glass
glass support	aluminum

Table 5.9 Materials used in the shading system

5.4.3 Assembly - Disassembly

Assembling the frame of the shading means connecting the pieces together as illustrated in Figure 5.27, right after the shading system is put in place for each case. Disassembly takes place in the factory, where the module is brought, in order to avoid any possible damage to the glass panels.

EXPLODED VIEWS



1 prefabricated module
2 bolts
3 steel plate
4 bolts
5 steel T or L profile
6 rubber profile
7 prefabricated frame including the shading system

Figure 5.27 Exploded isometric diagram of the module subcomponents and connection (own ill.)

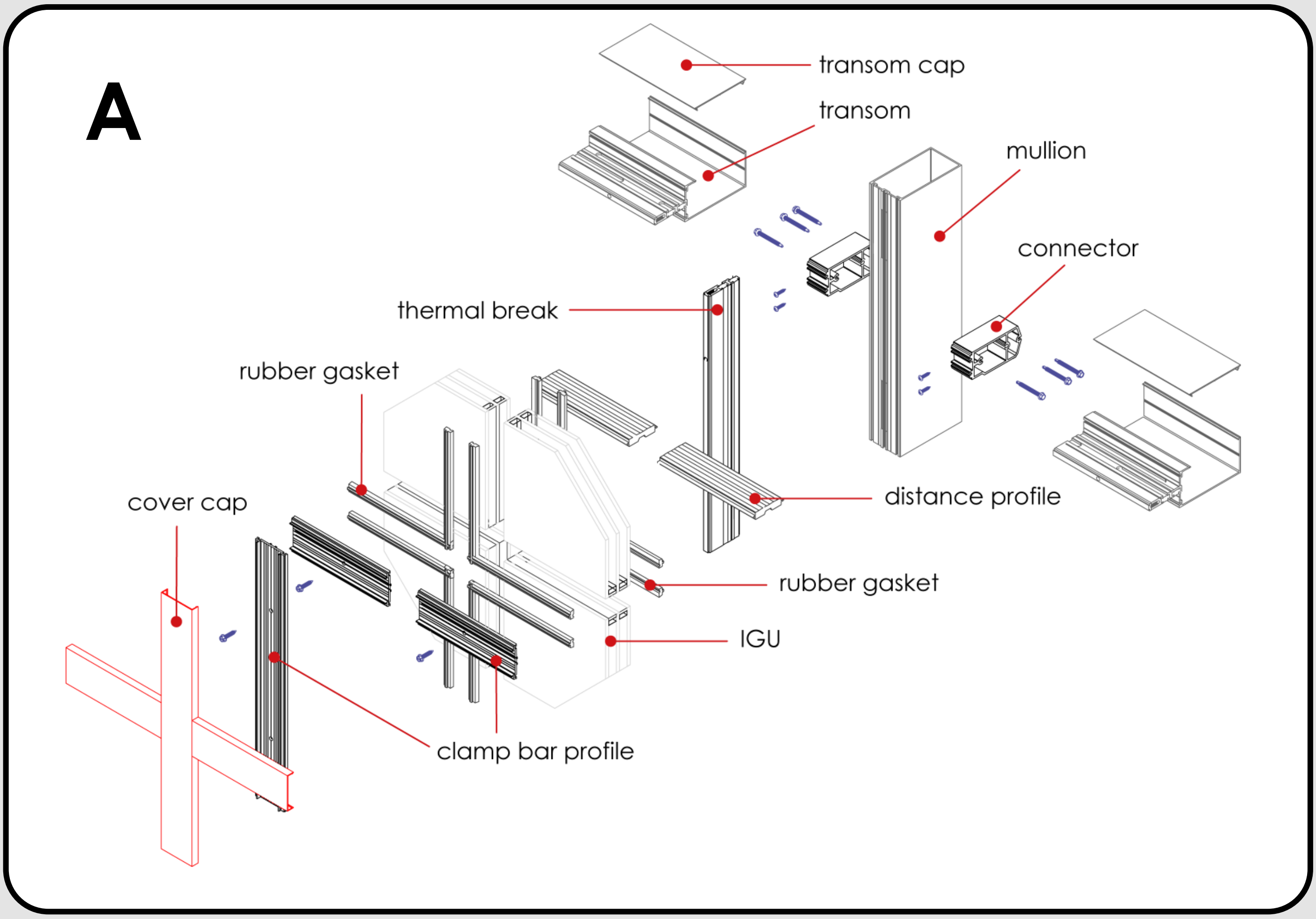


Figure 5.28 Exploded isometric diagram of the intersection mullion-transom (own ill.)

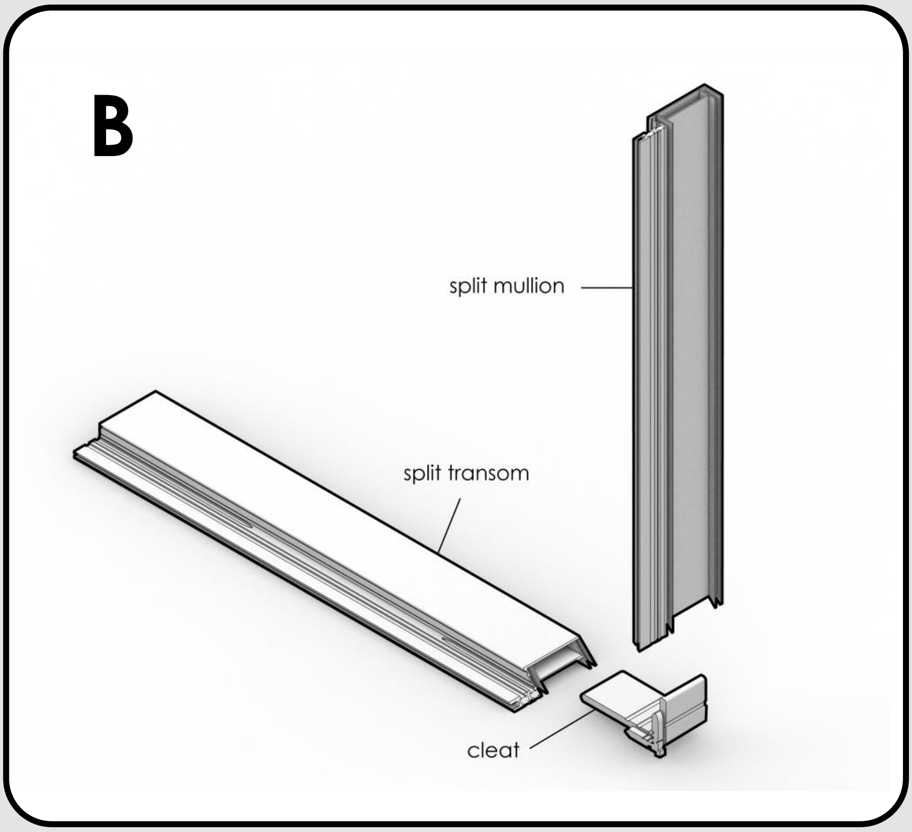


Figure 5.29 Exploded isometric diagram of the corner connection (own ill.)

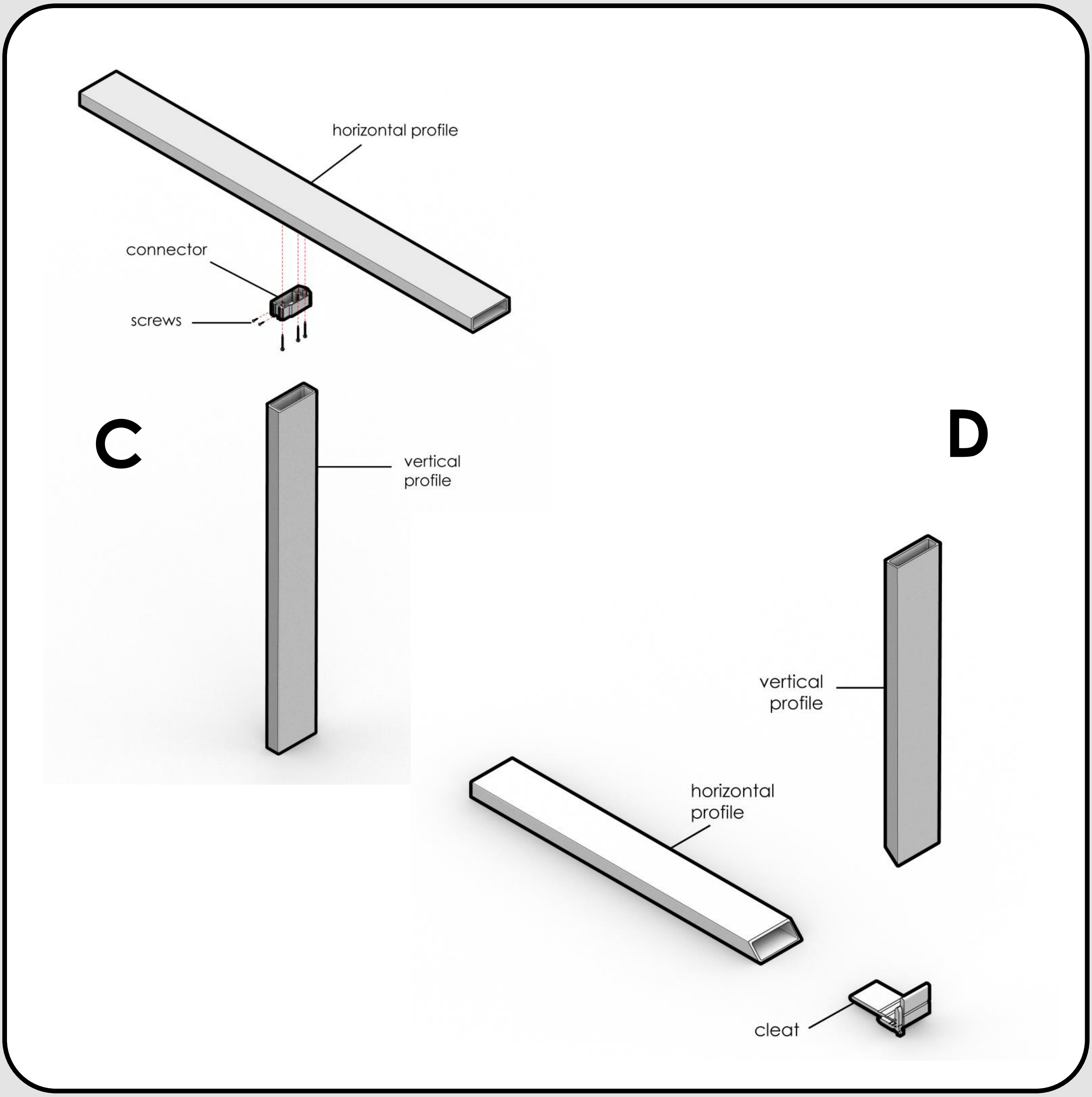
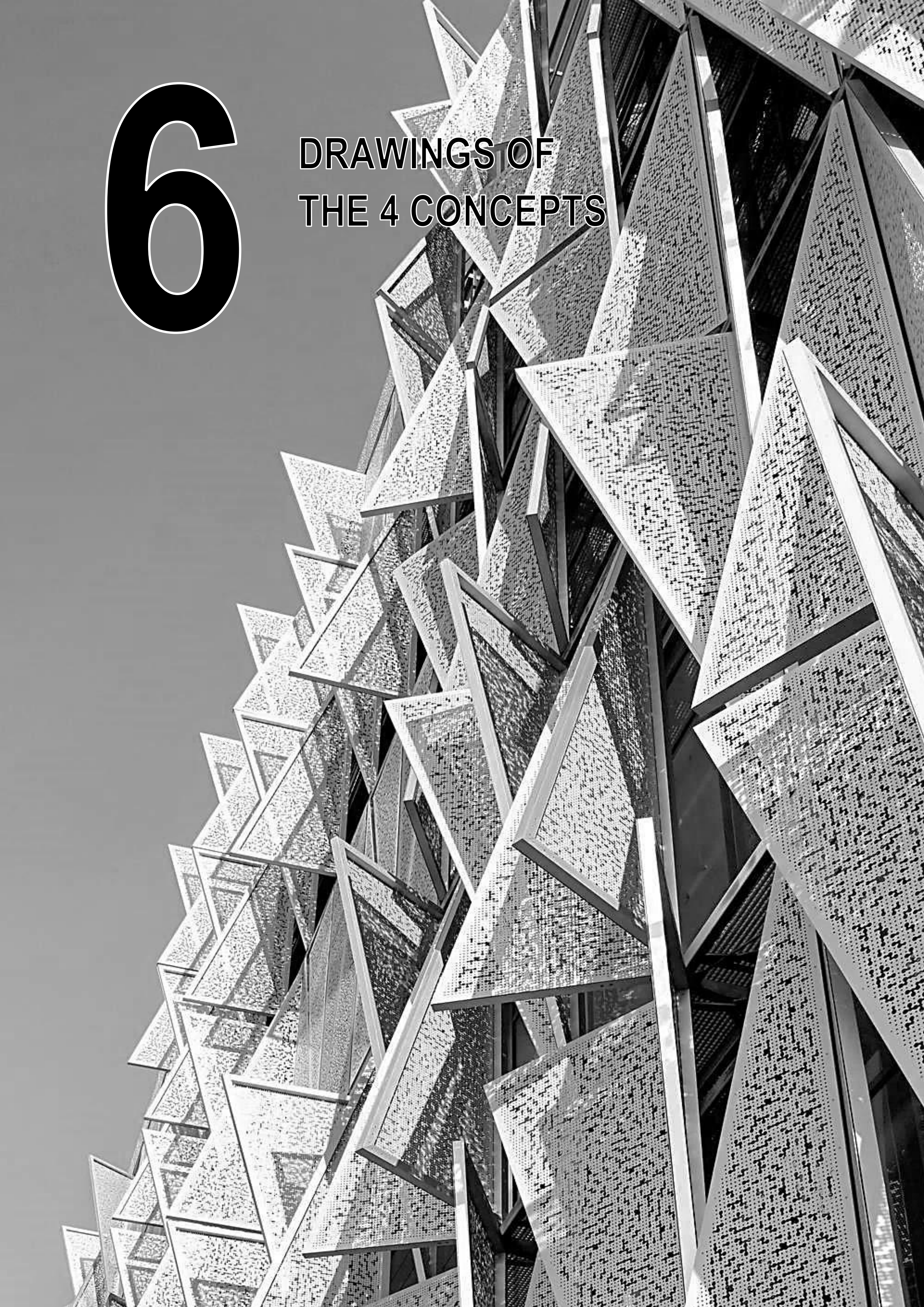


Figure 5.30 Exploded isometric diagrams of the connections C and D (own ill.)

6

DRAWINGS OF THE 4 CONCEPTS



6.1 introduction

This Chapter provides the drawings that were made for assessing the disassembly potential of the 4 Climate Adaptive facade concepts.

The 4 concepts are illustrated again in Figure 6.1, and named:

ADAPTIVE CONCEPT R1 – Vertical Rotating Fins

ADAPTIVE CONCEPT R2 – Horizontal Rotating Fins

ADAPTIVE CONCEPT F1 – Horizontally Folding Panels

ADAPTIVE CONCEPT F2 – Vertically Folding Panels

The drawings will be presented in Section 6.2 in the following order (for each concept):

First page:

Front view together with two sections: 1 horizontal and 1 vertical.

Second page:

3D illustration of the facade module, with 3 critical architectural details.

The full list of drawings is given in **Appendix A.** This section only presents a short overview, in order for the reader to get an impression of how the 4 compared concepts are designed.

It should be emphasized that although this research compares 2 mullion materials (aluminum and timber), the drawings are only done for aluminum, because it was considered more complex and profile information was available from manufacturers.

Section 6.3 provides the visualizations of these 4 concepts, as seen from the interior of the office. These rendered drawings were made with the aid of the software Rhinoceros.

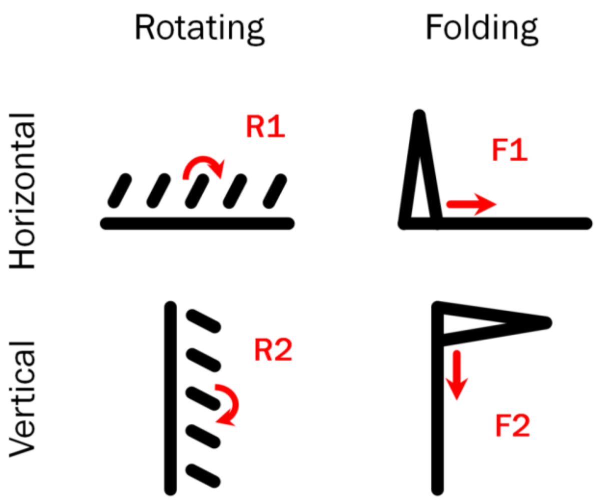


Figure 6.1 The 4 adaptive concepts (own illustr.)

6.2 sections and details

ADAPTIVE CONCEPT R1 – Vertical Rotating Fins

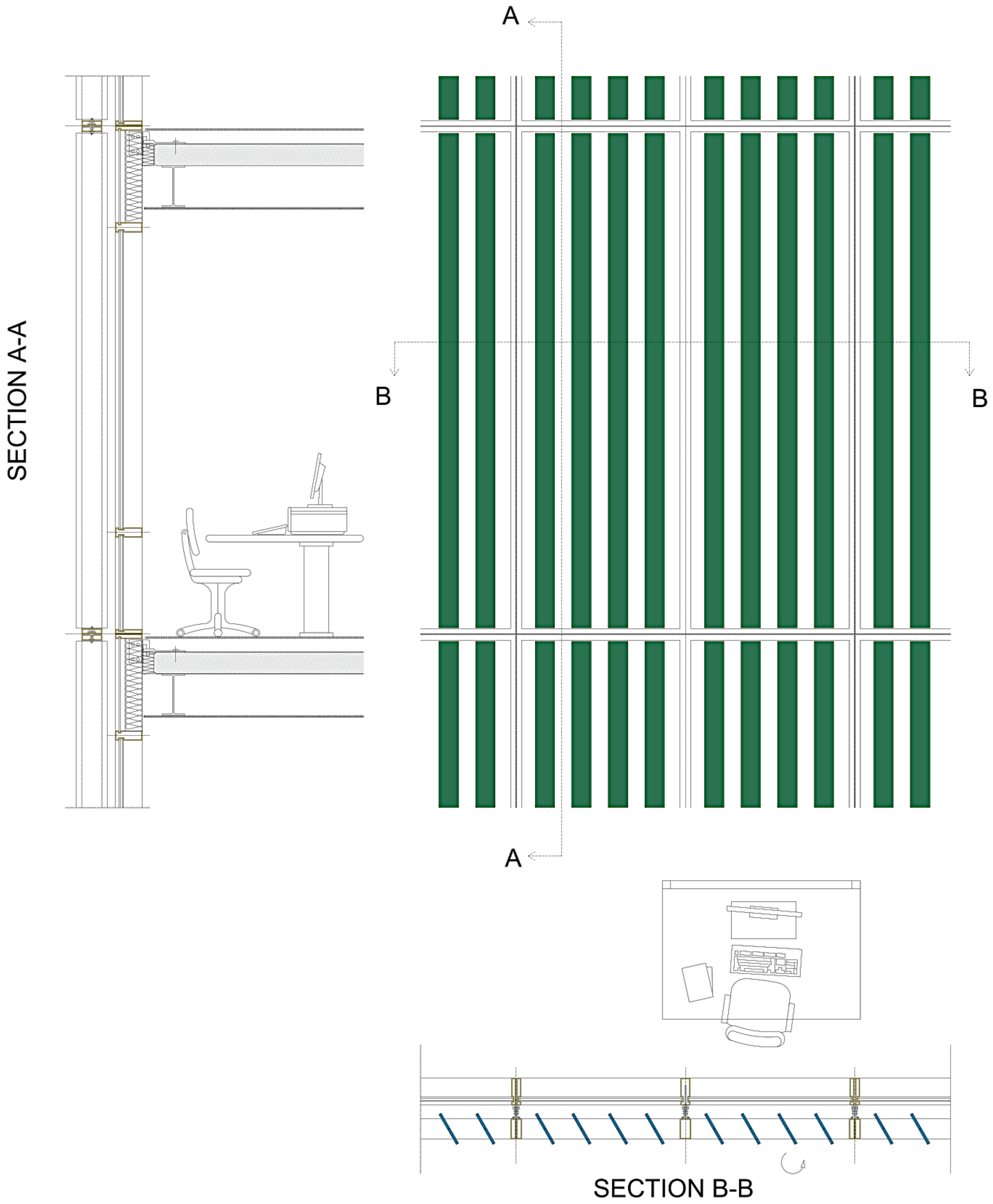


Figure 6.2 Sections and front view of R1 (own ill.)

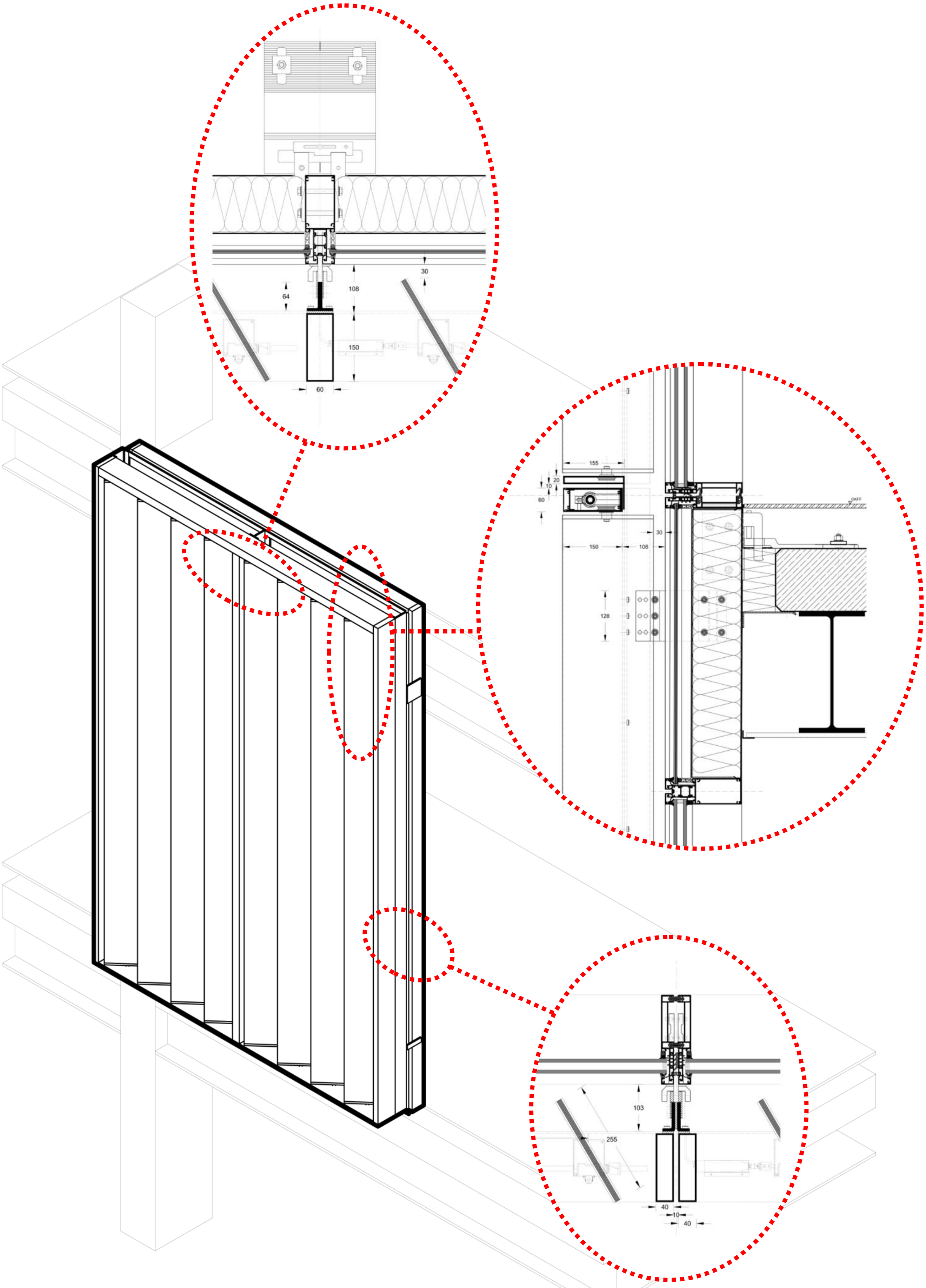


Figure 6.3 3D illustration and details of R1 (own ill.)

ADAPTIVE CONCEPT R2 – Horizontal Rotating Fins

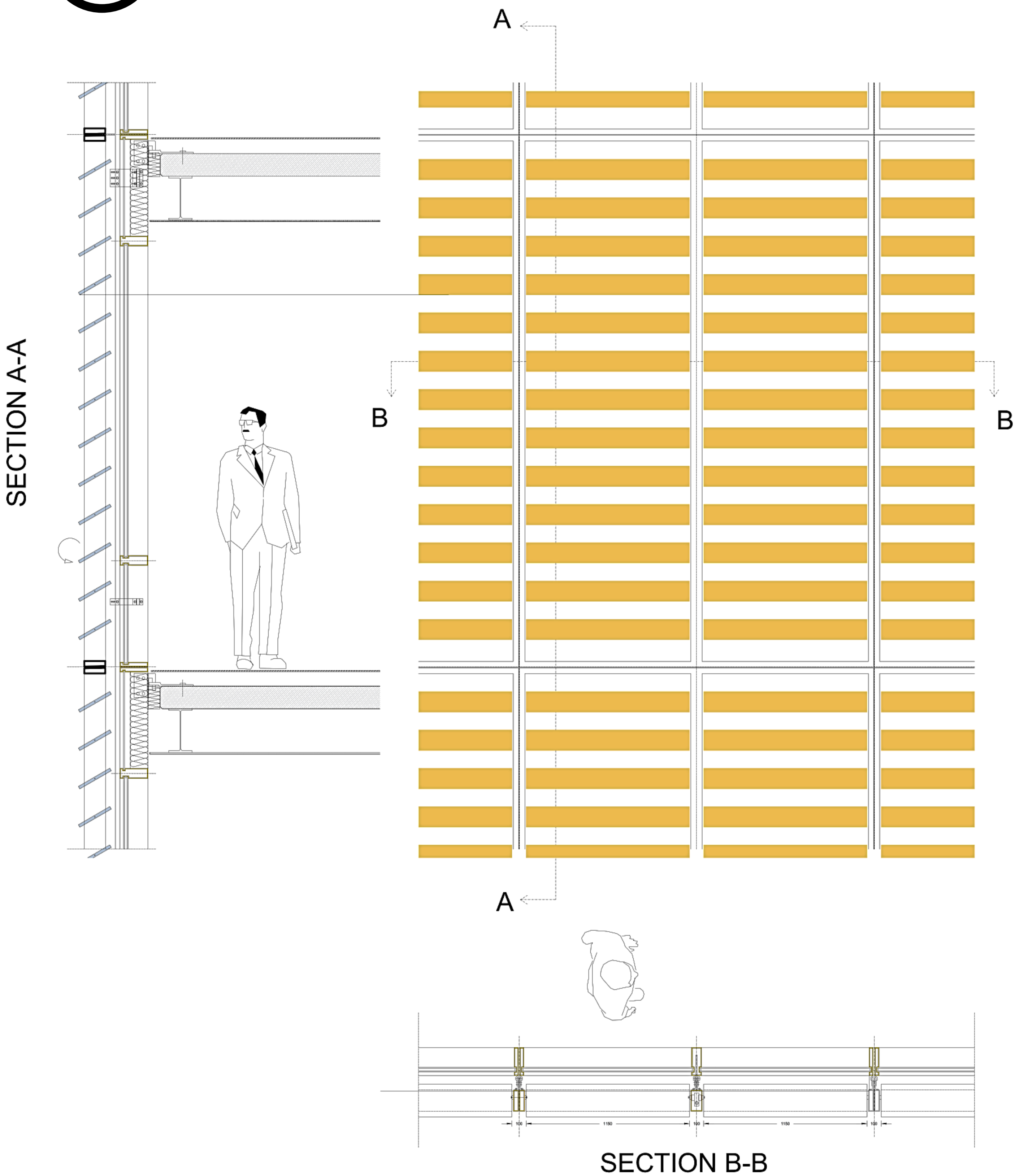


Figure 6.4 Sections and front view of R2 (own ill.)

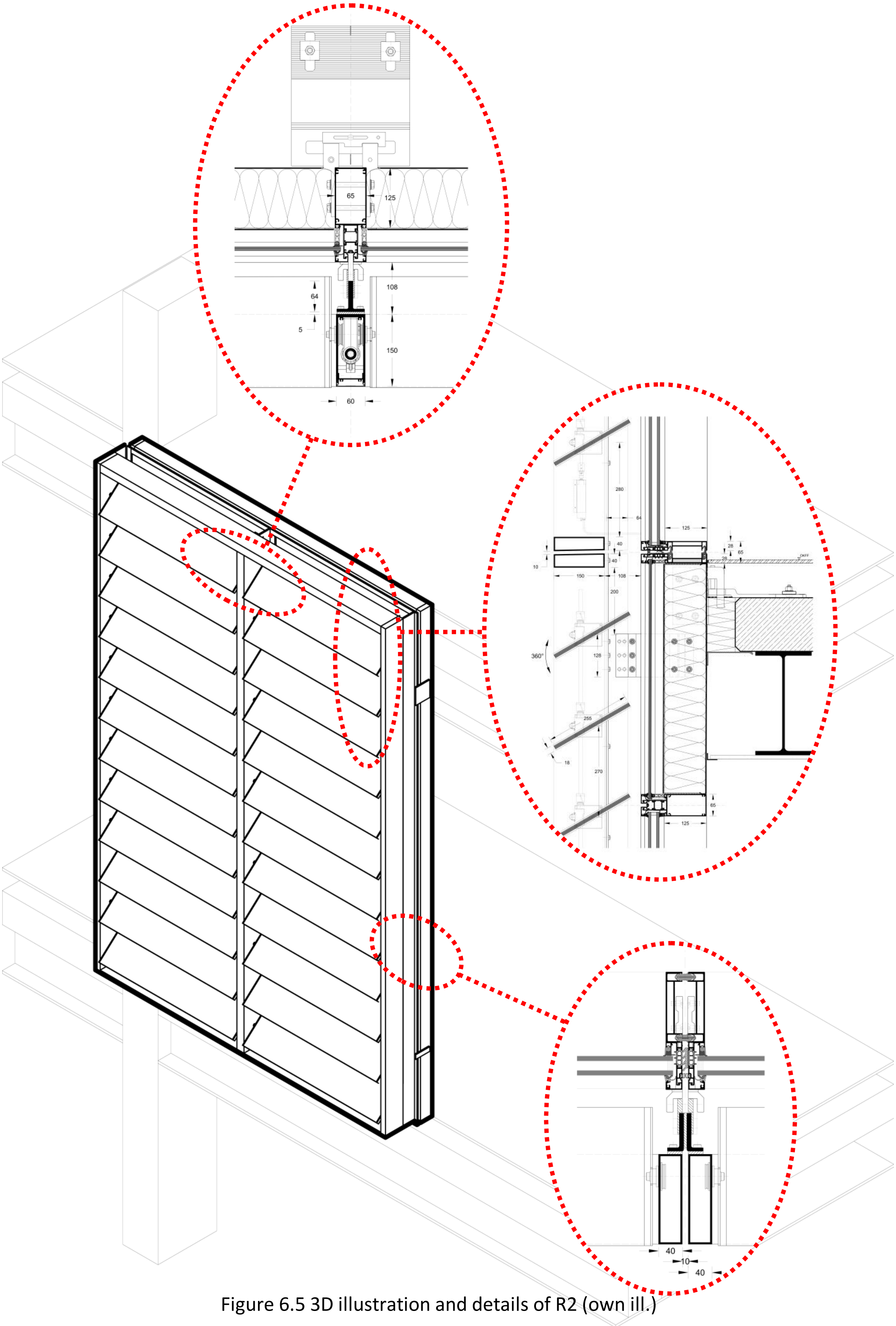


Figure 6.5 3D illustration and details of R2 (own ill.)

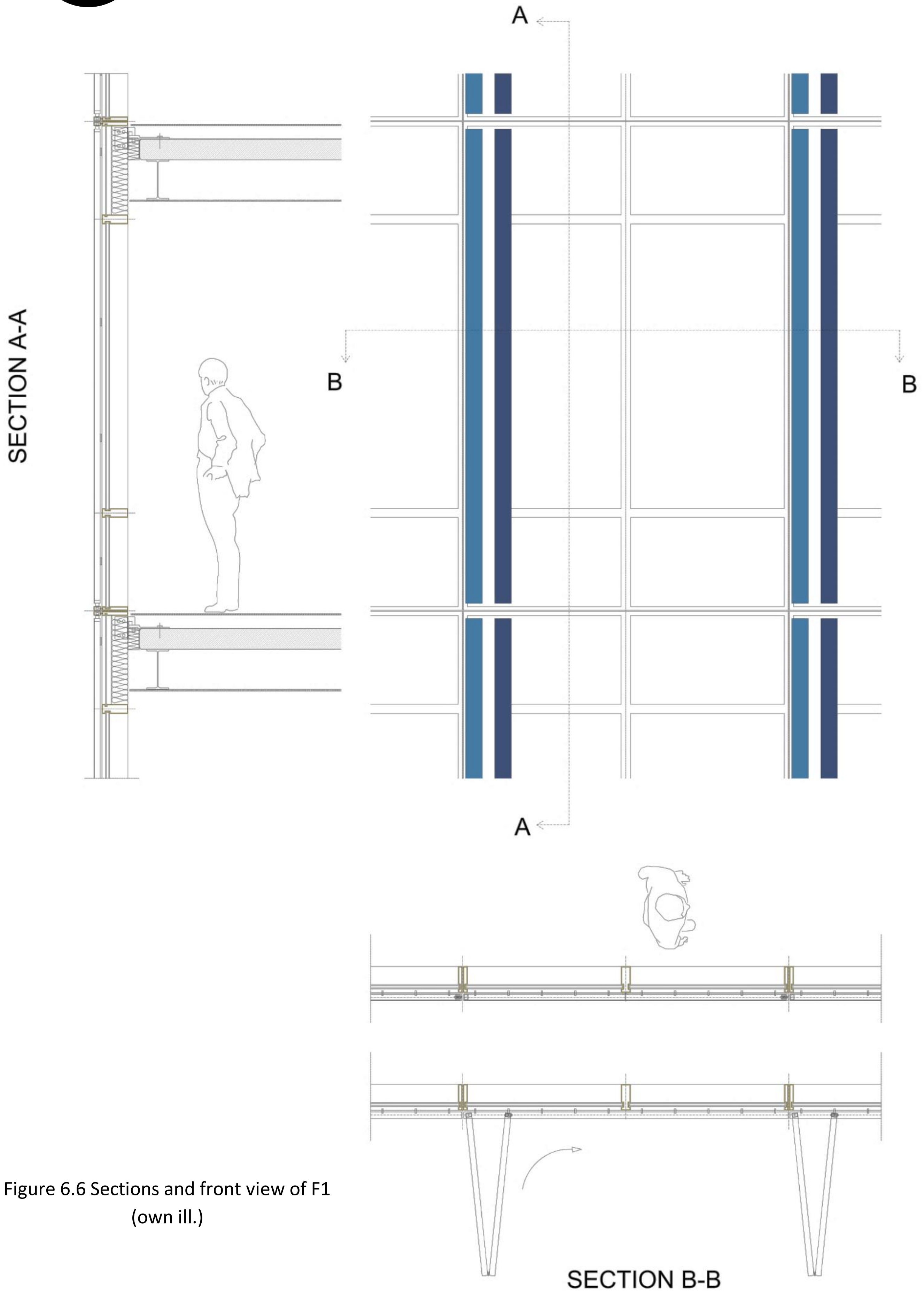


Figure 6.6 Sections and front view of F1 (own ill.)

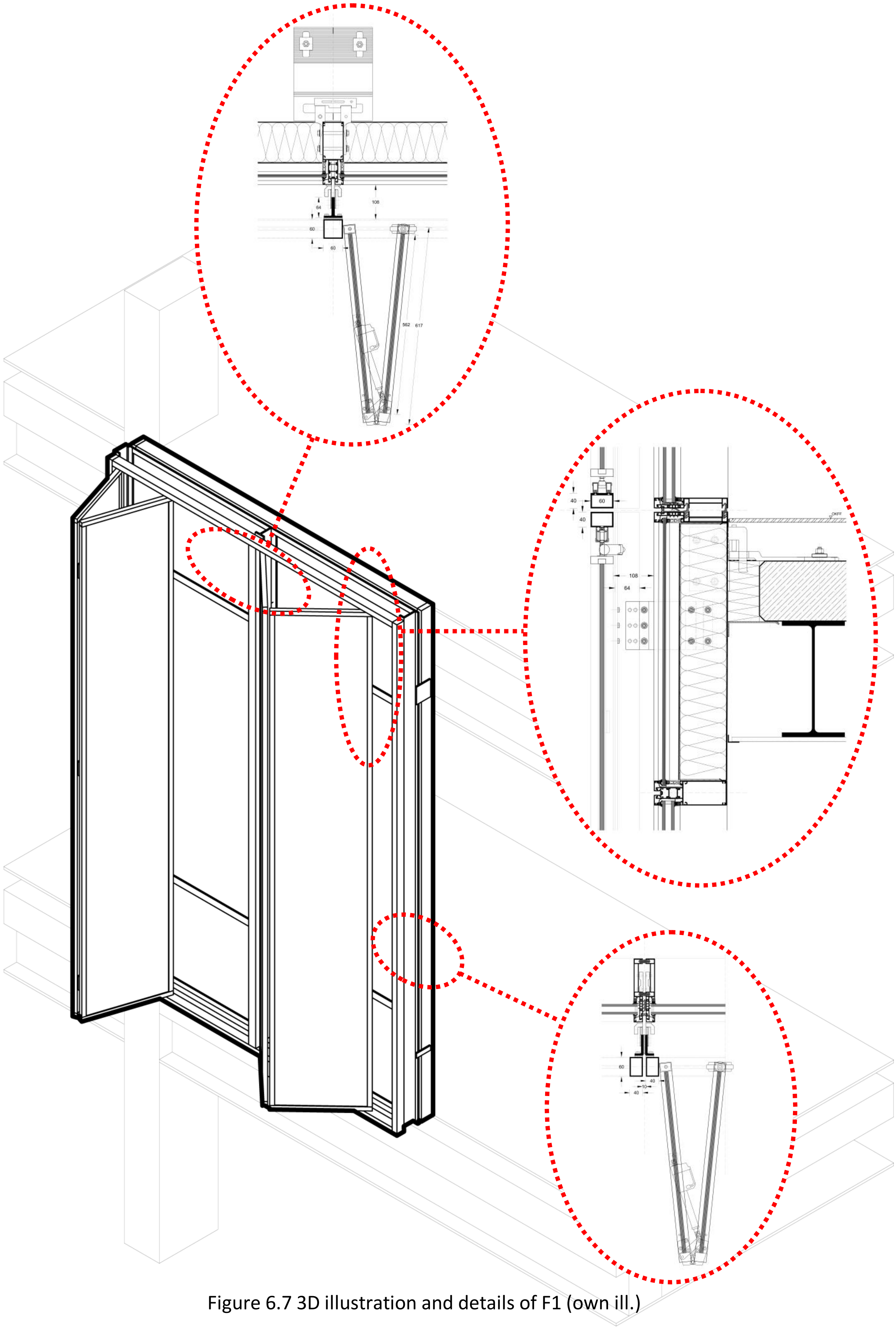


Figure 6.7 3D illustration and details of F1 (own ill.)

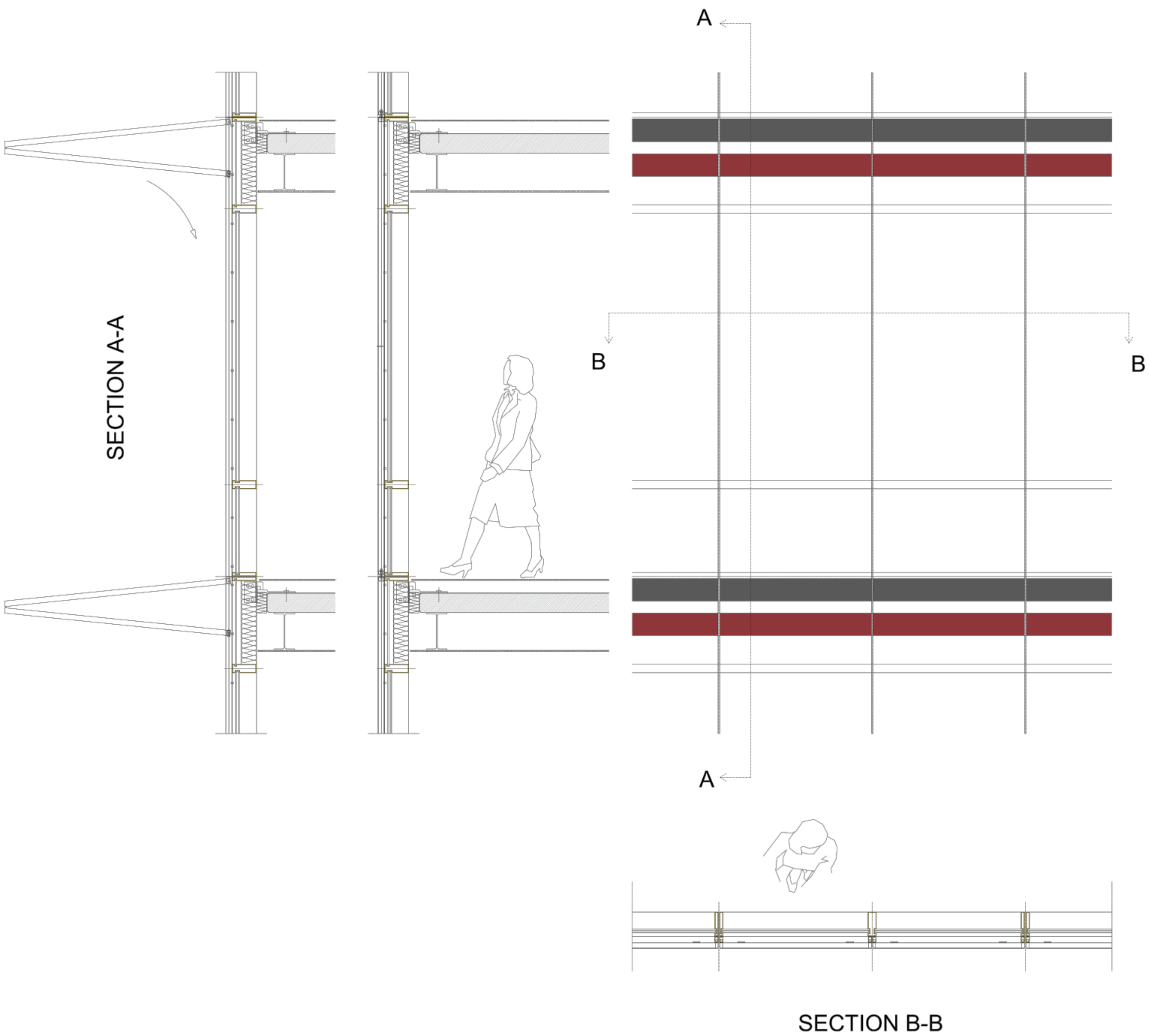


Figure 6.8 Sections and front view of F2 (own ill.)

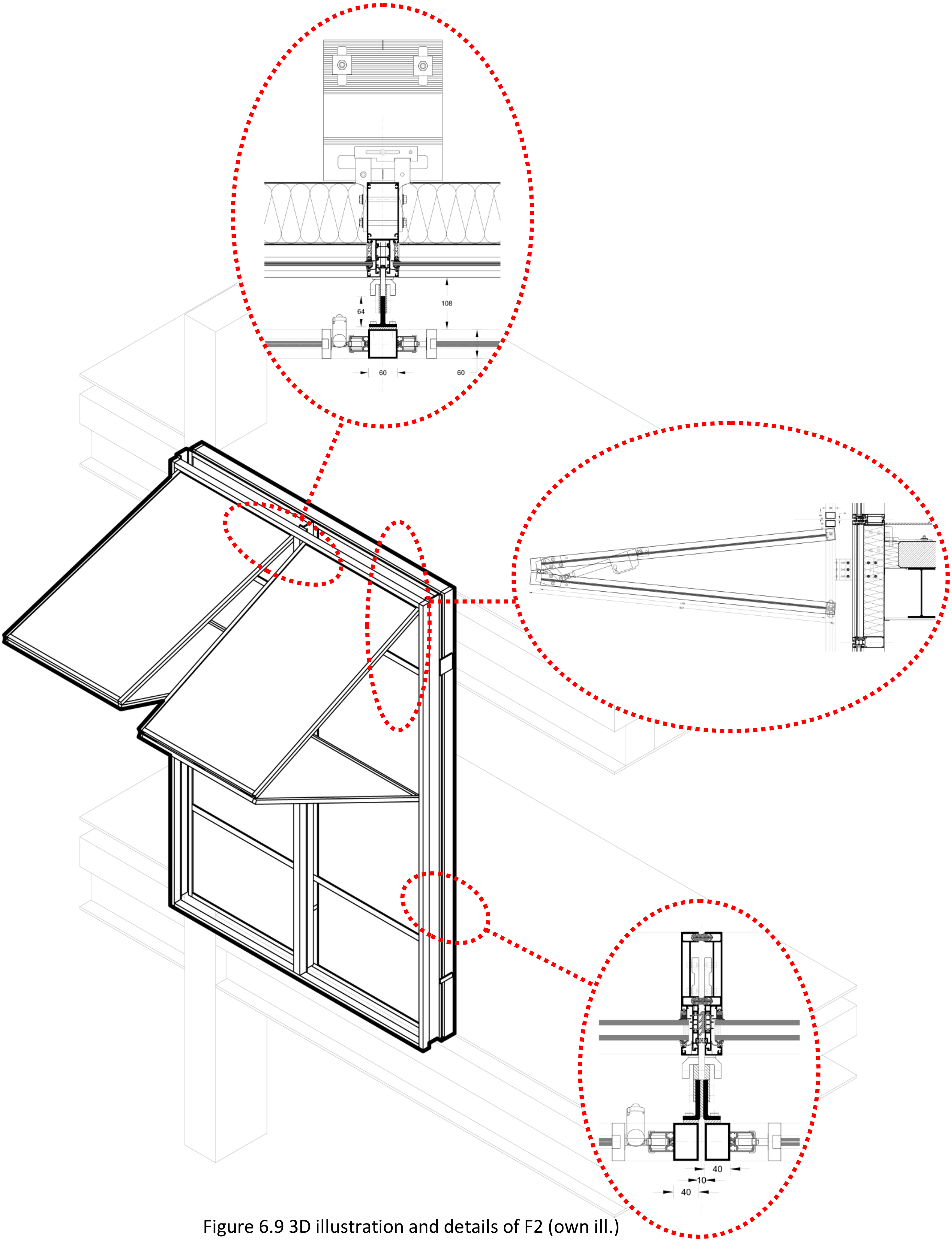
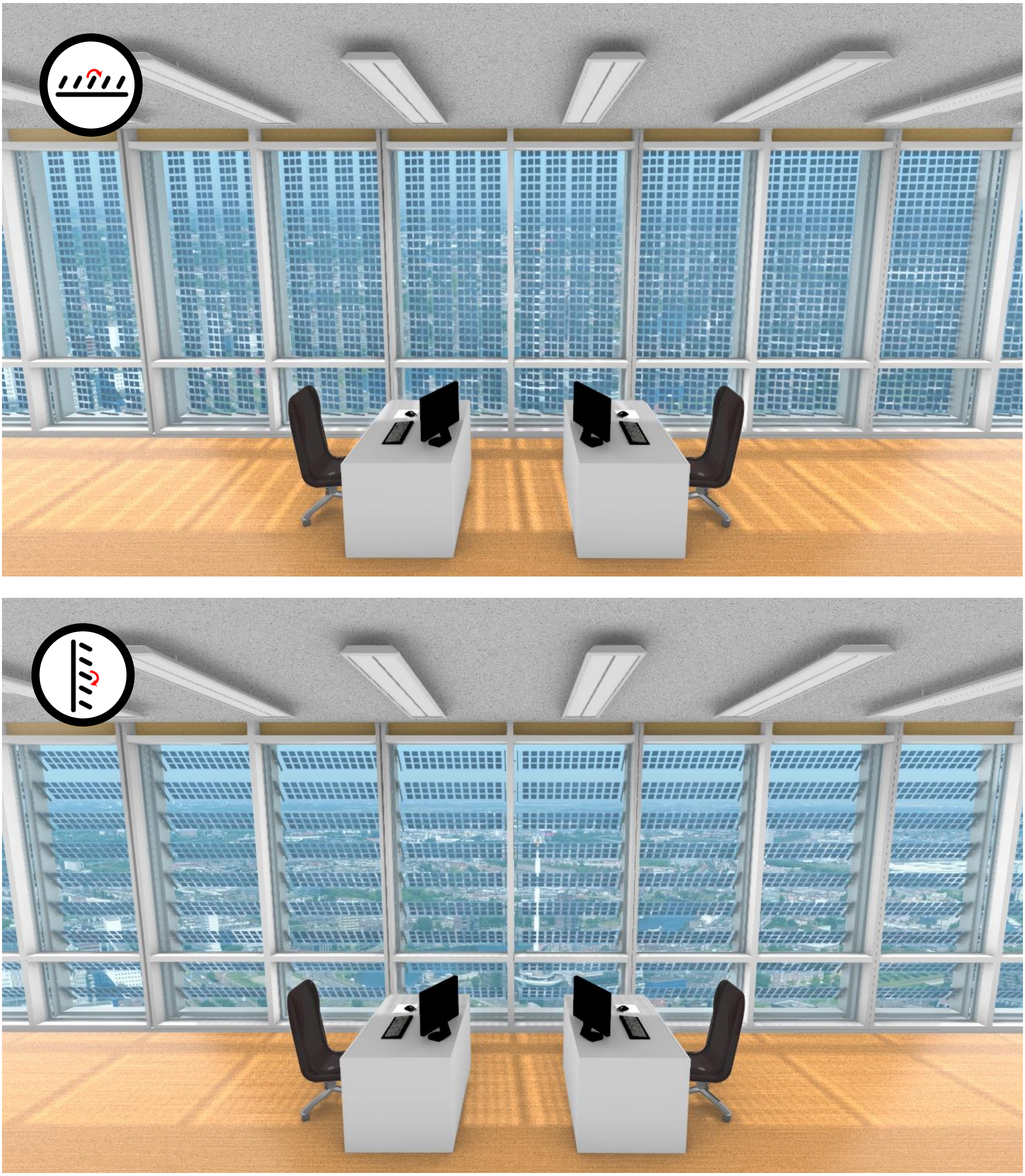


Figure 6.9 3D illustration and details of F2 (own ill.)

6.3 visualizations



Figures 6.9 – 6.10 Renders of R1 and R2 (own ill.)

Figures 6.11 – 6.12 Renders of F1 and F2 (own ill.)

7

ENVIRONMENTAL PRODUCT DECLARATION

image source:
unsplash.com – Scott Webb

7.1 introduction to LCA

In an attempt to give a definition, one could claim that Life-Cycle Assessment (LCA), which is also called Life-Cycle Analysis, is a *qualitative technique for the determination and evaluation of environmental impacts of construction materials and products, services, and processes through production, usage and disposal.* It is a 'cradle-to-grave' approach, which means that it begins with the raw material gathering from the earth, and has its ending point at the return of these materials to the earth. So far, it can be considered that LCA is the most comprehensive tool for the evaluation of the impact that materials have on the environment. However, it is still a quite complicated and time-consuming tool, and there are some limitations at a macro level.

In a more standard definition found in ISO 14040 (2006), LCA consists of a 'compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle'. It can be used either as an independent methodology, or combined with other tools, like for instance life cycle costing (LCC) and social life cycle assessment (SLCA). In this thesis, LCA will take place independently.

An LCA can both identify and quantify the environmental impact of the materials studied for a certain scope, through a:

- formation of an inventory
- evaluation of the impacts
- interpretation of the results

There are four main distinct phases that describe the above-mentioned, according to ISO 14040 and 14044, and are shown within the dotted line of Figure 7.1. These phases have an interdependency illustrated with the arrows, meaning that the result of one phase may affect another one. As shown in Figure 7.1, there is an additional interdependency to possible applications after the last phase, which may include further product development and improvement, strategic planning and marketing, etc.

The four main phases are provided in Table 7.1, where they are also shortly explained. A more extensive and detailed explanation of the 4 phases will be provided in the following sections, with a special focus on the adaptive and circular design concepts of this thesis.

1. Goal and Scope Definition
As the title implies, this first phase is where the purpose of the LCA is defined. This sets the context of the study, and clarifies both how and to whom the results will need to be communicated. Technical details are therefore included, regarding: • the functional unit • the system boundaries • the assumptions and limitations • the allocation method • the chosen impact assessment methodology
2. Inventory Analysis
Having defined the goal and scope, the Life Cycle Inventory (LCI) stands for the quantification of the energy and material flows and the environmental releases, which are associated with all the production stages. For this, a flow chart is constructed, with the use of the inputs and outputs. A clear picture should be provided regarding the activities and the boundaries.
3. Impact Assessment
This phase aims at the evaluation of the environmental impacts, associated with the energy and raw material inputs, as quantified in the LCI. The Life Cycle Impact Assessment (LCIA) includes the following: • selection of the impact categories and a representative indicator for each, together with an environmental model. • classification of elementary flows from the LCI, where the parameters are assigned to specific impact categories. • measurement of the impact, for which the classified LCI data is characterized by certain measures called 'midpoint indicators', into common equivalent units, which are then summed and give the overall impact.
4. Interpretation
The results from the LCIA are interpreted in order to: • identify the significant issues that occurred from the results of the LCI and LCIA • evaluate the level that the study is completed • reach a conclusion, provide the limitations and mention recommendations

Table 7.1 Phases of an LCA – a short description

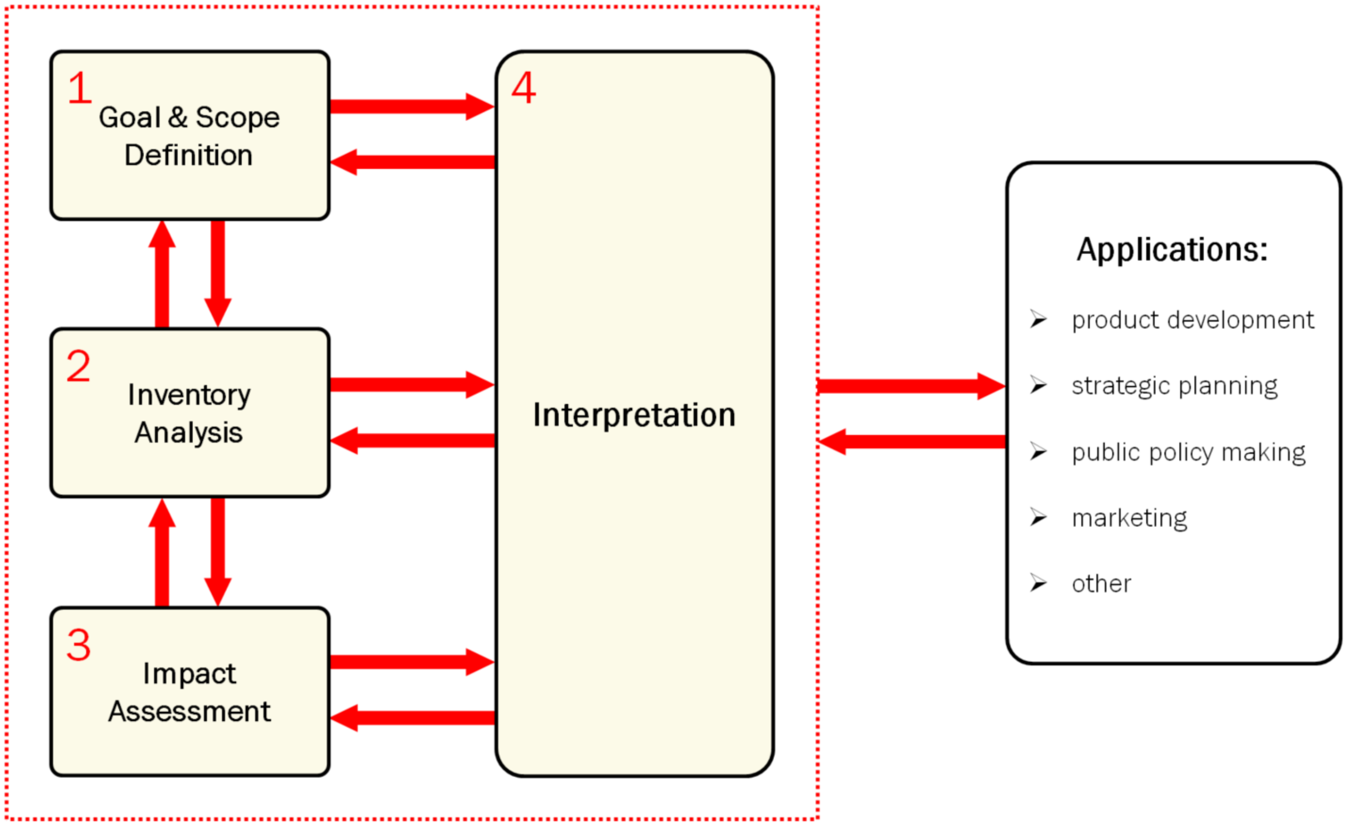


Figure 7.1 The LCA framework, as modified from the ISO 14040

7.2 life cycle stages

Before conducting an LCA, it is of paramount importance to know exactly which are the stages of the life cycle of the building envelope. It is therefore necessary to have full awareness of the bigger picture. Since buildings have an interference with the environment during their lifespan, the same is true for their exterior skin. In this section, a closer look at the many distinct life stages of a certain product will be provided; in this case being the unitized building envelope. These stages are:

1. product stage
2. construction process stage
3. use stage
4. end-of-life stage
5. benefits and loads beyond the system boundary

and they are depicted in Figure 4.2, where their sequence is shown. In the same figure, the numbering of the Life Cycle stages according to the EN standards is provided **in red** colour, and they are also shown in the scheme in Figure 7.3, which is adapted from the EN standards.

7.2.1. Product Stage

The product stage involves all the processes that are related to producing the construction materials that will be used in the building. This stage entails raw material extraction, transportation between the extraction point and the production site, as well as the final production of construction elements.

7.2.2. Construction Process Stage

In this stage, the whole journey that construction products take is considered, right from the production line, up to the finalised building. Transportation of the materials, the energy that is required to power the construction equipments, any waste that may need to be disposed of, are all parts of this 'journey', which ends with the installation on the building.

7.2.3. Use Stage

The use stage concerns the operational energy that is required in order to occupy or use the building during its life, such as energy and water, as well as processes required for maintenance, repairs and replacements of materials. Possible refurbishments and renovations also belong to the use stage.

7.2.4. End-of-Life Stage

The processes of this stage are based on scenarios, and they relate to whatever will happen after the end of the building's life. Demolishing the building and the processes that take turn afterwards, such as reprocessing of some elements, are all included within this stage.

7.2.5. Benefits and loads beyond the system boundary

Reuse, recycling and recovery of the materials used in the building are the pillars of this scenario-based stage. Calculation of the pros and cons of such actions will contribute outside of the system boundary, and therefore a seperate report shall be made, according to the European standards.

Definitions

Some important definitions that need to be clarified before conducting an LCA, are the following:

- **Cradle-to-grave** refers to the complete LCA from raw material extraction ('cradle') up to the use and disposal ('grave'). All of the inputs and outputs should be carefully considered in all the LC stages.
- **Cradle-to-gate** is a partial LC assessment of a product, that covers the raw material extraction stage up to manufacturing (factory 'gate'). Use and disposal are not included in this assessment.
- **Cradle-to-cradle** can be considered to be a special kind of cradle-to-grave assessment, in which the final stage is the recycling process instead of the end-of-life disposal.
- **Gate-to-gate** is an LCA that only looks at a specific process of the whole production chain.

It should be emphasized at this point that the environmental assessment conducted in this chapter is actually a **cradle-to-gate** assessment. This is because a separate DfD criterion is used for the end-of-life assessment, as well as for the life expectancy and maintenance, and therefore a simplification of this assessment was deemed necessary.

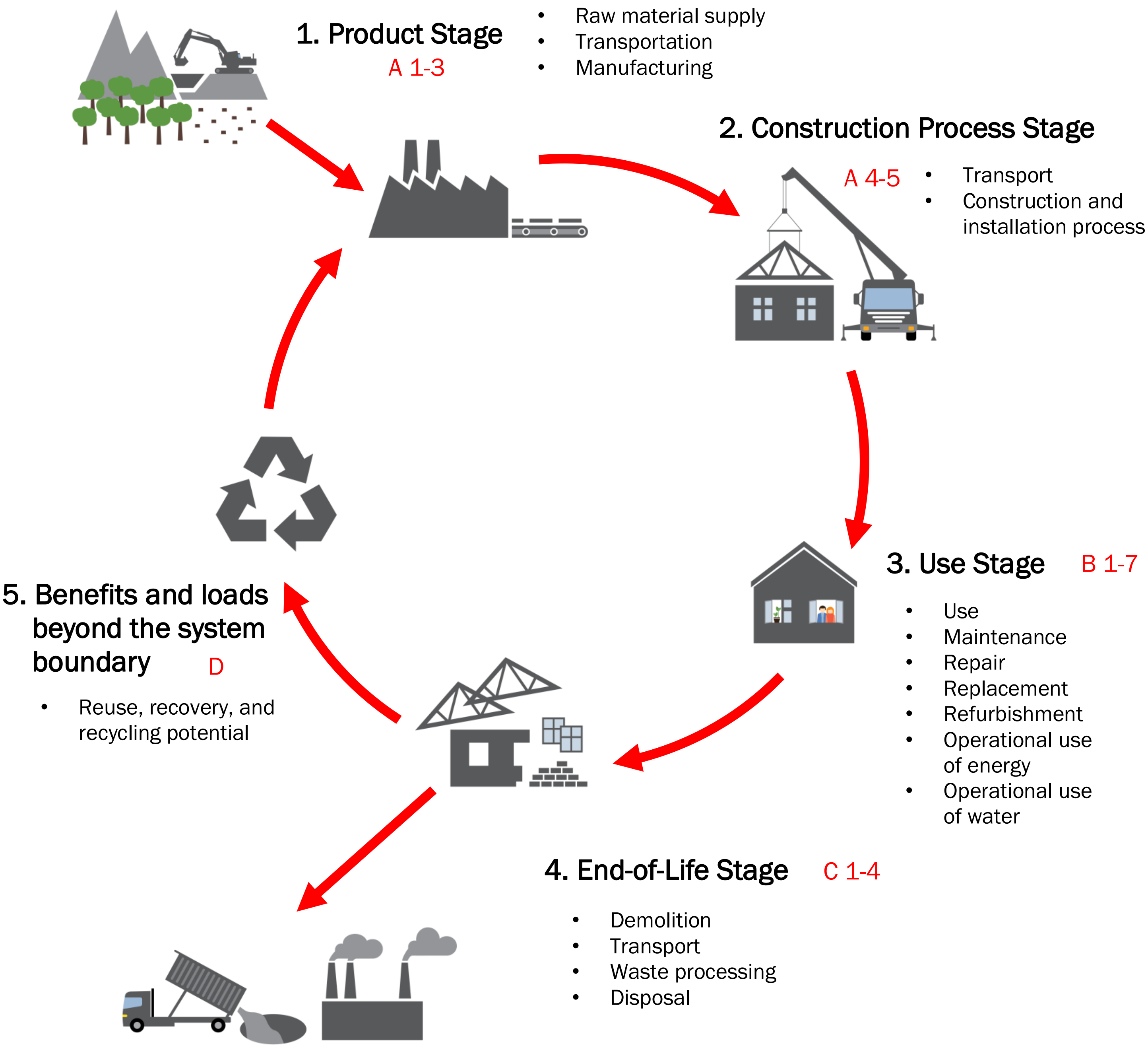


Figure 7.2 The Life Cycle Stages – adapted from Birgisdóttir & Rasmussen (2016)

A 1-3			A 4-5		B 1-7					C 1-4				D
PRODUCT stage			CONSTRUCTION PROCESS		USE stage					END OF LIFE stage				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction - Installation process	Use	Maintenance	Repair	Replacement	Refurbishment	De-construction - demolition	Transport	Waste Processing	Disposal	Reuse - Recovery - Recycling potential

Figure 7.3 The Life Cycle Stages – adapted from the EN standards
in red: the part of the current cradle-to-gate assessment

7.3 environmental indicators

Indications of the impact to the environment can be provided through either **endpoint** or **midpoint** indicators (Blom 2010). The former relate to problems threatening the life conditions; damage to ecosystems, humans etc. They are however difficult to quantify, since they have high uncertainties, being the result of multiple impact interactions. This is the main reason LCA works with the latter; the midpoint indicators.

This section provides a clear overview of the 10 environmental impact categories that are most frequently used in LCAs in the Netherlands; namely the abiotic resource depletion, the global warming potential, the ozone layer depletion. the human toxicity, the fresh-water aquatic ecotoxicity, the marine aquatic ecotoxicity, the terrestrial ecotoxicity, the photochemical oxidation, the acidification and the eutrophication. These are the ones that the Dutch National Database uses to perform the Impact Assessment, and they are therefore also used in this thesis.

7.3.1. Abiotic Depletion

The abiotic resource depletion is a measure for the depletion of minerals and fossil fuels that are not renewable in nature within a span of 500 years. This way, the resources can be unavailable and possible extraction may cause disruption to the ecosystems, meaning that there is an impact on prosperity. The midpoint indicator that is used in this case is the Abiotic Depletion Potential (**ADP**) expressed in **kg Sb eq**.

7.3.2. Global Warming

This impact category measures the emissions of greenhouse gases to the air, which increase the earth's temperature by absorbing the infrared radiation. This category can have impacts on prosperity, human health and ecosystems, and the midpoint indicator that is used is the Global Warming Potential (**GWP**) which is expressed in **kg CO_2 eq**.

7.3.3. Ozone Layer Depletion

The impact category Ozone layer depletion measures the emissions of ozone layer depleting substances to the air. The sources can be cooling agents, aerosols, solvents etc., and the impacts are mainly on human and animal health, terrestrial and aquatic ecosystems, and materials. The impact score uses the midpoint: Ozone Depletion Potential (**ODP**), expressed in **kg CFC-11 eq**.

7.3.4. Human Toxicity

The effect of toxic substances in our health is covered by this category. It's the result of emissions of toxic substances to air, water and soil which influences humans' air breathing or water drinking. It can also harm humans indirectly, when plants or animals - which have toxins - are consumed. The exposure is modelled with fate models, and the midpoint in this case is Human Toxicity Potential (**HTP**), rated in **kg 1,4-DB** (dichlorobenzene) **eq**.

7.3.5. Fresh-water Aquatic Ecotoxicity

This indicator refers to the impact that the emissions of toxic substances to air, water and soil have on fresh-water ecosystems. The impact categories for ecotoxicity (4.3.5 – 4.3.7) are in an ongoing debate for their use due to their complexity and the big number of ecosystems through which the toxic substances travel, spread or degrade. The characterisation factors are expressed in **1,4-DB eq**. (dichlorobenzene equivalents/kg emission).

7.3.6. Marine Aquatic Ecotoxicity

This impact category measures the effect that toxic substances have on the marine ecosystems. The same as freshwater ecotoxicity (4.3.5) applies in this case, both in terms of complexity and in expression units - **1,4-DB eq**.

7.3.7. Terrestrial Ecotoxicity

This category refers to impacts of toxic substances on terrestrial (soil) ecosystems. In this case also, the description of fresh-water ecotoxicity covers the content and the units (1,4-DB eq.) of this impact category as well.

7.3.8. Photochemical Oxidation

Photochemical oxidation refers to the formation of reactive chemicals in the troposphere (mainly ozone). Such substances can be harmful to human health and ecosystems and they can damage crops. This problem is also known as “summer smog”. The midpoint in this case is Photochemical Ozone Creation Potential (**POCP**) for emission of substances to air and is expressed in kg C_2H_4 eq. (ethylene equivalents/kg emission).

7.3.9. Acidification

Acidic elements may be the cause of a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems. In other words, it can range from degradation of building materials to fish mortality. Acidification Potentials (**AP**) is expressed in kg SO_2 eq. (sulfuric dioxide equivalents/kg emission).

7.3.10. Eutrophication

Eutrophication includes all impacts which result from emissions of nutrients to air, water and soil causing macro-nutrients to exceed the acceptable level. Nitrogen and phosphorus have the biggest impact and they originate from fertilizers. Nutrification potential (**NP**) is the midpoint for this category and it is expressed in kg PO_4^3 eq. (phosphate equivalents/ kg emission).

7.3.11 Normalization and weighting

The wide range of environmental impacts used in a Life Cycle Assessment, as described in sections 7.3.1 - 7.3.10, can pose some difficulties in interpreting the results, as there seems to be no relative comparison from one impact to another. This is why normalization and weighting take place, which are used for combining the results of the different categories into one, thus enabling easier interpretation of the result. For instance, BRE Eco-points can be used for the methodology of normalization and weighting of the environmental impacts. (source: white paper - Bruce-Hyrkäs)

In an attempt to define them, **normalization** can be described as the method that compares the results of the different environmental impact categories to a norm, thus enabling a fair measurement on the same scale. This aids in understanding the importance of each result.

Weighting, on the other hand, can be defined as the method in which a certain value is given to each normalized impact category, according to its estimated importance.

In the Netherlands a 'monetarisation' step is included for weighing and adding up the environmental costs of the included impact categories. This is done according to the method 'Bepalingsmethode Milieuprestatie gebouwen en GWW-werken' (Assessment method environmental impact buildings and civil engineering works) as prescribed by the 'Stichting Bouwkwaliteit' (Building Quality Foundation), according to the Dutch Building Regulations 2012, using shadow costs. These shadow costs are the costs in Euro required to compensate the environmental impacts and bring them to a sustainable level. The shadow costs of the respective impact categories are calculated in the 'Shadow prize' table in section 7.5.

7.4 goal and scope definition

7.4.1. Goal of the study

The reason that lies behind the whole research done in this chapter of the master thesis is to inform the industry and construction researchers, such as architects and designers, of the environmental performance of the 4 different adaptive facade concepts, by using 2 different mullion materials. Therefore, **goal of the EPD performed in this research is to compare the environmental impact (from cradle to gate) that the eight different adaptive and demountable unitized facade concepts will have on the environment**. The result could provide useful information regarding the best concept in relation to the environment that combines the adaptive nature to the demountability and modularity.

7.4.2. Scope of the study

7.4.2.1. The functional unit

In this section, a definition of the precise study should be given, together with a quantification of the product system service, which assures that an equivalent function or service will be compared. This way, a reference is provided, which helps relate the inputs and outputs.

In this research, the 4 different adaptive and circular concepts will be compared with eachother for 2 different mullion materials; namely aluminum and timber, comprising a total of 8 different facade modules. The functional unit of this assessment, therefore, is **"1 unitized facade module of 3.75 meters high and 2.5 meters wide** (as indicated in Figure x)**, which encloses part of a high-rise office building for a 50-year service life."**

7.4.2.2. System boundaries

A definition for what system boundaries stand for in an LCA can be given by ISO 14040:*"A set of criteria that specify which of the unit processes are actually part of the product system."*

But before going more deeply into the specific processes, the names and characteristics of the various elements which are studied are shown in Table 7.2. This is the table that quantifies the study.

Figures 7.4 and 7.5 illustrate the boundaries of each CW system, all the way from the production of the compared elements, up to landfilling.

7.4.2.3. Assumptions and Limitations

In order to provide a fair and direct comparison between the different systems, some boundary conditions were assumed to be constant. These are:

- the installation method (unitized)
- the geometry of the structure to be attached
- the type of building (office)
- the human comfort
- any maintenance needed due to unexpected event is neglected (e.g. glass breakage)

The production of the materials that were used, is assumed to take place within a certain radius from the building site. As far as transportation for disposal is concerned, it is also supposed to be in a certain distance from the site. These distances can be inserted when doing an LCA, but in this specific case will be neglected, due to being assumed almost equal in all different module concepts. A potentially false assumption could lead to inaccuracies and thereforwe it is avoided.

All of the assumptions concerning the design of the 8 unitized systems are summarized in Table 7.2.

7.4.2.4. Allocation Method

Normally this is the part where the allocation procedures are described, which are used for partitioning the impacts of a certain process, when the same process should be shared into many products or functions. Common allocation methods are: substitution, system expansion, and partition. The results of different methods may vary, because allocation is a complex procedure. For this LCA, no allocation procedure is performed, since the system has no by-products.

7.4.2.5. Impact assessment methodology

According to ISO 14040, the inventory data is always in association with specific environmental impact categories (see Section 7.3) in an impact assessment.

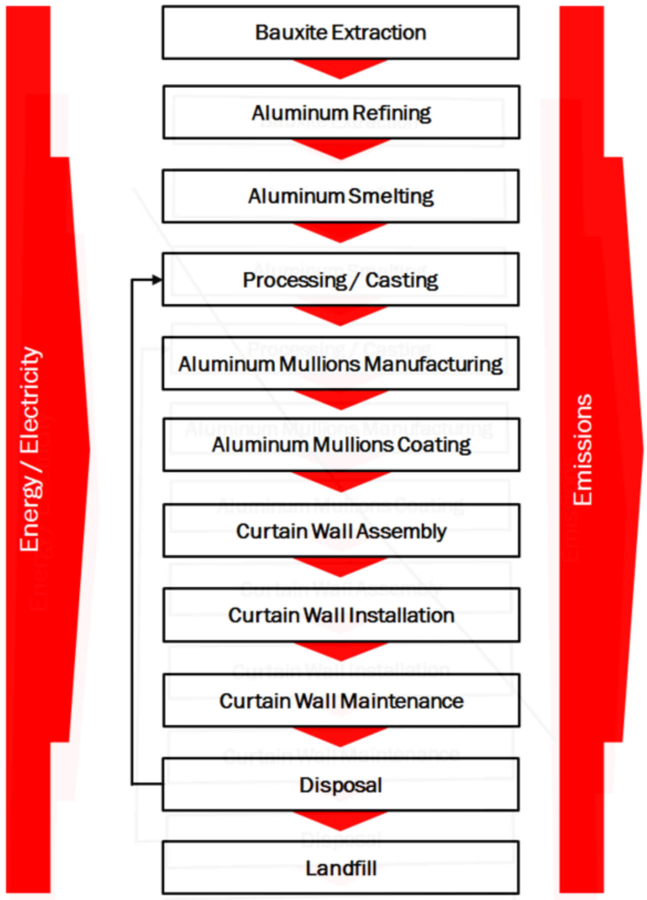


Figure 7.4 System boundaries for aluminum CW (adapted from Y.Kim, 2012)

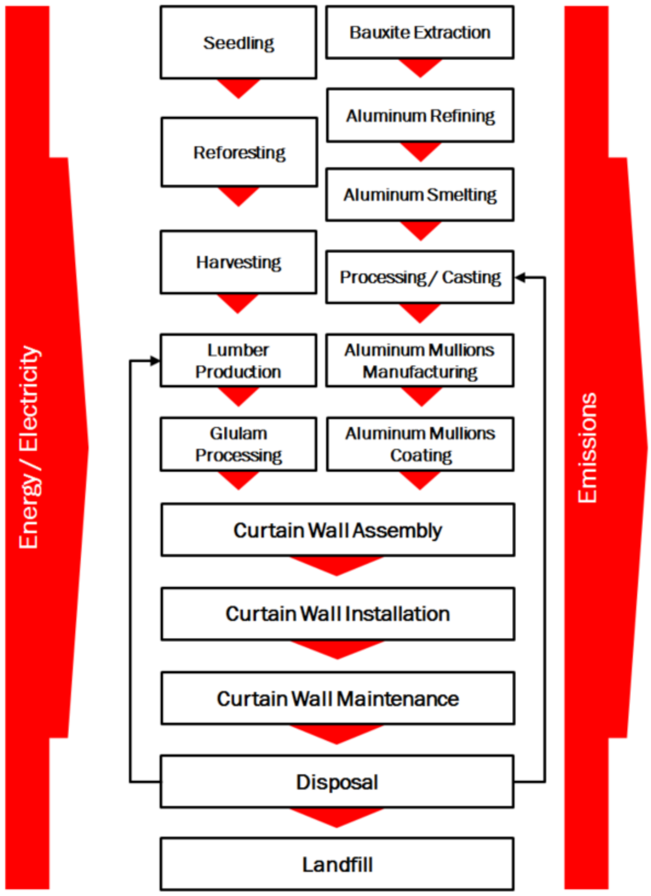


Figure 7.5 System boundaries for timber CW (adapted from Y.Kim, 2012)

ASSUMPTIONS concerning the design	
1	The maintenance and cleaning that is required is about the same for all 8 adaptive concepts, and can therefore be left out of this comparative analysis.
2	The anchors can be ignored, since they are assumed to be the same in all the different concepts.
3	The elements of the curtain walls can be considered the same among all concepts, except for the inner mullions which can be either aluminum or timber.
4	All the infill materials are the same for all 8 concepts and therefore neglected in this LCA - their insulation properties are considered to be adequate in terms of thermal comfort.
5	In the shading system, the laminated PV glazing can be considered to be of equal amount in all 8 concepts, and thus it is also neglected.
6	The motors are also assumed to be of equal amount among all concepts - therefore left out of the LCA.
7	The connections between the different CW elements (mullions - transoms, etc.) are assumed to be of approximately the same weight of materials. They are accounted for in another DfD criterion.
8	It is assumed that the life expectancy of the timber mullions (and transoms) is half of the aluminum's.
9	The density for aluminum is considered 2700kg/m^3 and for timber 380kg/m^3

Table 7.2 Summary of assumptions regarding the design of the systems

7.5 inventory analysis

The life cycle inventory (LCI) deals with the quantification of the raw materials and the energy that is consumed throughout the whole life of the curtain wall scenarios. The final inputs and outputs of each scenario are the outcome of this phase, and they are based on assumptions made when defining the **scope**, the **system boundaries**, the types, distances and fuels of the **transportation**, as well as the **data sources** that are used. A description of the scope, system boundaries and assumptions was given in the previous section. This section will focus on the material quantification.

It was already mentioned in Section 7.4.2.3 that the **transportation** procedures which take place in order to carry the curtain wall system initially from the manufacturer to the site, and eventually from the site to the landfill were assumed to be almost the same for aluminium and timber in all the different concept modules, and therefore neglected.

It was assumed (in number 8 of Table 7.2) that life expectancy of a timber element is half as much as the aluminium element. This means that the timber frame needs to be replaced twice as often. This is why the impact of timer elements is doubled, in order to equal the aluminium respectively.

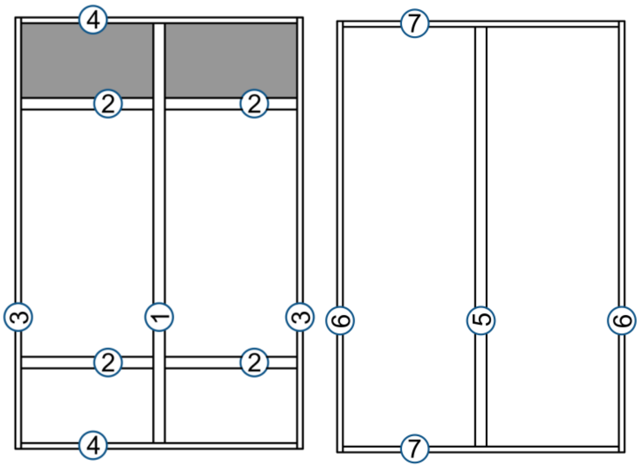


Figure 7.7 Module with numbered mullions and transoms of the back facade on the left and of the exterior shading on the right (own illustration)

Tables 7.3 and 7.4 on the next page show the list of all the elements that are used in the Life Cycle Assessment as indicated in Figure 7.7 and their weights, which are summed according to material. The colours used indicate the material. For example orange is used for timber, and the rest are aluminium, grouped according to its use. Then the calculation of the impact is performed, as explained in the next section.

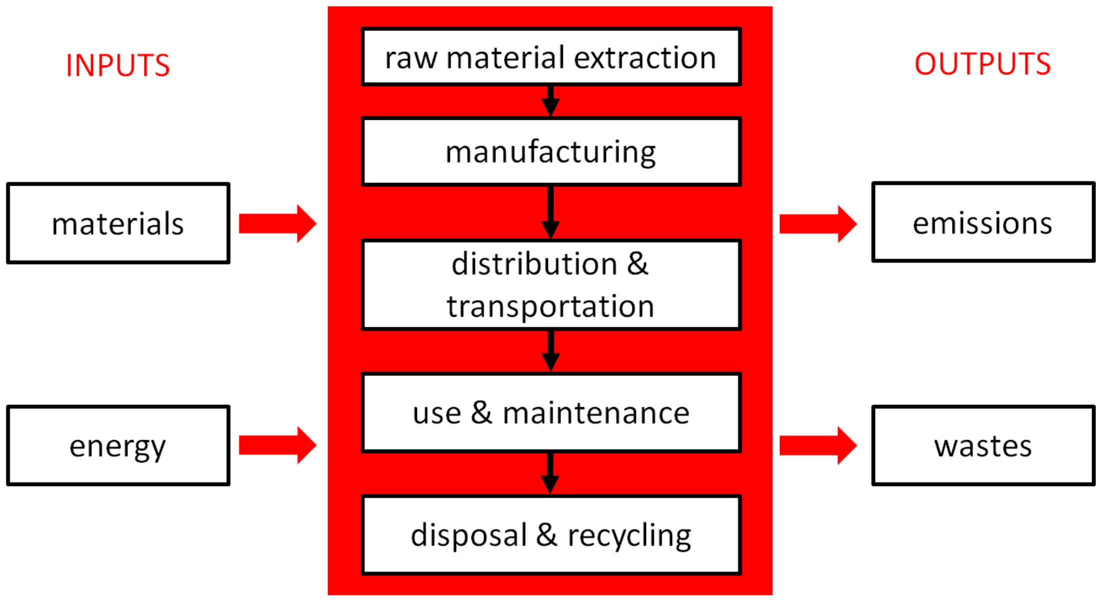


Figure 7.6 The inventory general flow diagram, which covers the LC stages. (own illustration)

ALUMINUM CW									
concept	part of the module	element name	material name	amount nr.	area mm2	height/length mm	volume m3	density kg/m3	weight kg
R1 - A	CW - A	mullion (1)	aluminum	1	1625	3750	0.00609375	2700	16.453125
		transom (2)	aluminum	4	6500	1250	0.008125	2700	21.9375
		split mullion (3)	aluminum	2	2100	3750	0.007875	2700	21.2625
		split transom (4)	aluminum	2	2100	2500	0.00525	2700	14.175
	SHADING	exterior mullion (5)	aluminum	1	1800	3750	0.00675	2700	18.225
		exterior split mullion (6)	aluminum	2	3600	3750	0.0135	2700	36.45
		exterior split transom (7)	aluminum	2	3600	2500	0.009	2700	24.3
R2 - A	CW - A	mullion (1)	aluminum	1	1625	3750	0.00609375	2700	16.453125
		transom (2)	aluminum	4	6500	1250	0.008125	2700	21.9375
		split mullion (3)	aluminum	2	2100	3750	0.007875	2700	21.2625
		split transom (4)	aluminum	2	2100	2500	0.00525	2700	14.175
	SHADING	exterior mullion (5)	aluminum	1	1800	3750	0.00675	2700	18.225
		exterior split mullion (6)	aluminum	2	3600	3750	0.0135	2700	36.45
		exterior split transom (7)	aluminum	2	3600	2500	0.009	2700	24.3
F1 - A	CW - A	mullion (1)	aluminum	1	1625	3750	0.00609375	2700	16.453125
		transom (2)	aluminum	4	6500	1250	0.008125	2700	21.9375
		split mullion (3)	aluminum	2	2100	3750	0.007875	2700	21.2625
		split transom (4)	aluminum	2	2100	2500	0.00525	2700	14.175
	SHADING	exterior mullion (5)	aluminum	1	720	3750	0.0027	2700	7.29
		exterior split mullion (6)	aluminum	2	960	3750	0.0036	2700	9.72
		exterior split transom (7)	aluminum	2	960	2500	0.0024	2700	6.48
F2 - A	CW - A	mullion (1)	aluminum	1	1625	3750	0.00609375	2700	16.453125
		transom (2)	aluminum	4	6500	1250	0.008125	2700	21.9375
		split mullion (3)	aluminum	2	2100	3750	0.007875	2700	21.2625
		split transom (4)	aluminum	2	2100	2500	0.00525	2700	14.175
	SHADING	exterior mullion (5)	aluminum	1	720	3750	0.0027	2700	7.29
		exterior split mullion (6)	aluminum	2	960	3750	0.0036	2700	9.72
		exterior split transom (7)	aluminum	2	960	2500	0.0024	2700	6.48

TIMBER CW									
concept	part of the module	element name	material name	amount nr.	area mm2	height/length mm	volume m3	density kg/m3	weight kg
R1 - T	CW - T	mullion (1)	timber	1	8125	3750	0.03046875	380	11.578125
		transom (2)	timber	4	32500	1250	0.040625	380	15.4375
		split mullion (3)	timber	2	7000	3750	0.02625	380	9.975
		split transom (4)	timber	2	7000	2500	0.0175	380	6.65
	SHADING	exterior mullion (5)	aluminum	1	1800	3750	0.00675	2700	18.225
		exterior split mullion (6)	aluminum	2	3600	3750	0.0135	2700	36.45
		exterior split transom (7)	aluminum	2	3600	2500	0.009	2700	24.3
R2 - T	CW - T	mullion (1)	timber	1	8125	3750	0.03046875	380	11.578125
		transom (2)	timber	4	32500	1250	0.040625	380	15.4375
		split mullion (3)	timber	2	7000	3750	0.02625	380	9.975
		split transom (4)	timber	2	7000	2500	0.0175	380	6.65
	SHADING	exterior mullion (5)	aluminum	1	1800	3750	0.00675	2700	18.225
		exterior split mullion (6)	aluminum	2	3600	3750	0.0135	2700	36.45
		exterior split transom (7)	aluminum	2	3600	2500	0.009	2700	24.3
F1 - T	CW - T	mullion (1)	timber	1	8125	3750	0.03046875	380	11.578125
		transom (2)	timber	4	32500	1250	0.040625	380	15.4375
		split mullion (3)	timber	2	7000	3750	0.02625	380	9.975
		split transom (4)	timber	2	7000	2500	0.0175	380	6.65
	SHADING	exterior mullion (5)	aluminum	1	720	3750	0.0027	2700	7.29
		exterior split mullion (6)	aluminum	2	960	3750	0.0036	2700	9.72
		exterior split transom (7)	aluminum	2	960	2500	0.0024	2700	6.48
F2 - T	CW - T	mullion (1)	timber	1	8125	3750	0.03046875	380	11.578125
		transom (2)	timber	4	32500	1250	0.040625	380	15.4375
		split mullion (3)	timber	2	7000	3750	0.02625	380	9.975
		split transom (4)	timber	2	7000	2500	0.0175	380	6.65
	SHADING	exterior mullion (5)	aluminum	1	720	3750	0.0027	2700	7.29
		exterior split mullion (6)	aluminum	2	960	3750	0.0036	2700	9.72
		exterior split transom (7)	aluminum	2	960	2500	0.0024	2700	6.48

Tables 7.3 – 7.4 All the elements that are used with their properties and final weights for alum. and timber

7.6 impact assessment

The methodology that is followed in order to successfully perform a Life Cycle Impact Assessment (LCIA) is standard, and a short description of the steps followed is provided in this section.

As already mentioned in the LCI and shown in table x, there are certain characterization factors per kg for a range of materials. In order to calculate the impact scores for each individual impact category, for a certain materials, the following multiplication should be performed:

$$\boxed{IS_{m,x} = M_m \times C_{m,x}} \qquad (1)$$

where $IS_{m,x}$ stands for the **Impact Score** for the material m and the impact category x, M_m is the amount of **Material** m being assessed, and $C_{m,x}$ is the **Characterisation factor** for material m and impact category x. Summing characterization factors of different impact categories is not right. However, for each impact category, characterization factors can be added, thus providing aggregated scores.

Second step is the calculation of normalized impact scores, again with a multiplication:

$$\boxed{NIS_{m,x} = IS_{m,x} \times N_x} \qquad (2)$$

In this case, $NIS_{m,x}$ stands for the **Normalized Impact Score** of the material m and impact category x, $IS_{m,x}$ is explained above and N_x is the **Normalization** factor for the impact category x. Adding normalized impact scores is advised only when weighed.

The third step includes the calculation of the shadow cost, which is given with the following formula:

$$\boxed{SP_{m,x} = IS_{m,x} \times sp_x} \qquad (3)$$

where $SP_{m,x}$ is the **shadow cost** of the material m and the impact category x, $IS_{m,x}$ is explained above and finally sp_x stands for the **shadow price** per unit of impact category x. It is worth mentioning that the shadow costs are calculated from the impact scores; not from the normalized impact scores.

The shadow costs of all different impact categories can be summed into one total shadow cost, since they represent a weighted impact score.

Applying these formulas to this research resulted in a large collective table of calculations for the 8 design concepts, which are numbered C1 – C8. These calculations are shown in Table 7.5, where data from Tables 7.3 and 7.4 is used.

Firstly, the Impact Scores of the aluminium are calculated according to formula (1). Then the same is done for timber. It can easily be observed that the concepts C1-C4 get a 0 since they do not include any timber, whereas aluminium is present in all the concepts. After having calculated these impact scores, the total IS can be derived as the sum of the 2 materials for each impact category.

The second step that includes the normalization does not apply to this specific LCA, and so it is omitted.

Finally, the shadow cost for each concept is calculated, according to equation (3). The shadow price for each impact category is provided in Euro per kg equivalents. The total SP is calculated for each impact category and then a sum of the SP for all impact categories is calculated for each concept, thus resulting in 8 final comparable numbers. These, of course, represent the material-related environmental impact, and are provided in Table 7.6.

	Impact category	Unit	Abiotic depletion	Global warming (GWP100)	Ozone layer depletion (ODP)	Human toxicity	Fresh water aquatic ecotox.	Marine aquatic ecotoxicity	Terrestrial ecotoxicity	Photochemical oxidation	Acidification	Eutrophication
	Unit		kg Sb eq	kg CO2 eq	kg CFC-11 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg C2H4	kg SO2 eq	kg PO4--- eq
Cal,x	Aluminium, coated	kg	6.10E-02	9.62E+00	6.72E-07	4.88E+01	3.92E+00	4.59E+03	1.09E-01	3.38E-03	4.22E-02	3.88E-03
ISal,x	R1 - A		9.32E+00	1.47E+03	1.03E-04	7.45E+03	5.99E+02	7.01E+05	1.66E+01	5.16E-01	6.44E+00	5.93E-01
	R2 - A		9.32E+00	1.47E+03	1.03E-04	7.45E+03	5.99E+02	7.01E+05	1.66E+01	5.16E-01	6.44E+00	5.93E-01
	F1 - A		5.94E+00	9.36E+02	6.54E-05	4.75E+03	3.82E+02	4.46E+05	1.06E+01	3.29E-01	4.10E+00	3.78E-01
	F2 - A		5.94E+00	9.36E+02	6.54E-05	4.75E+03	3.82E+02	4.46E+05	1.06E+01	3.29E-01	4.10E+00	3.78E-01
	R1 - T		4.82E+00	7.60E+02	5.31E-05	3.85E+03	3.10E+02	3.62E+05	8.57E+00	2.67E-01	3.33E+00	3.07E-01
	R2 - T		4.82E+00	7.60E+02	5.31E-05	3.85E+03	3.10E+02	3.62E+05	8.57E+00	2.67E-01	3.33E+00	3.07E-01
	F1 - T		1.43E+00	2.26E+02	1.58E-05	1.15E+03	9.21E+01	1.08E+05	2.55E+00	7.93E-02	9.91E-01	9.12E-02
	F2 - T		1.43E+00	2.26E+02	1.58E-05	1.15E+03	9.21E+01	1.08E+05	2.55E+00	7.93E-02	9.91E-01	9.12E-02
Ctim,x	Timber average NMD	kg	8.65E-03	5.45E+00	1.11E-08	6.81E-02	1.48E-02	2.41E+01	7.90E-04	6.15E-05	8.44E-04	1.37E-04
IStim,x	R1 - A		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	R2 - A		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	F1 - A		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	F2 - A		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	R1 - T		7.55E-01	4.76E+02	9.70E-07	5.94E+00	1.29E+00	2.10E+03	6.90E-02	5.37E-03	7.37E-02	1.20E-02
	R2 - T		7.55E-01	4.76E+02	9.70E-07	5.94E+00	1.29E+00	2.10E+03	6.90E-02	5.37E-03	7.37E-02	1.20E-02
	F1 - T		7.55E-01	4.76E+02	9.70E-07	5.94E+00	1.29E+00	2.10E+03	6.90E-02	5.37E-03	7.37E-02	1.20E-02
	F2 - T		7.55E-01	4.76E+02	9.70E-07	5.94E+00	1.29E+00	2.10E+03	6.90E-02	5.37E-03	7.37E-02	1.20E-02
TOTAL ISm,x	R1 - A		9.32E+00	1.47E+03	1.03E-04	7.45E+03	5.99E+02	7.01E+05	1.66E+01	5.16E-01	6.44E+00	5.93E-01
	R2 - A		9.32E+00	1.47E+03	1.03E-04	7.45E+03	5.99E+02	7.01E+05	1.66E+01	5.16E-01	6.44E+00	5.93E-01
	F1 - A		5.94E+00	9.36E+02	6.54E-05	4.75E+03	3.82E+02	4.46E+05	1.06E+01	3.29E-01	4.10E+00	3.78E-01
	F2 - A		5.94E+00	9.36E+02	6.54E-05	4.75E+03	3.82E+02	4.46E+05	1.06E+01	3.29E-01	4.10E+00	3.78E-01
	R1 - T		5.57E+00	1.24E+03	5.41E-05	3.86E+03	3.11E+02	3.64E+05	8.64E+00	2.72E-01	3.40E+00	3.19E-01
	R2 - T		5.57E+00	1.24E+03	5.41E-05	3.86E+03	3.11E+02	3.64E+05	8.64E+00	2.72E-01	3.40E+00	3.19E-01
	F1 - T		2.19E+00	7.02E+02	1.68E-05	1.15E+03	9.34E+01	1.10E+05	2.62E+00	8.47E-02	1.06E+00	1.03E-01
	F2 - T		2.19E+00	7.02E+02	1.68E-05	1.15E+03	9.34E+01	1.10E+05	2.62E+00	8.47E-02	1.06E+00	1.03E-01
spx	Shadow price (Euro per kg equivalents)		0.16	0.05	30	0.09	0.03	0.0001	0.06	2	4	9
TOTAL SPm,x	R1 - A		1.49E+00	7.35E+01	3.08E-03	6.71E+02	1.80E+01	7.01E+01	9.95E-01	1.03E+00	2.58E+01	5.34E+00
	R2 - A		1.49E+00	7.35E+01	3.08E-03	6.71E+02	1.80E+01	7.01E+01	9.95E-01	1.03E+00	2.58E+01	5.34E+00
	F1 - A		9.50E-01	4.68E+01	1.96E-03	4.27E+02	1.14E+01	4.46E+01	6.34E-01	6.57E-01	1.64E+01	3.40E+00
	F2 - A		9.50E-01	4.68E+01	1.96E-03	4.27E+02	1.14E+01	4.46E+01	6.34E-01	6.57E-01	1.64E+01	3.40E+00
	R1 - T		8.92E-01	6.18E+01	1.62E-03	3.47E+02	9.33E+00	3.64E+01	5.19E-01	5.44E-01	1.36E+01	2.87E+00
	R2 - T		8.92E-01	6.18E+01	1.62E-03	3.47E+02	9.33E+00	3.64E+01	5.19E-01	5.44E-01	1.36E+01	2.87E+00
	F1 - T		3.50E-01	3.51E+01	5.03E-04	1.04E+02	2.80E+00	1.10E+01	1.57E-01	1.69E-01	4.26E+00	9.29E-01
	F2 - T		3.50E-01	3.51E+01	5.03E-04	1.04E+02	2.80E+00	1.10E+01	1.57E-01	1.69E-01	4.26E+00	9.29E-01

Table 7.5 The calculations described in section 7.6, done for all 8 different scenarios

The final results of the shadow costs (shown in Table 7.6) are derived by adding all the impact categories for each facade module. The sums show a declining impact from top to bottom, which will be explained in more detail in the Figure 7.8 of the next section: Interpretation.

	TOTAL IMPACT
R1 - A	867.13
R2 - A	867.13
F1 - A	552.26
F2 - A	552.26
R1 - T	473.27
R2 - T	473.27
F1 - T	158.40

Table 7.6 The final shadow costs for the modules

7.7 interpretation

In this phase, an analysis of the impacts is given, and how these relate to the goal definition and the intentions of this EPD. In order to do this, the graphs produced by the data explained in the impact assessment will be provided and conclusions will be drawn based on them.

First, the total impact of the various concepts is provided in the graph of Figure 7.8, which can give a good overview of the impacts, and quick conclusions can be drawn based on that. This is also the graph that is used to sort and rank the different concepts in the environmental impact rating of Section 8.2.

In addition, the graph of Figure 7.9 illustrates the different impact categories and the concept impact, and gives a clear mapping of the results for the most dominant impact category, which apparently is the Human Toxicity. This comes in contrast to the expected result, which would presumably have the Global Warming Potential (GWP) as the highest.

At a first glance, it is quite clear from Figure 7.9, that the red-coloured R1-A and R2-A have the highest impact in all categories, and the there is an analogous pattern for the whole graph, no matter what the intensity of the category is. However, this is not true for all concepts, since the green-coloured R1-T and R2-T appear to be lower than the yellow F1-A and F2-A in the Human Toxicity impact, but the opposite is true for the Global Warming Potential category.

Appendix B provides the full environmental profiles of all 8 concepts in Figures C.1 to C.8. These can show in more detail how much the shadow cost of each concept is for each impact category. Last but not least, the 3D graph of Figure 7.10 provides a very good visual overview of the shadow cost mapping among the modules.

It goes without saying that the modules that have mullions made of aluminium have an overall larger impact than the timber-framed concepts. This can be derived from Figure 7.8. What can also be observed is that the concepts are grouped by 2, having an equal impact. The reason for this is that during the assumptions, it was considered that the shading mechanism is considered the same among all 8 concepts, and therefore omitted.

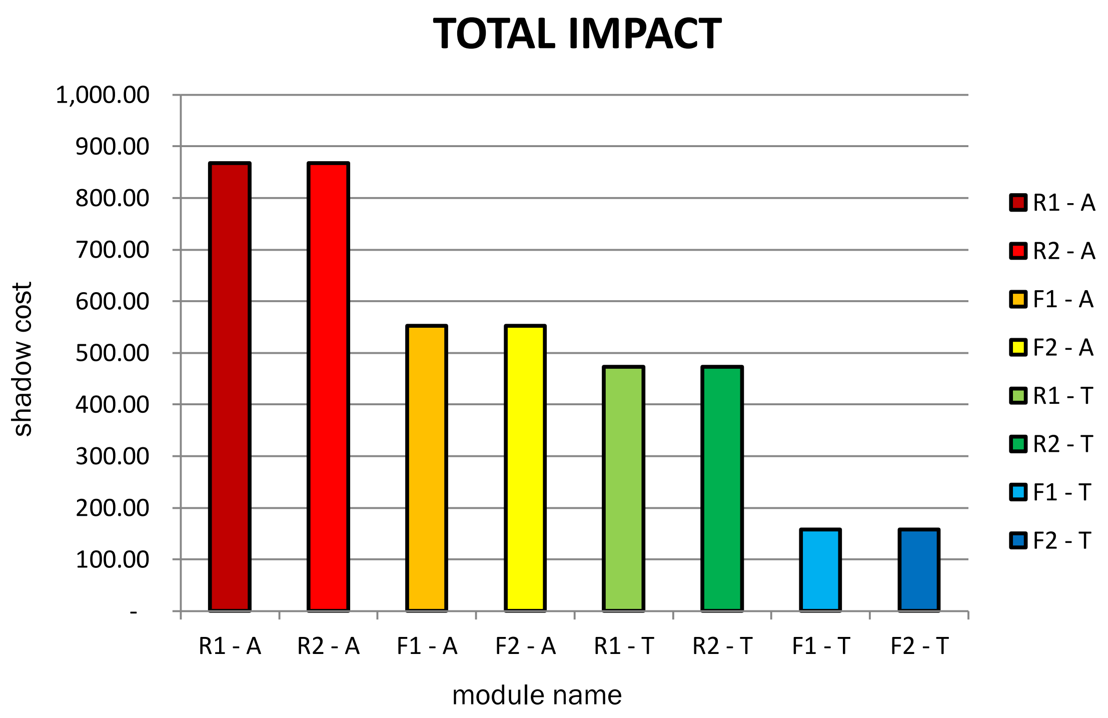


Figure 7.8 The total impact of the 8 facade module concepts

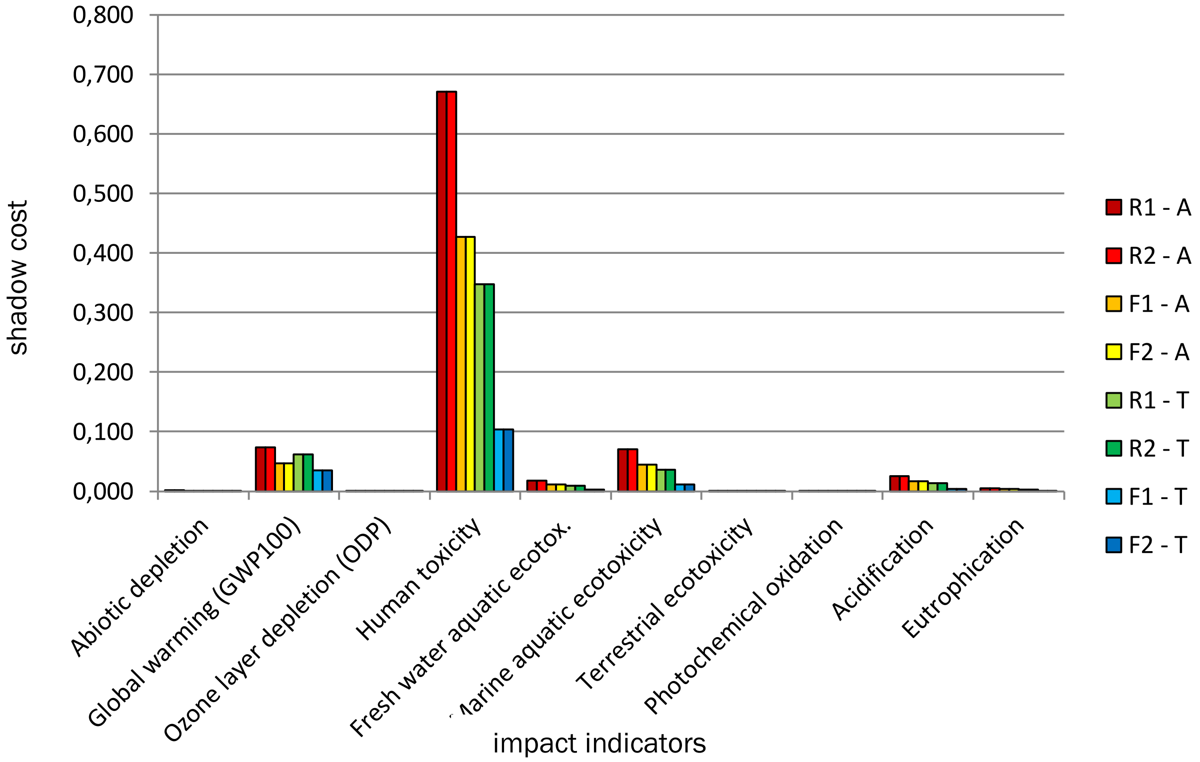


Figure 7.9 The mapping of the impact categories of the 8 facade module concepts

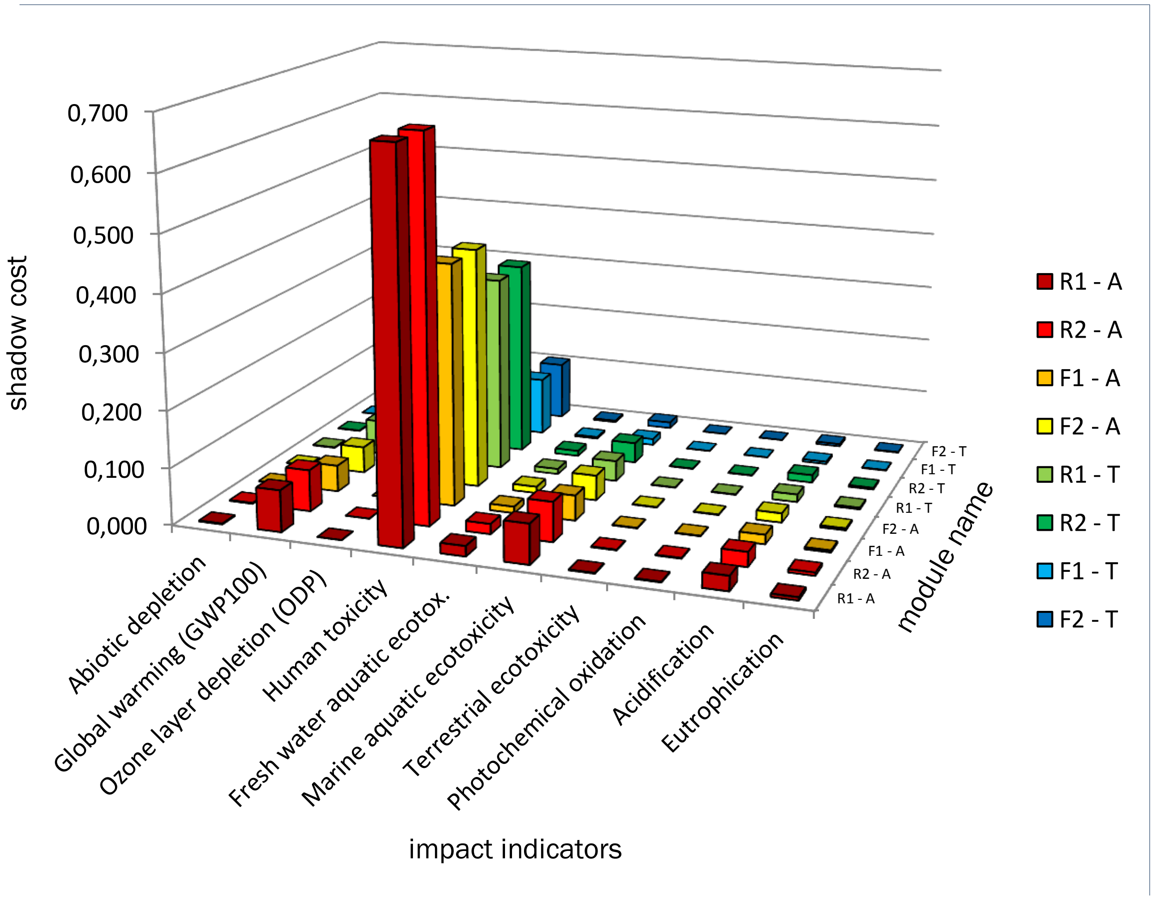


Figure 7.10 The 3D mapping of the 8 facade module concepts for all impact categories

7.8 references

Azari-N, R. et al. (2012) Comparative assessment of life cycle impacts of curtain wall mullions

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8 THE FINAL RATING OF THE 8 CONCEPTS

image source:
unsplash.com - Christian Holzinger

8.1 introduction

This chapter concludes the research by performing the rating of the criteria and then a final comparison where all weight factors are taken into account. This way, each adaptive concept will eventually have a specific score, thus concluding on a best and worst performing concept in terms of disassembly potential.

Such a strategy can help engineers assess the circularity of a certain facade concept or compare a certain number of designs in the early design phase, as was done in this thesis. This way, a sophisticated and environmentally viable selection can be made, thus contributing on an overall better design.

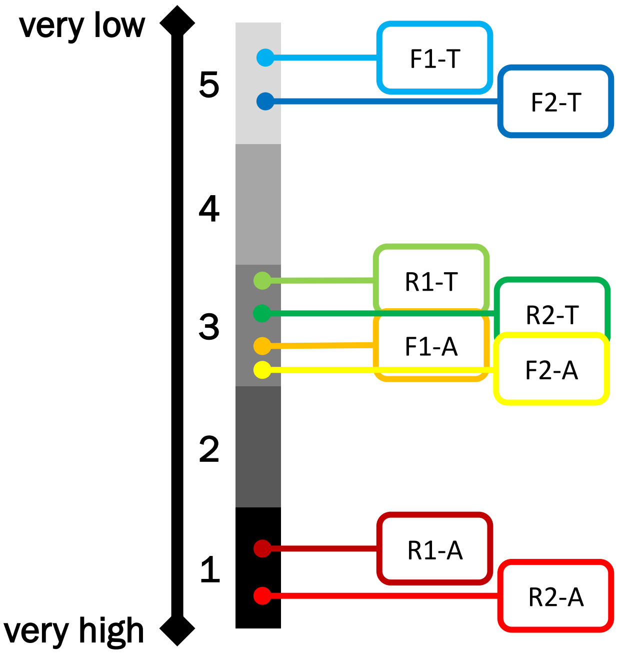
First, an overview of the criteria that comprise the design guidelines will be shown again in section 8.2, together with their specific weights. Then, a detailed explanation of the concept rating for each criterion will be provided in the same section, together with an illustration that contains labels with the module names. This will provide a better overview and an easier understanding of the explanation. Eventually, the final comparison will be performed in section 8.3, by following the steps of the strategy, as summarized previously in section 3.5.

8.2 criteria rating

Disassembly Criteria	Scale of rating	Weight
1. environmental impact		
overall impact (Life Cycle Assessment)	very high ——— very low	1
2. durability of the components		
life expectancy	1y. ——— 100y.	0.6
maintenance	every 1y. ——— never	0.2
resistance to wear	extremely fragile ——— extremely resistant	0.2
3. recycle/reuse potential		
end-of-life activity	landfill ——— reuse	0.8
side effects when reused/recycled	very toxic ——— 100% safe	0.2
4. reversibility of connections		
reversibility of connections	more non-reversible ——— all con. reversible	1
5. ease of (dis)assembly		
complexity of the conn. techniques	extremely complicated ——— extremely simple	0.5
accessibility of connections	completely obscured ——— completely accessible	0.5
6. speed of (dis)assembly		
amount of connections	∞ ——— 0	0.8
types of connections	≥5 ——— 1	0.2

Table 8.1 Criteria of the 6 DfD strategies, their scale of rating and specific weight

OVERALL IMPACT



According to the interpretation that was already done in the previous chapter and the figures that show the environmental impact, it can be concluded that the timber-framed facades have a lower environmental impact when compared to aluminum-framed, especially the ones with the folding mechanism on the shading.

This is why in the overall environmental impact scale, the timber-framed folding concepts F1-T and F2-T score a 5, whereas the rotating timber concepts R1-T and R2-T are slightly lower, scoring a 3 in the scale. As for the aluminum-framed facades, the rotating ones (R1-A and R2-A) were by far the worst option for future disassembly, thus getting a 1 in the scale. This can be clearly observed in Figure 8.1. Last but not least, F1-A and F2-A earn a 3 (medium impact).

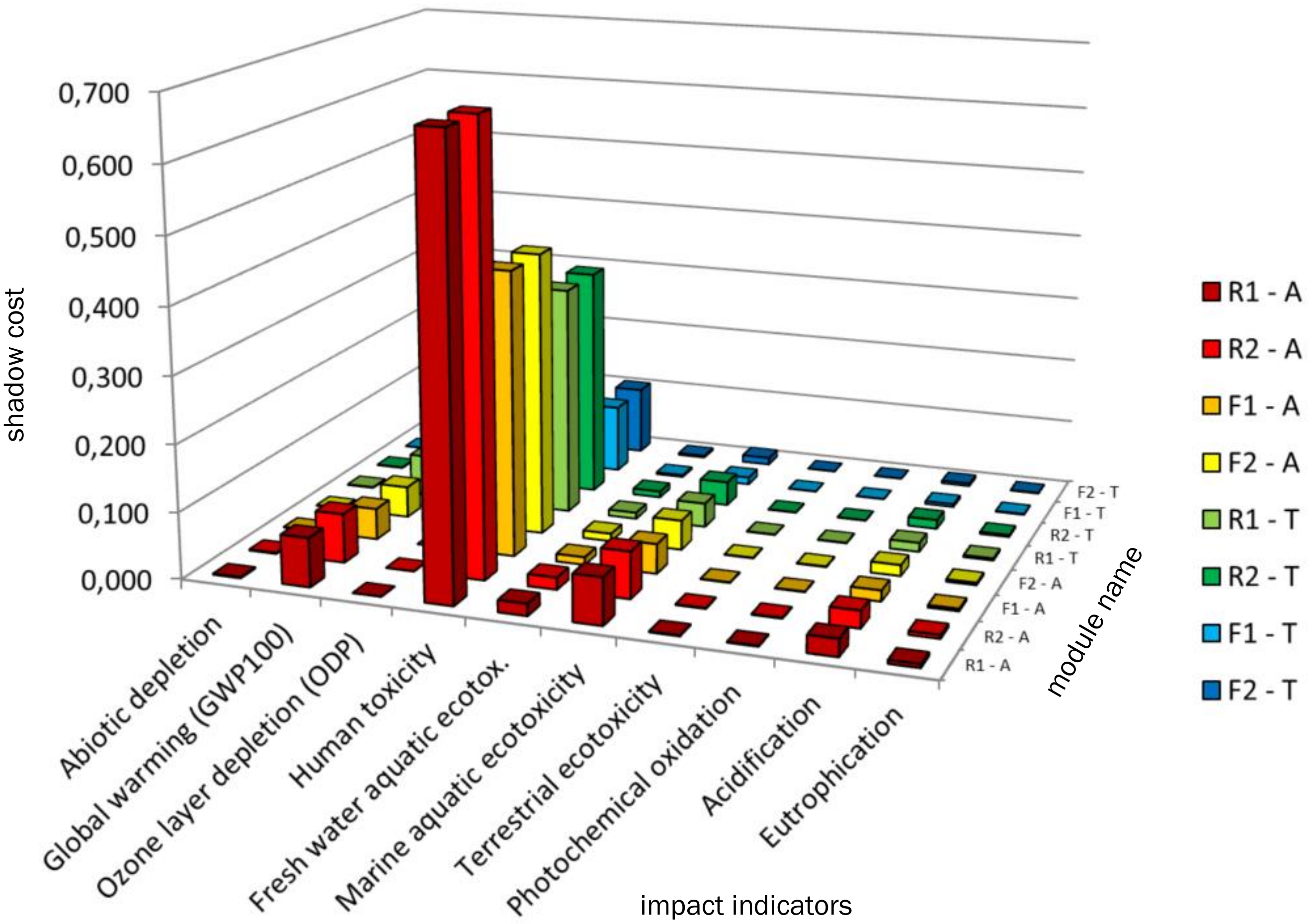
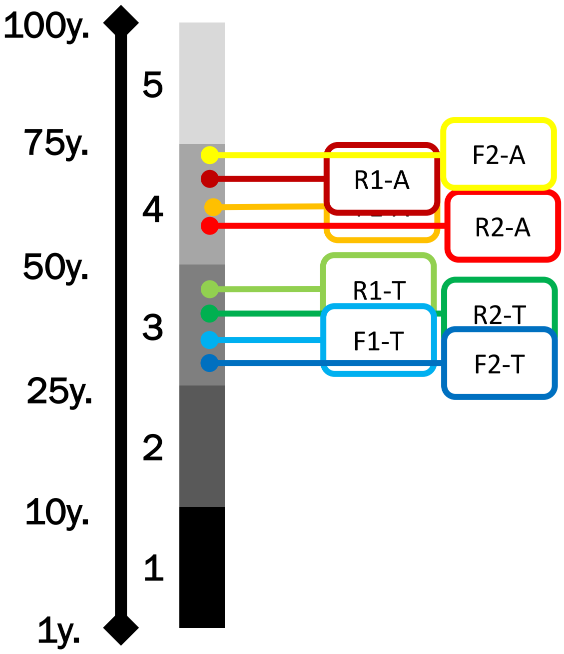


Figure 8.1 The 3D scheme produced via the EPD

2. durability of the components

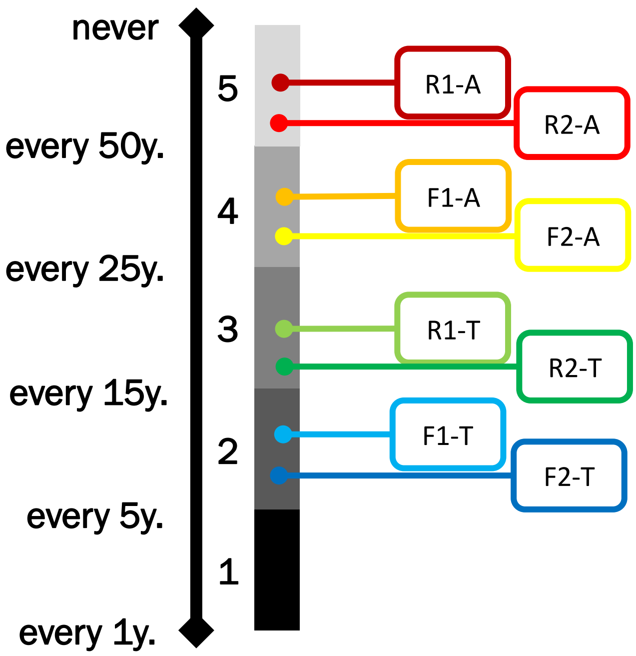
LIFE EXPECTANCY



When it comes to timber and aluminum, there is a high variability on the expected life span, as found in literature. Timber can have a life that may span from 25 to 80 years depending on the type of wood used, the choice of engineered timber and the type of fasteners. This huge variance can only be overcome in this case through an assumption. For the current research, it is assumed that timber has life expectancy of 30 years, while aluminum has 60. This was also mentioned in the Life Cycle Assessment, in the section with the assumptions.

When assessing the 8 concepts, the 4 timber-framed modules will have the lowest expected life span. This is why a 3 is assigned to all 4 of them in the scale from 1 to 5. As it can be seen, 3 stands for 25 to 50 years. Aluminum-framed facade modules, on the other hand, score 4, which can be translated to 50-75 years.

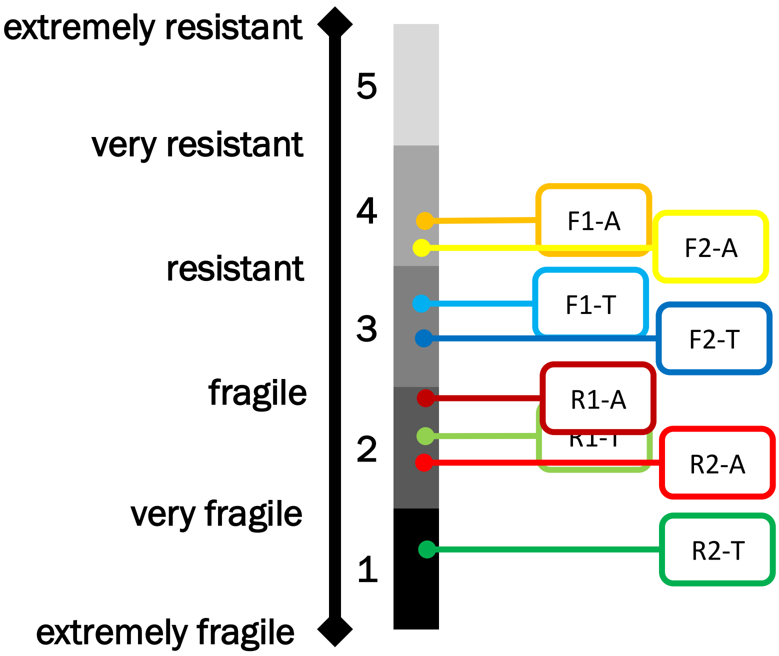
MAINTENANCE



Timber-framed curtain walls have a more frequent need for maintenance in comparison to aluminum. This always depends on the type of timber chosen, and can have huge variations from type to type, but in this research a mean will be taken for the grading. Therefore it is considered that timber needs to be maintained about every 20 years.

As for the difference between folding and rotating mechanism, it is not an easy task to compare two different exterior adjustable systems on their maintenance need. It is however safe to say that the folding systems require more frequent inspection than the rotating ones with the hidden motors being protected.

RESISTANCE TO WEAR

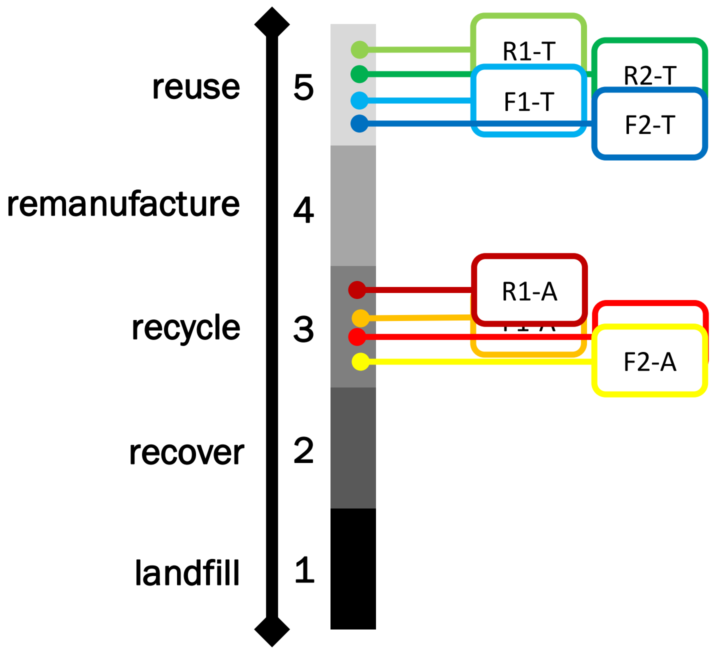


This criterion refers to the degree of resistance that the modules have when transported, assembled and maintained. It is quite clear that having facade modules with an additional exterior shading system is prone to wearing during transportation for example, a fact that calls for a lot of care throughout the construction process.

It is obvious that the modules with a lot of small elements that protrude are very fragile when transported. The aforementioned poses the concept R2 the most fragile of all, since it has the most glass louvers among the concepts. In addition, timber is more prone to damage than aluminum when getting hit, a fact that makes it less resistant. Consequently R2-T is given the worst score of 1: extremely fragile. It is also the aluminum frames in the exterior glazing of concepts F1 and F2 that make them more resistant than the rotating ones which have bare glass panels. This is why F1-A and F2-A are awarded with a 4: very resistant.

3. recycle/reuse potential

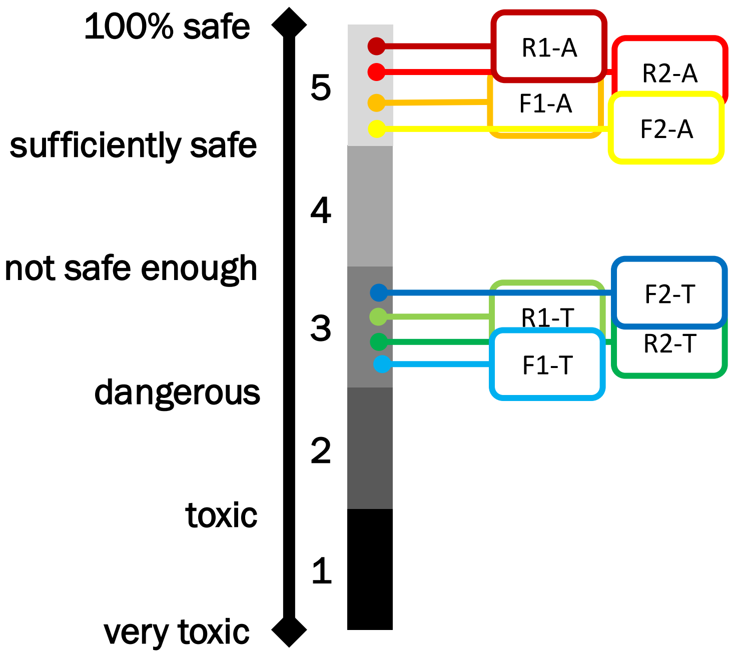
END-OF-LIFE ACTIVITY



In order to recycle used aluminum profiles, they first need to go through a shredding, cleaning and melting process. However, the process of making secondary aluminum only requires 5% of the energy that is necessary for primary aluminum production. It is assumed that 95% of the aluminum used in the module is recycled into secondary aluminum.

As for the timber, it is assumed that 80% of it is reused for pallets (down-cycled) and the rest 20% is recovered. Therefore, all timber concepts earn a 5 and aluminum concepts get a 3.

SIDE EFFECTS

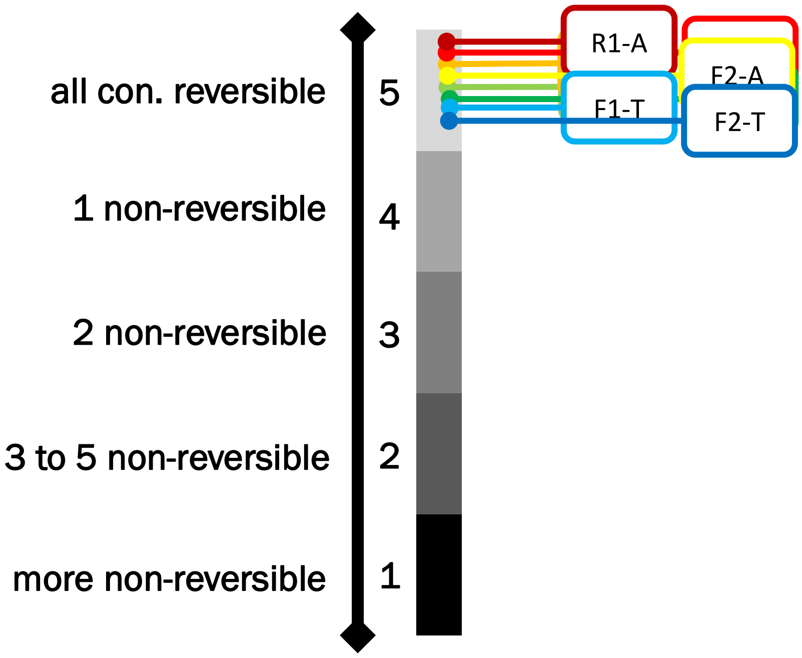


Subcomponents that are made of toxic materials may not only prove harmful for the occupants of the building during its life span, but also for the workers that will handle these components after the end of the life; in the disassembly phase. For example, extruded polystyrene (XPS) which is frequently used for insulation, contains brominated flame retardants that provide fire safety, but are very harmful to the human health when inhaled.

In this comparison only the timber and aluminum elements of the components compared will be taken into account. As already mentioned, aluminum profiles will be recycled, and their quality is guaranteed by the manufacturer of the curtain wall. Therefore a 5 is given to all aluminum-framed concepts. On the other hand, treated timber may contain harmful substances and this is why a 3 is given.

4. reversibility of connections

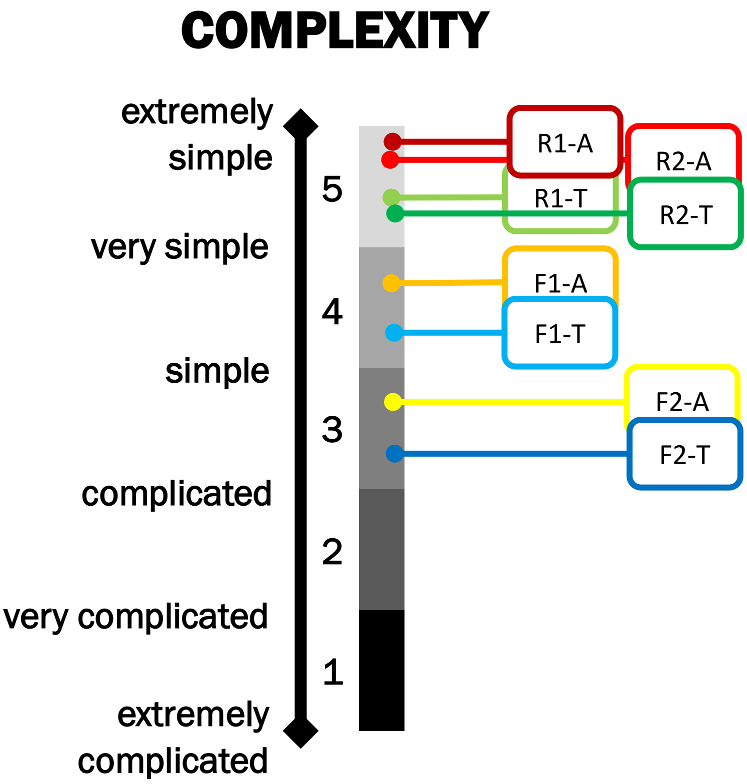
REVERSIBILITY



Appendix C includes the table that shows the connections used for the module types. Apparently, all of the connections used in this comparison are completely reversible, since they are either bolts or screws. This is the ideal case when designing for future disassembly. Therefore all concepts are ranked first scoring a 5.

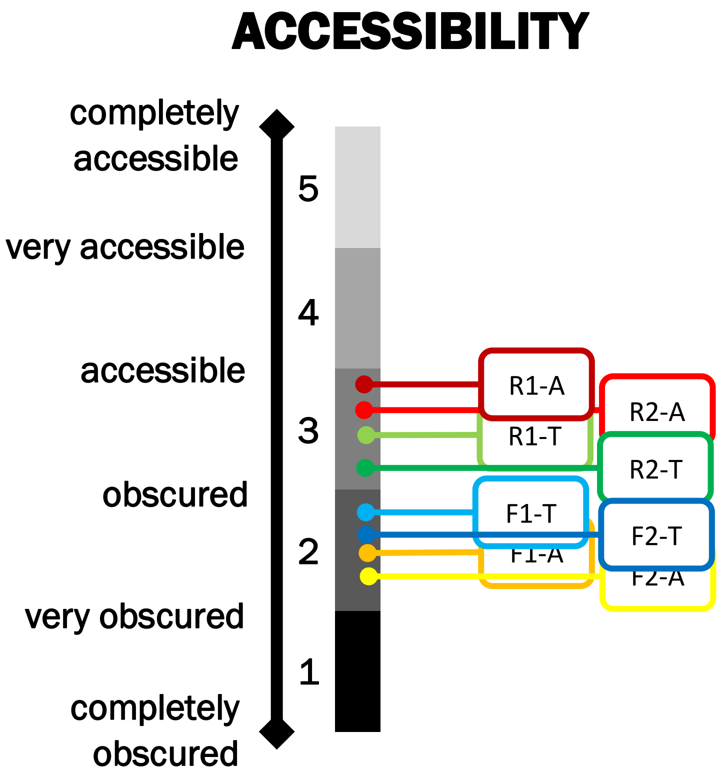
However, special attention should be paid to the rest of the connections which are not taken into account in this comparison study. A good score in this criterion does not equal a good score in general for all concepts. It just means that the **compared** connections are all reversible.

5. ease of (dis)assembly



It is pretty obvious that complex joining techniques slow down both the assembly and disassembly process, thus increasing the labor costs. This is why not only simple and standard connections are preferred, but also connections that are easy to disassemble by using a drill or a wrench for example. All 8 module concepts have numerous connections, but the comparison focusses on the ones that differ from concept to concept. Appendix C provides the table where all different connections are listed, and which assesses, among others, their complexity. The folding modules F1 and F2 (either for Aluminum or Timber mullions) entail more than 1 type of connection, and therefore a weighted grade can be given.

For rotating modules, the glass rotators are the only connections to be assessed. A 4 is given to them as they are very simple to disassemble. As regards the folding concepts, a 3 is given for the sliders and the hinge, since these are neither complex nor simple connections. The rotator earns a 5 due to being by far the simplest element to be disassembled. This is how the 3.5 for F1 is reached. Similarly, F2 is graded with a 3.33. Putting everything in the comparative scale, the best performing are R1 and R2, thus earning a 5. Accordingly F1 gets a 4 and F2 gets a 3. No concepts scored below 3.

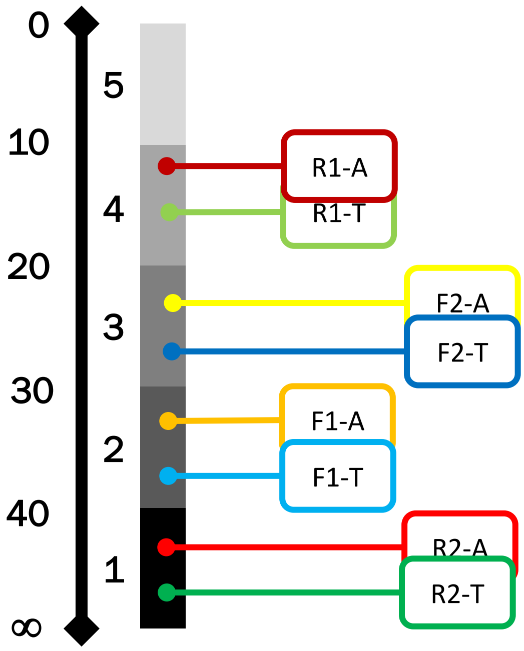


Accessibility refers to the ease of disassembly in terms of visual, physical and ergonomically accessible connections. For instance if a connection is behind a component and is therefore difficult to access, it will take a long time to remove it. There must also be sufficient space around the connection to maneuver with the necessary tools and remove the component.

Table C.1 in Appendix C shows the grading given to the different connections of the concepts. Based on that, which calculated the mean of each element for each module, the ratings are done.

6. speed of disassembly

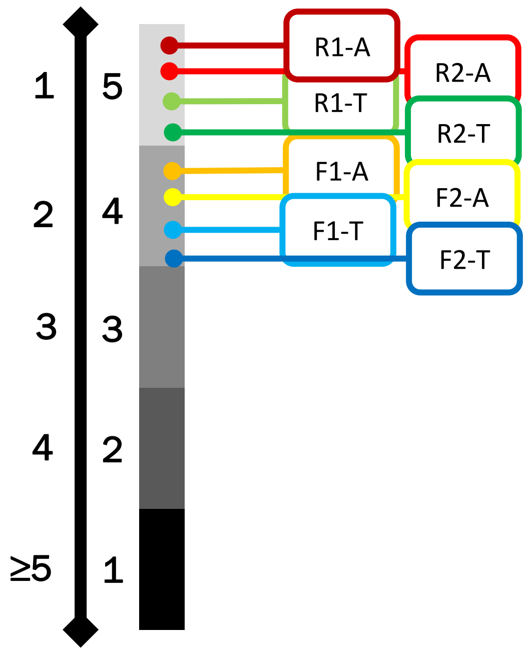
AMOUNT OF CONNECTIONS



The criterion ‘amount of connections’ is about the minimization of the total number of joining techniques. This has an instant effect on the speed of disassembly.

According to the designs, the Table xx in Appendix xx shows that modules R1 have the least connections with a total of 16, with F2 coming second with 28. Then F1 has 36 and R2 has the most joining techniques, counting a total of 48. The aforementioned are graded according to the scale used, and so for example R2-A and R2-T earn the lowest rank, with 40 connections or more. The same is done for the rest accordingly.

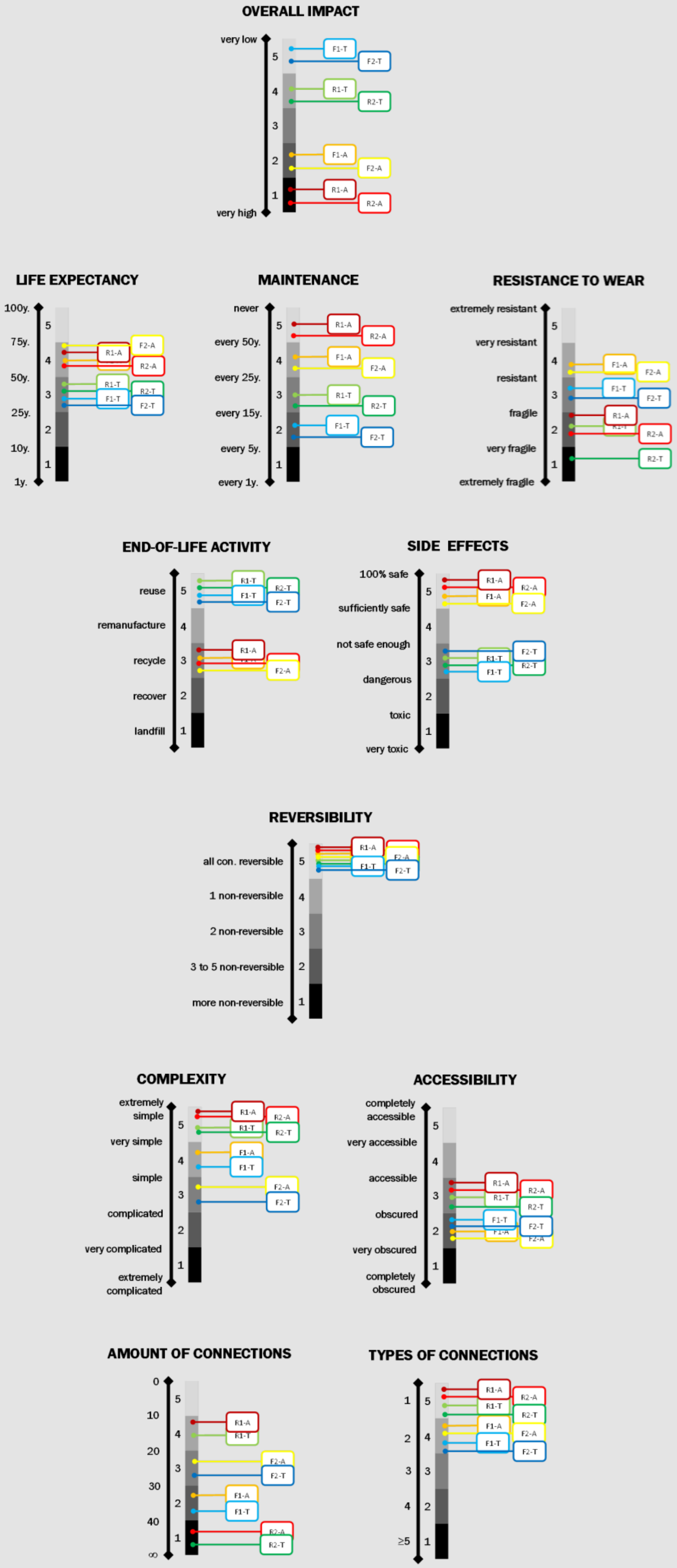
TYPES OF CONNECTIONS



This criterion refers to the amount of different types of connections present in a module. As already mentioned in section 3.2.6, the less the types, the faster the assembly and disassembly can be, since the complexity is lowered.

As illustrated in Table C.1 of Appendix C, rotating modules have 1 type of connector compared to the rest, while the folding ones have 2. This difference forms the grading, with rotating getting a 5 and folding earning a 4 in the scale.

overview



OVERALL IMPACT
very low
very high
LIFE EXPECTANCY
100y.
75y.
50y.
25y.
10y.
1y.
MAINTENANCE
never
every 50y.
every 25y.
every 15y.
every 5y.
every 1y.
RESISTANCE TO WEAR
extremely resistant
very resistant
resistant
fragile
very fragile
extremely fragile
END-OF-LIFE ACTIVITY
reuse
remanufacture
recycle
recover
landfill
SIDE EFFECTS
100% safe
sufficiently safe
not safe enough
dangerous
toxic
very toxic
REVERSIBILITY
all con. reversible
1 non-reversible
2 non-reversible
3 to 5 non-reversible
more non-reversible
COMPLEXITY
extremely simple
very simple
simple
complicated
very complicated
extremely complicated
ACCESSIBILITY
completely accessible
very accessible
accessible
obscured
very obscured
completely obscured
AMOUNT OF CONNECTIONS
0
10
20
30
40
∞
TYPES OF CONNECTIONS
1
2
3
4
≥5
F1-T
F2-T
R1-T
R2-T
F1-A
F2-A
R1-A
R2-A

8.3 final comparison

All the information regarding the ratings of Section 8.2 are now summarized in Table 8.2.

	1. env. impact	2. durability of the components			3. recycle/reuse potential		4. reversibility of con.	5. ease of (dis)assembly		6. speed of disassembly	
	OVERALL IMPACT	LIFE EXPECT.	MAINTENANCE	RES. TO WEAR	END-OF-LIFE ACTIVITY	SIDE EFFECTS	REVERSIBILITY	COMPLEXITY	ACCESSIBILITY	AMOUNT OF CON.	TYPES OF CON.
R1-A	1	4	5	2	3	5	5	5	3	4	5
R2-A	1	4	5	2	3	5	5	5	3	1	5
F1-A	3	4	4	4	3	5	5	4	2	2	4
F2-A	3	4	4	4	3	5	5	3	2	3	4
R1-T	3	3	3	2	5	3	5	5	3	4	5
R2-T	3	3	3	1	5	3	5	5	3	1	5
F1-T	5	3	2	3	5	3	5	4	3	2	4
F2-T	5	3	2	3	5	3	5	3	3	3	4

Table 8.2 Ratings of the criteria

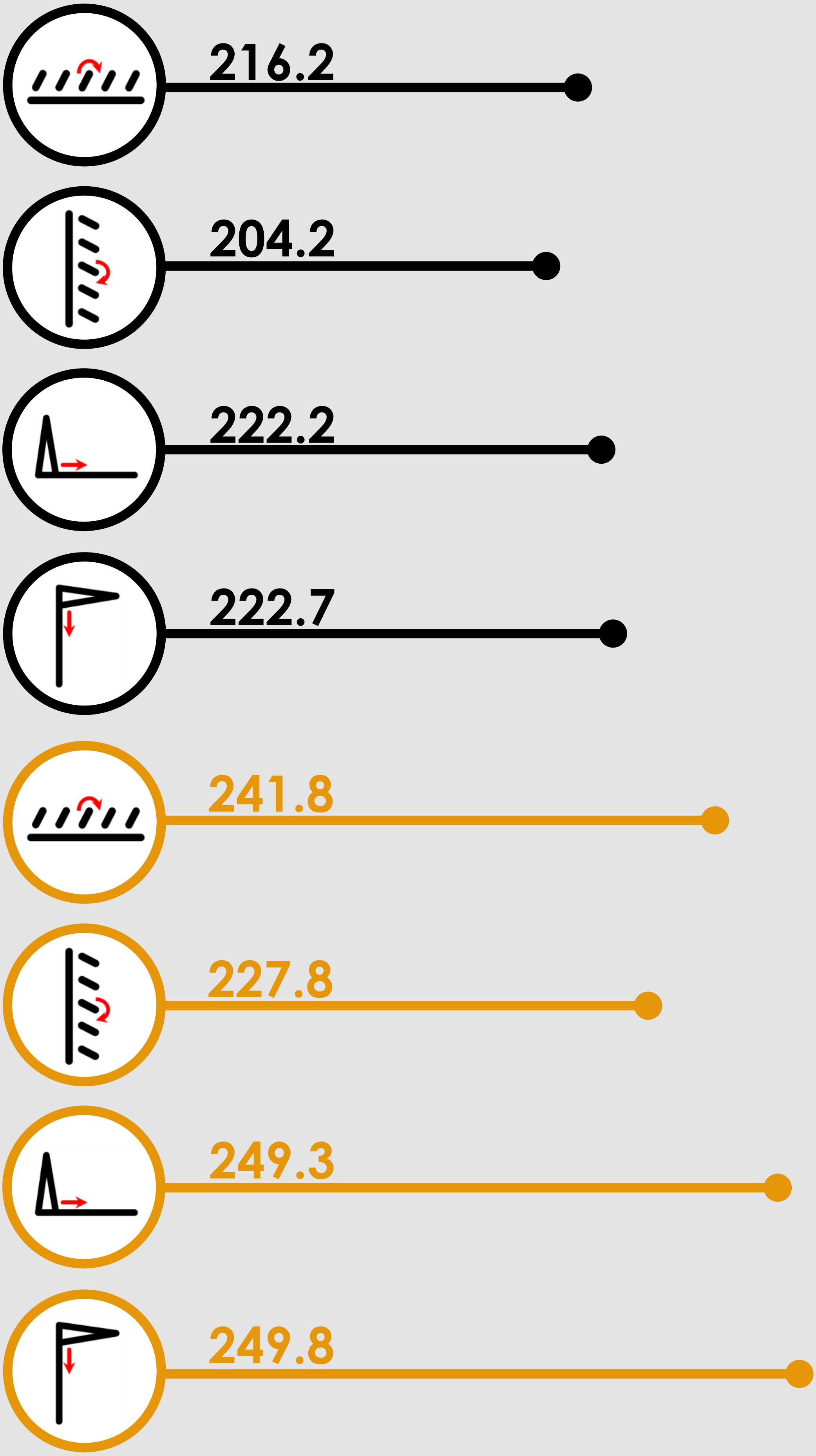
In order to do the final comparison, a transition table should be formed, which includes the information of table 8.2 weighted with the specific weights, as given in Table 8.1. The resulting transition table is provided in the following table 8.3 and shows the resulting grades of the design guidelines.

	1. env. impact	2. durability of the components	3. recycle/reuse potential	4. reversibility of con.	5. ease of (dis)assembly	6. speed of disassembly
R1-A	1	3.8	3.4	5	4	4.2
R2-A	1	3.8	3.4	5	4	1.8
F1-A	3	4	3.4	5	3	2.4
F2-A	3	4	3.4	5	2.5	3.2
R1-T	3	2.8	4.6	5	4	4.2
R2-T	3	2.6	4.6	5	4	1.8
F1-T	5	2.8	4.6	5	3.5	2.4
F2-T	5	2.8	4.6	5	3	3.2

Table 8.3 Final Ratings of the design guidelines

The final weighted rating of the 8 facade modules – according to the weight factors applied on the design guidelines in section 3.4 – is shown on Table 8.4. A colored scale from yellow (being the worst performing) to dark green (being the best) is given, and apparently the concepts R1-T, F1-T and F2-T have the highest performance rating in this final comparison.

final ratings



8.4 references

Efthymiou, E. et al. (2010) Sustainable Aluminium Systems

9 CONCLUSIONS AND RECOMMENDATIONS

9.1 conclusions

In this final chapter, first the research questions are addressed in section 9.1, and short summary and reflection of the thesis are provided. The final section 9.2 contains the recommendations for future research.

research questions

1. Which of the principles of designing for a **Circular Economy** apply to **unitized curtain walls**?
2. What kind of **rating system** will be adopted in order to form the new DfD strategy?
3. How can the many different **subcomponents** of a unitized curtain wall be disassembled?
4. What could be the preferred **material for mullion** in terms of reducing the environmental impact and in terms of future disassembly?
5. Which **adaptive** system could eventually be the best choice (from the ones compared) for the circular building envelope?

answers through research & design

1. The Circular Economy principles for unitized curtain walls are provided in Chapter 3, where the strategy is formed. These principles are named ‘design guidelines’ for the Design for Disassembly and each guideline includes various criteria that need to be taken into account. These are summarized in Table 9.1.

related to:	design guidelines	criteria
material	environmental impact	production impact
	durability of the components	life expectancy
		maintenance
		resistance to wear
	recycle/reuse potential	end-of-life activity
		side effects when reused/recycled
connection	reversibility of connections	reversibility of connections
	ease of (dis)assembly	complexity of the conn. techniques
		accessibility of connections
	speed of (dis)assembly	amount of connections
		types of connections
component	prefabrication of components	Unitized CW Systems satisfy these guidelines
	independence of components	
	compatibility of dimensioning	
special attention during design	non-reversible connections should connect the same materials	
	surface treatments should be avoided	
	toxic materials should not be used	
	clear documentation of all elements	

Table 9.1 Summary of the guidelines for DfD of Unitized CW

2. The rating system that was formed through the research of the guidelines was presented at the end of Chapter 3. It is also provided here for clarity in Figure 9.1. Should a future engineer have a different view on the weights applied according to a specific application, they are free to modify the numbers and conduct this strategy on their preferred way. Such modifications can either take place on Table 3.4 or Figure 3.18, or even at both of them.

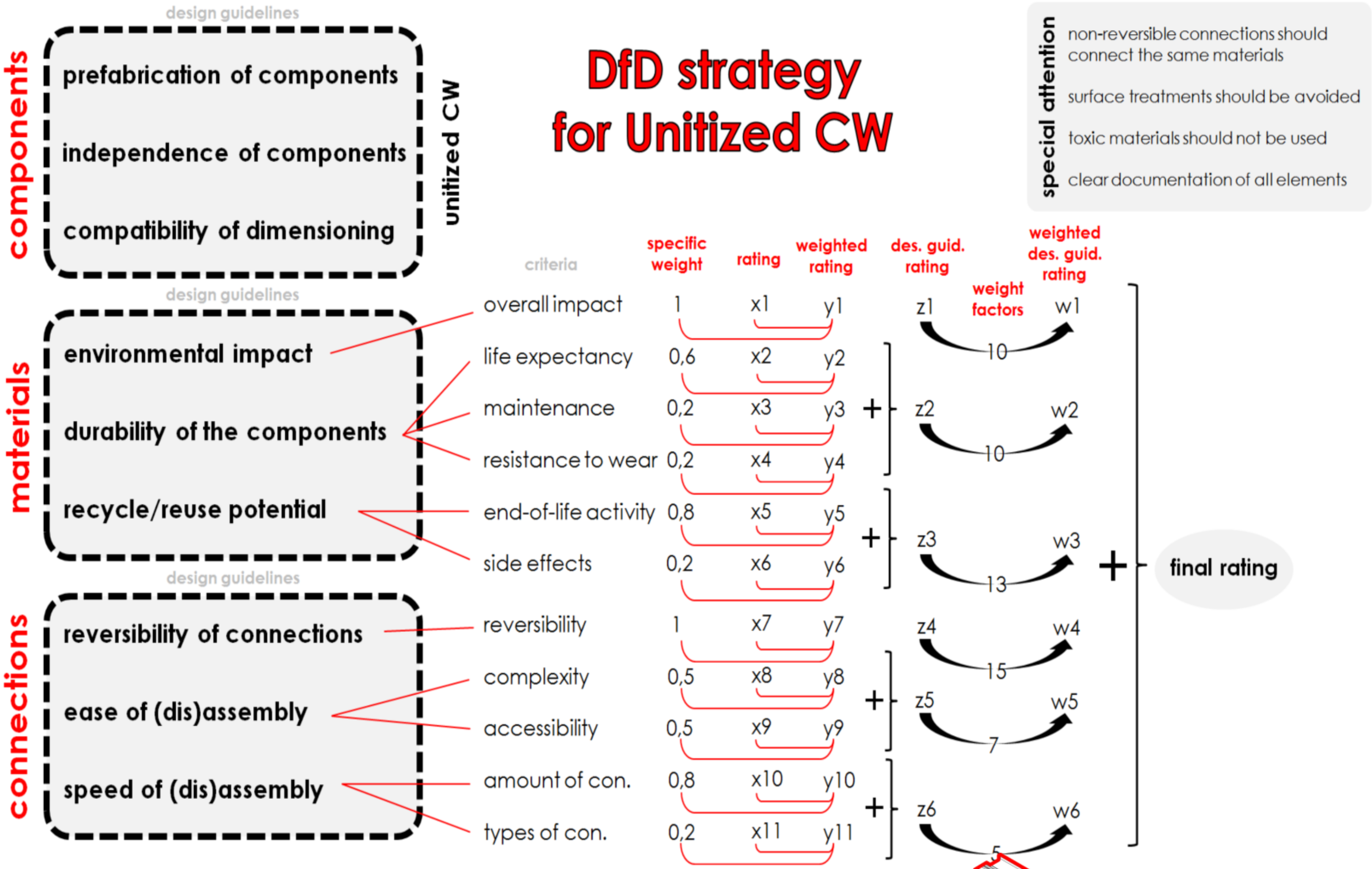


Figure 9.1 The DfD strategy and rating system

3. The disassembly of the various subcomponents of each module was both described and illustrated in Chapter 5. Figure 9.2 shows an exploded 3D view of the different parts of the curtain wall with the highlighted prefabricated parts

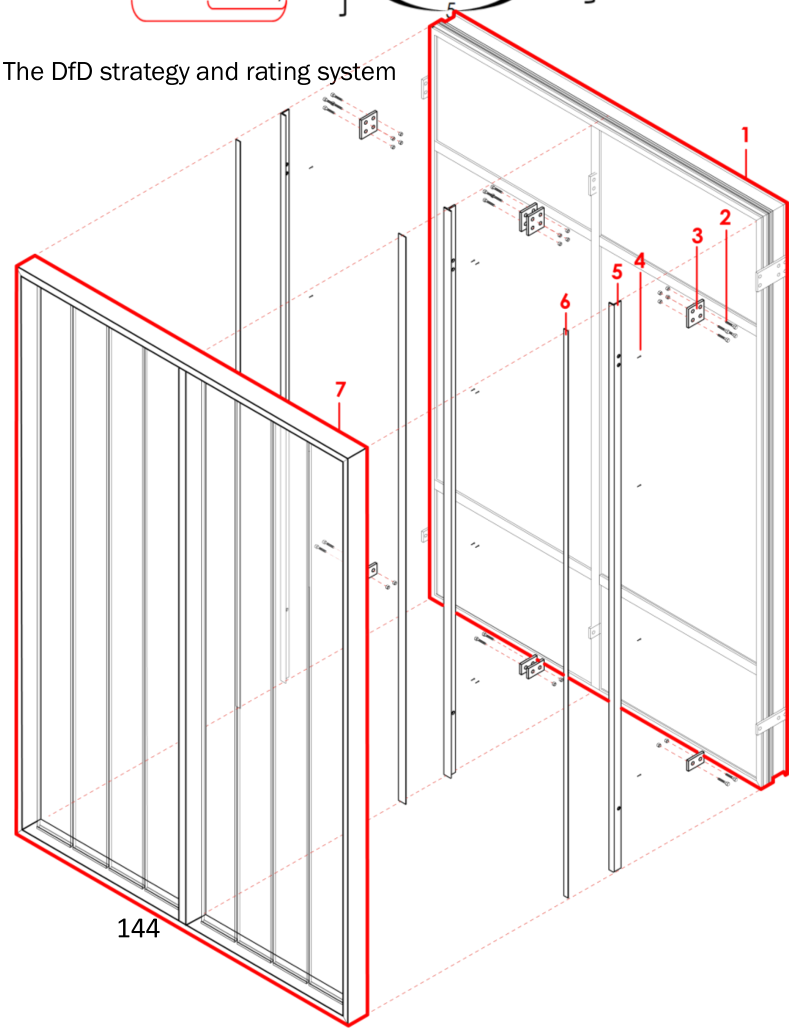


Figure 9.2 Exploded view of the mullion-transom connection

4. The mullion material that apparently performs better for DfD was found to be timber, as presented in Chapter 8. The collective graph with the results of the ratings is repeated in Figure 9.3, where one can observe that timber scores higher.

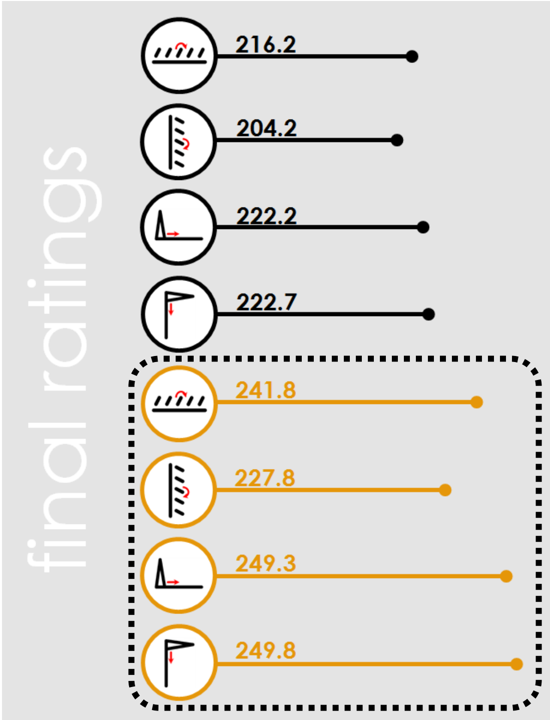


Figure 9.3 The results of the concepts comparison – timber modules are highlighted

5. As for the best performing module that is derived from this comparison assessment, no clear choice can be made among the 4 concepts, as they all score pretty close. Especially for F1-T and F2-T, the final scores only show slight deviations. A slight lead is given to the last timber-framed folding module (F2-T). This can again be noticed from the results, as shown in Figure 9.4, where the winning concepts is highlighted.

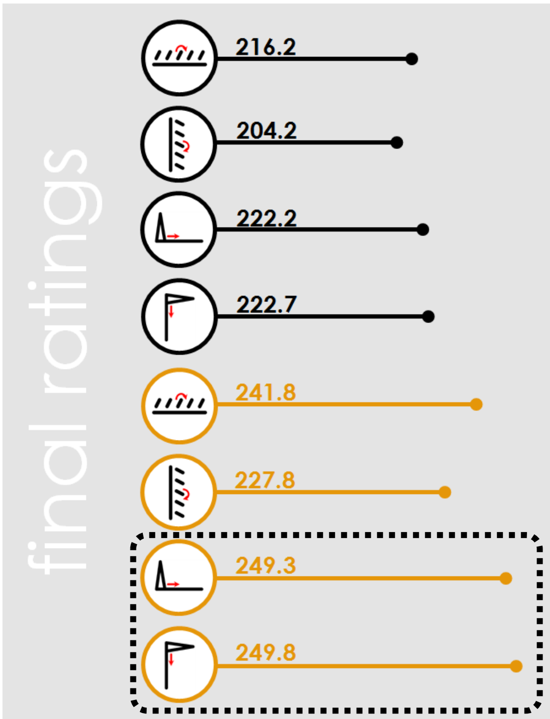


Figure 9.4 The results of the concepts comparison – the top performing module

It should be emphasized at this point that such slight differences in the results among the concepts may not eventually be crucial for the choice of the final design module. Apart from the fact that the units used do not have an absolute value, there are also other important factors that always need to be taken into consideration when designing a facade and, depending on the case, may even have a higher influence on the final design. Such considerations include:

- energy performance
- life cycle costs
- user comfort
- aesthetics and overall appearance
- maintenance

9.2 recommendations

There is a large number of recommendations for further research provided in this section, which can be considered very useful for further development of the current DfD strategy, and even for the conception of other strategies for circular design.

- **Development of a DfD startegy for the stick system in curtain walls.**

The research conducted in this master thesis focussed exclusively on the unitized systems used for facades. This means that other assembly techniques, such as the stick-built, which is the most common for curtain walls, still need to have a certain framework for their DfD potential prior to construction.

The use of either a unitized or stick system highly depends on a number of factors, the most important of which are:

- The size of the project [the larger and taller the building, the more sense it makes to go for the unitized],
- The degree of repetition [if the main grid is standard with constant dimensions between floors, unitized systems are preferred]
- The shape of the building [flat and vertical walls are much more simple to assemble and install on site than complex 3D geometries, and thus the choice of a stick system might be preferred]

In general, most of the DfD principles apply to both systems, but there may be some differentiations on the design guidelines at the component level. It would be also interesting to investigate the differentiations that may occur on the weight factors used for the rating.

- **Energy performance simulations**

The overall energy efficiency that a certain facade can achieve is one of the most important considerations during the design phase. The final choice of an adaptive system for a certain orientation is highly dependent on its performance. Therefore, it is always good to compare both the DfD rating and the energy efficiency of different facades.

- **Comparison of other adaptive concepts and other mullion materials**

There is quite a large number of design choices that were made in the assessment part of this thesis. It could be quite interesting to discover the possibilities of assessments with different boundary conditions, such as different kind of adaptations (current: optical, thermal and electrical), different climate conditions (current: temperate) and/or different building type (current: office).

- **life cycle costs**

Having an approximation of the total costs is always of paramount importance when designing a facade. This could be calculated for one module, and then a comparison of the costs among the concepts can be made.

- **materials for CW**

Going more into depth on the research for the best material choices for curtain walls is essential. Foe instance, comparing the different insulation materials and sandwich panels derived, can lead to useful outcomes for a future modular design. This can both relate to material properties, such as recyclability, or attachment methods, such as the potential for material division during deconstruction.

APPENDICES

picture taken
by the author

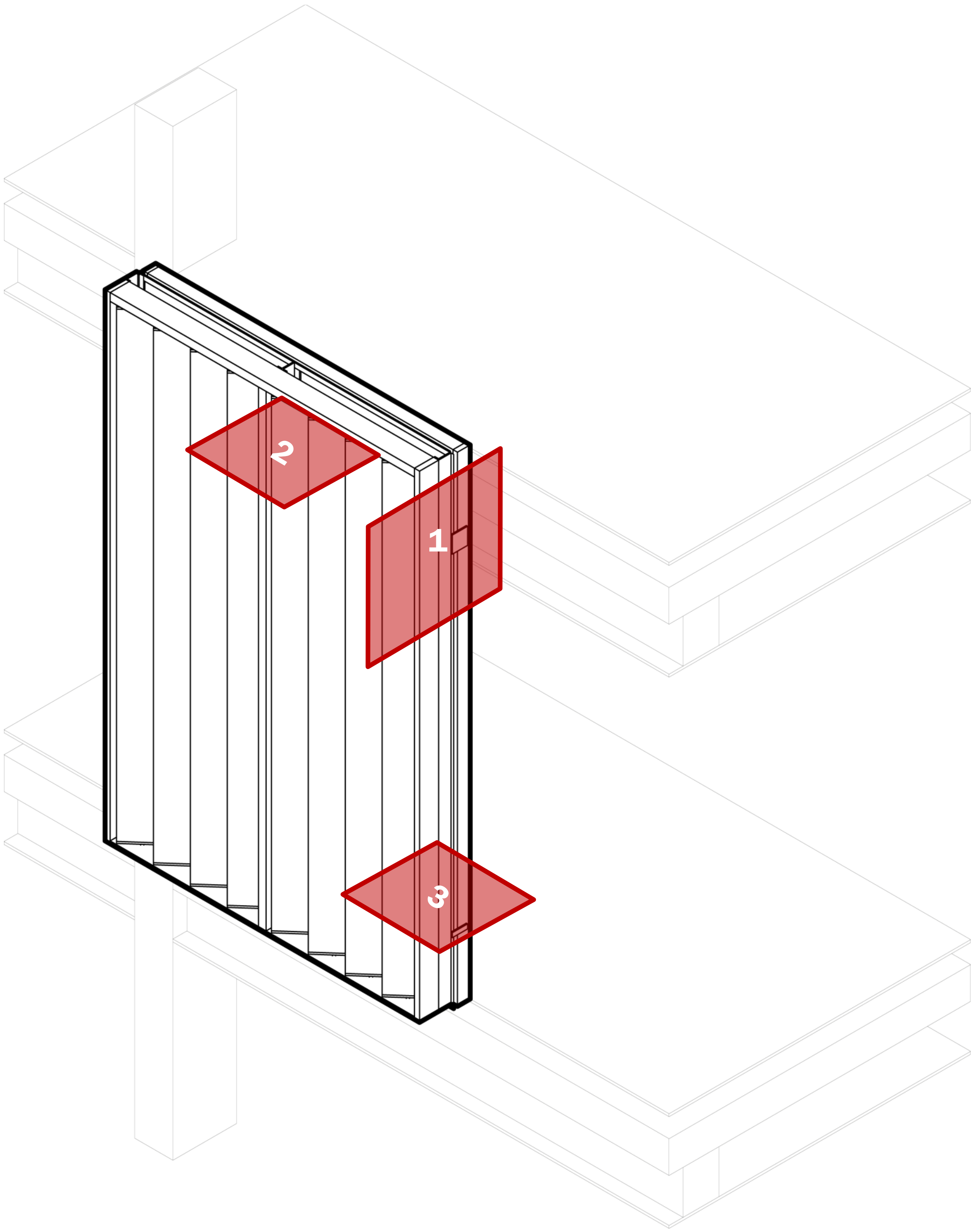
APPENDIX A

DETAILED DRAWINGS

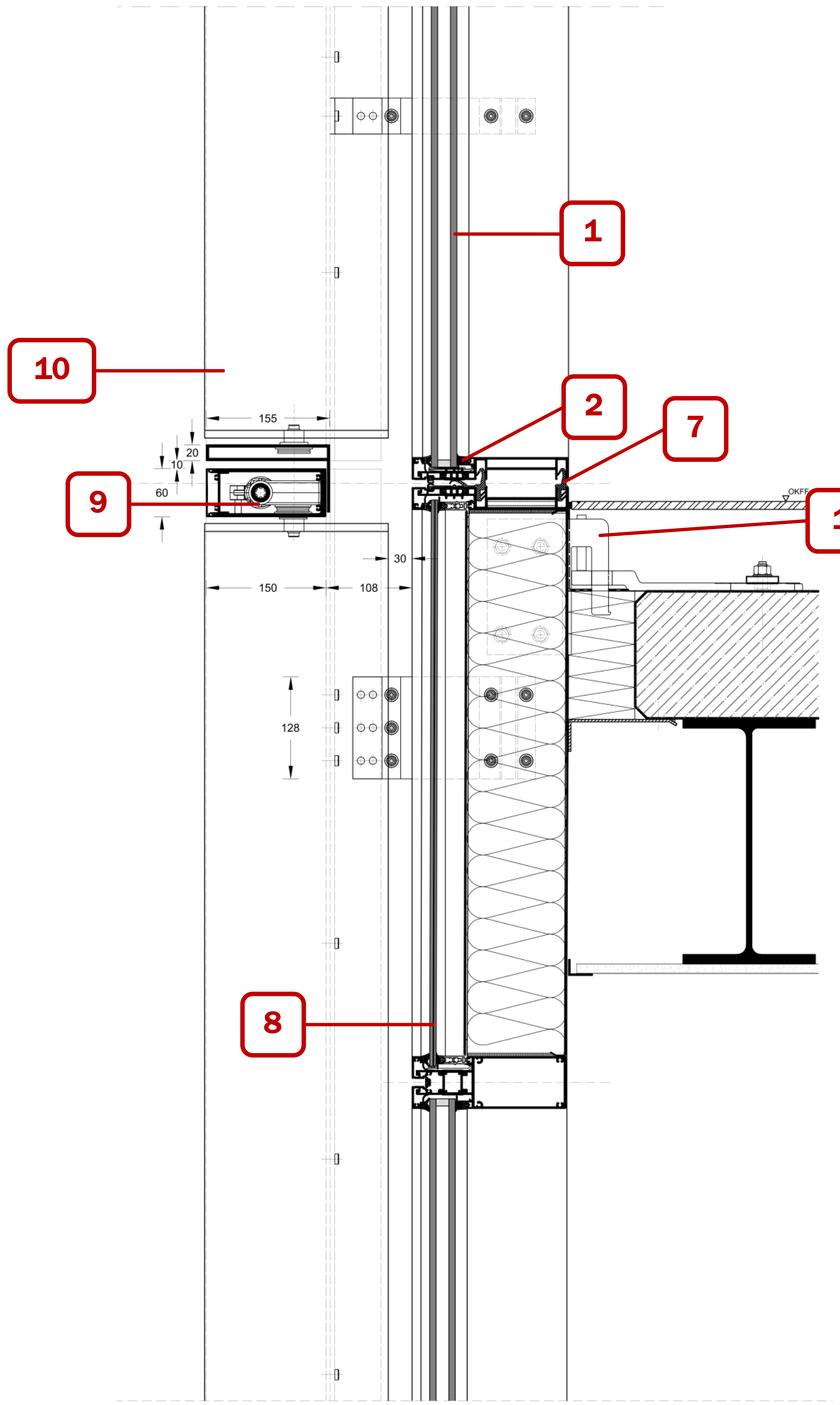
INDICATION FOR ALL THE DETAILS:

1. Double Glazing
2. Gasket
3. Aluminium Profile
4. Thermal Break
5. Pressure Plate
6. Cover Cap
7. Coupling Gasket
8. Spandrel Glass
9. Motor
10. Laminated Photovoltaic Glass
11. Insulating ‘Sandwich’ Panel
12. Anchor
13. Steel Plate
14. Steel Profile
15. Rubber Profile

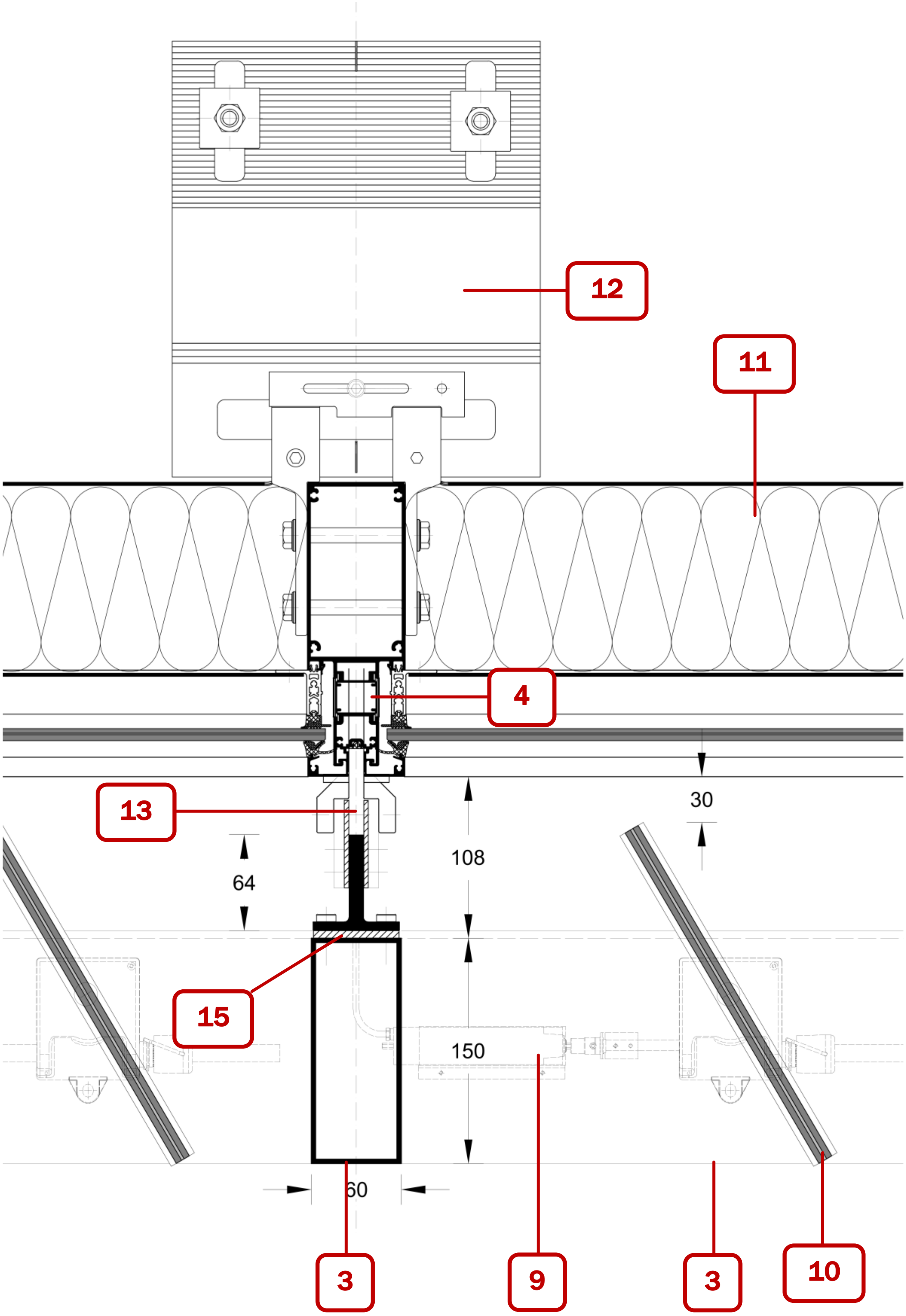
ADAPTIVE CONCEPT R1 – Vertical Rotating Fins



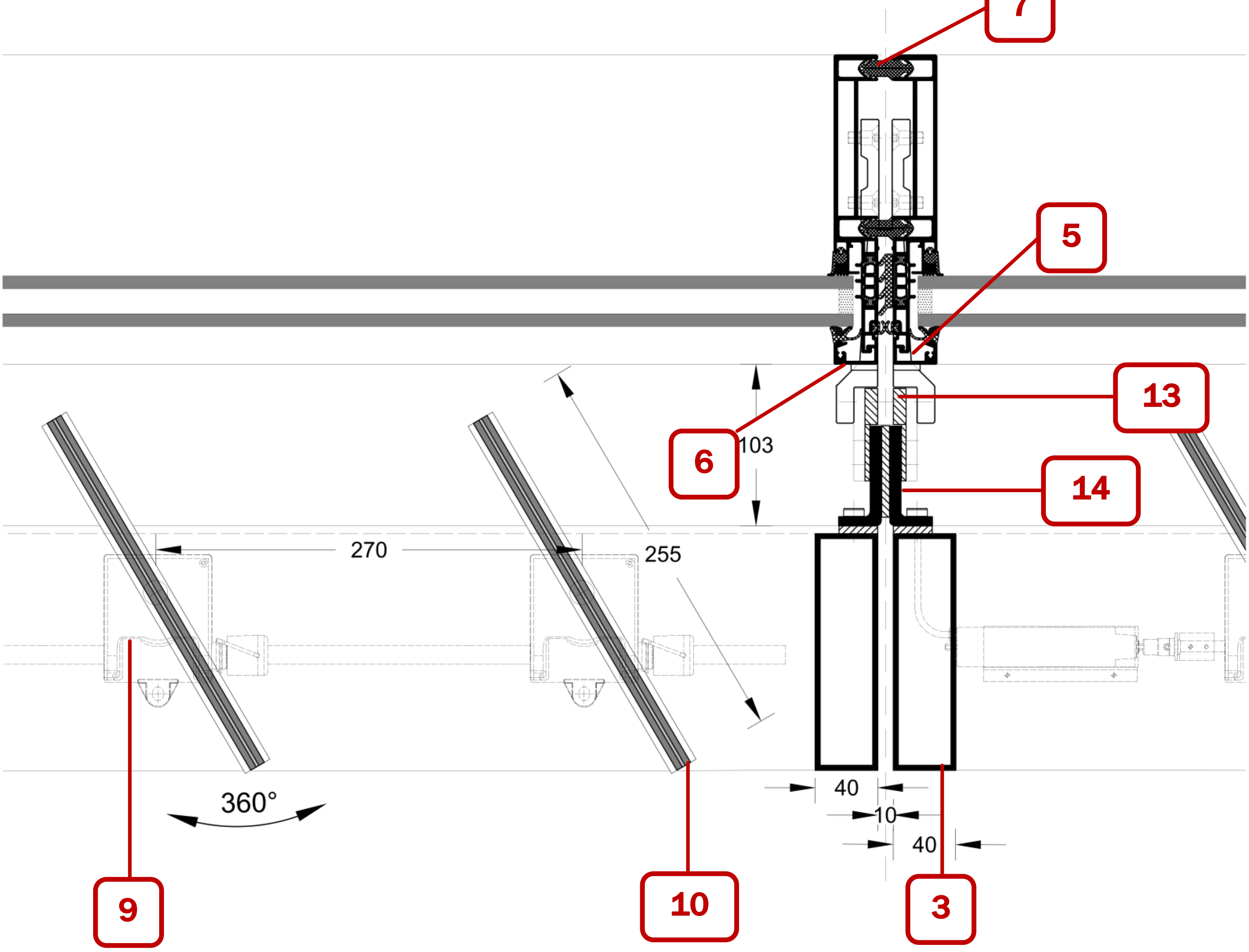
DETAIL 1



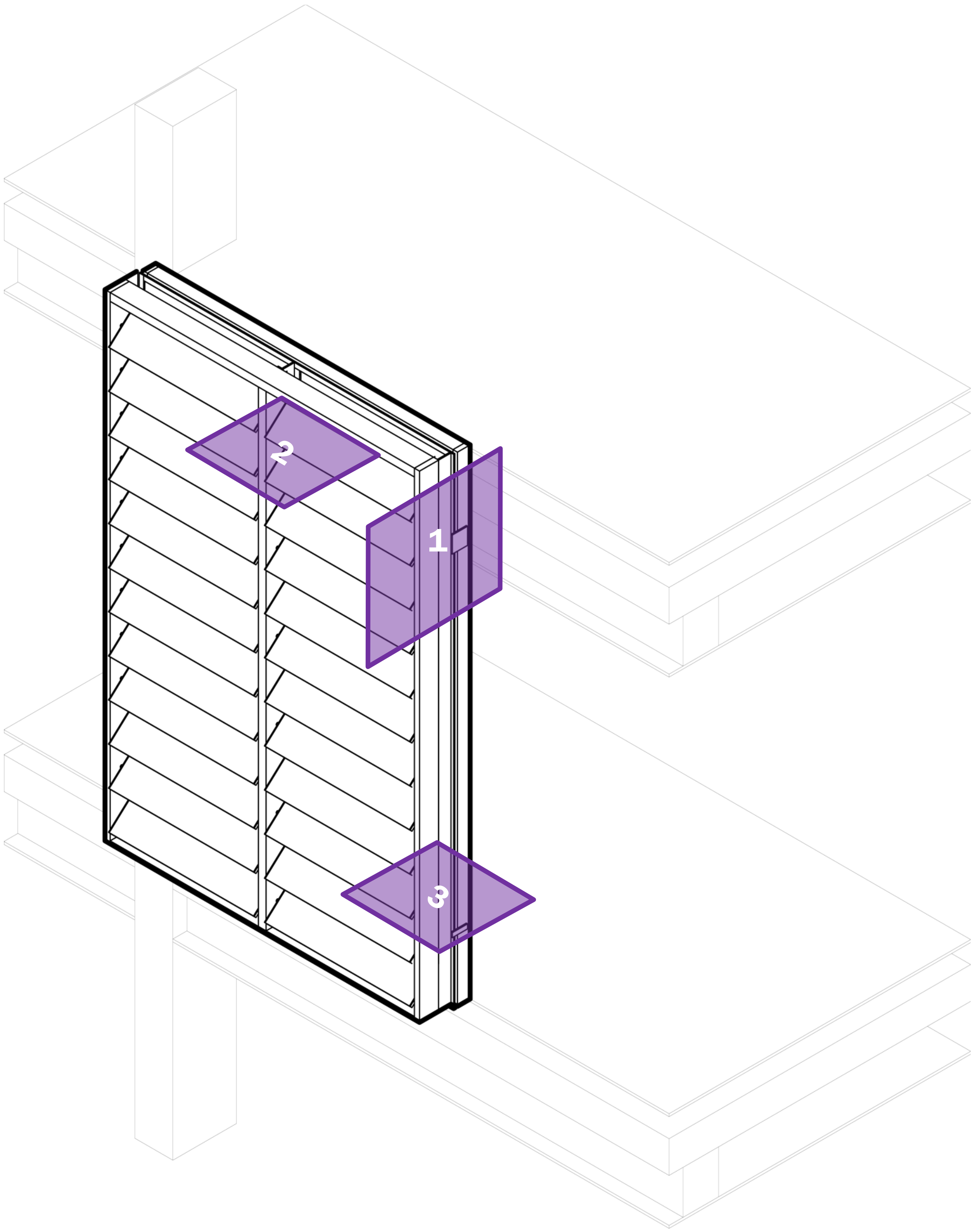
DETAIL 2



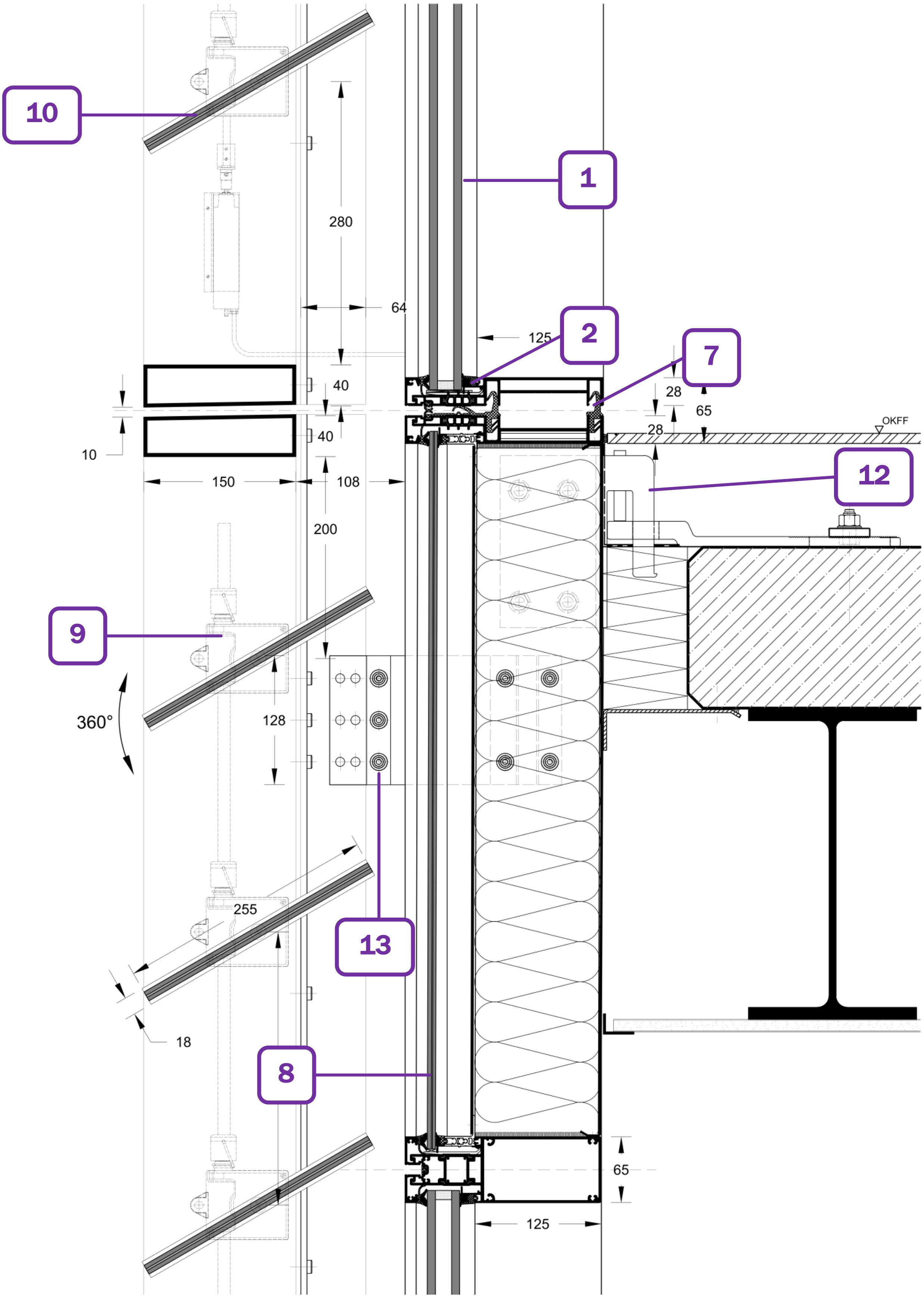
DETAIL 3



ADAPTIVE CONCEPT R2 – Horizontal Rotating Fins



DETAIL 1



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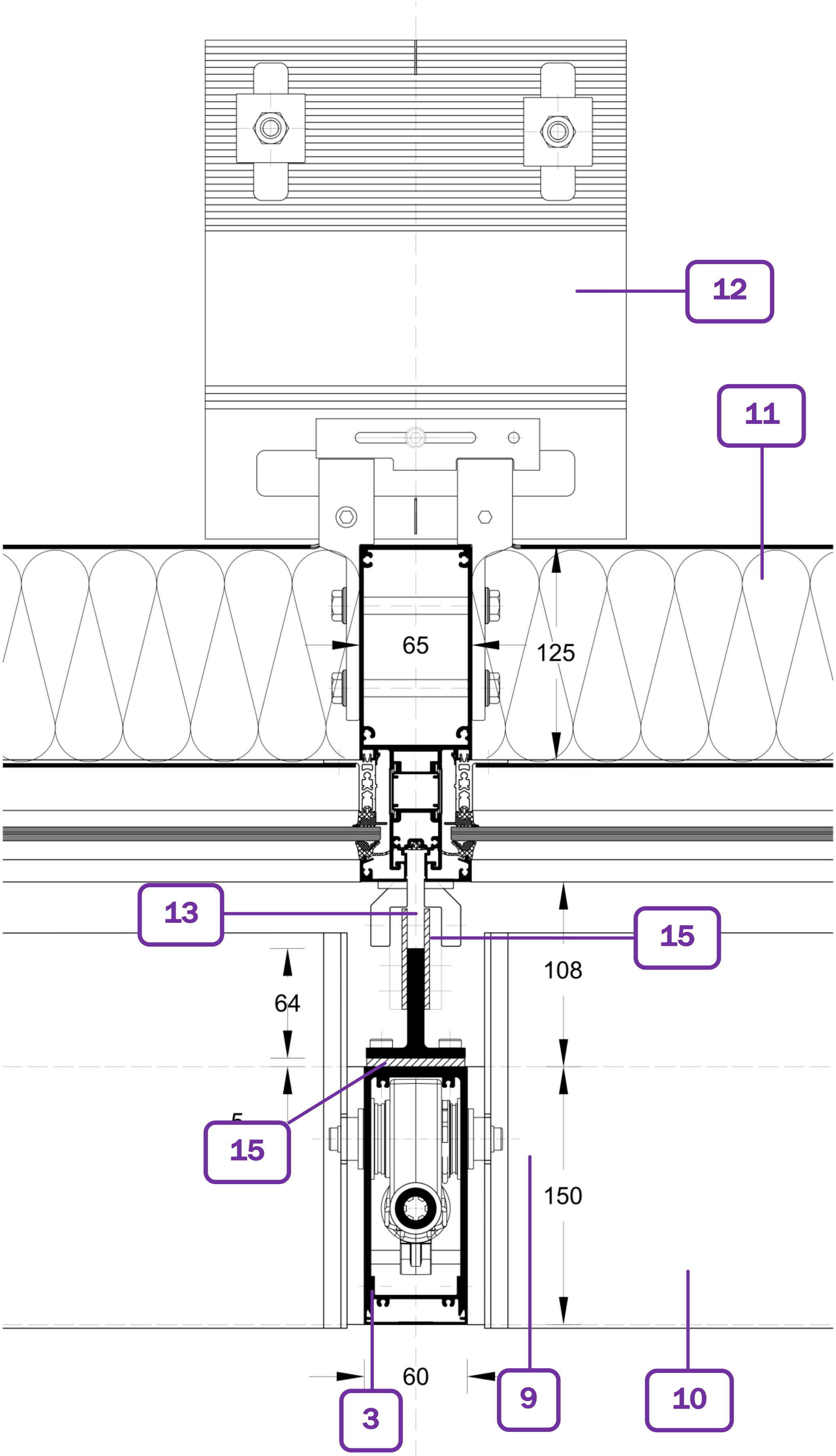
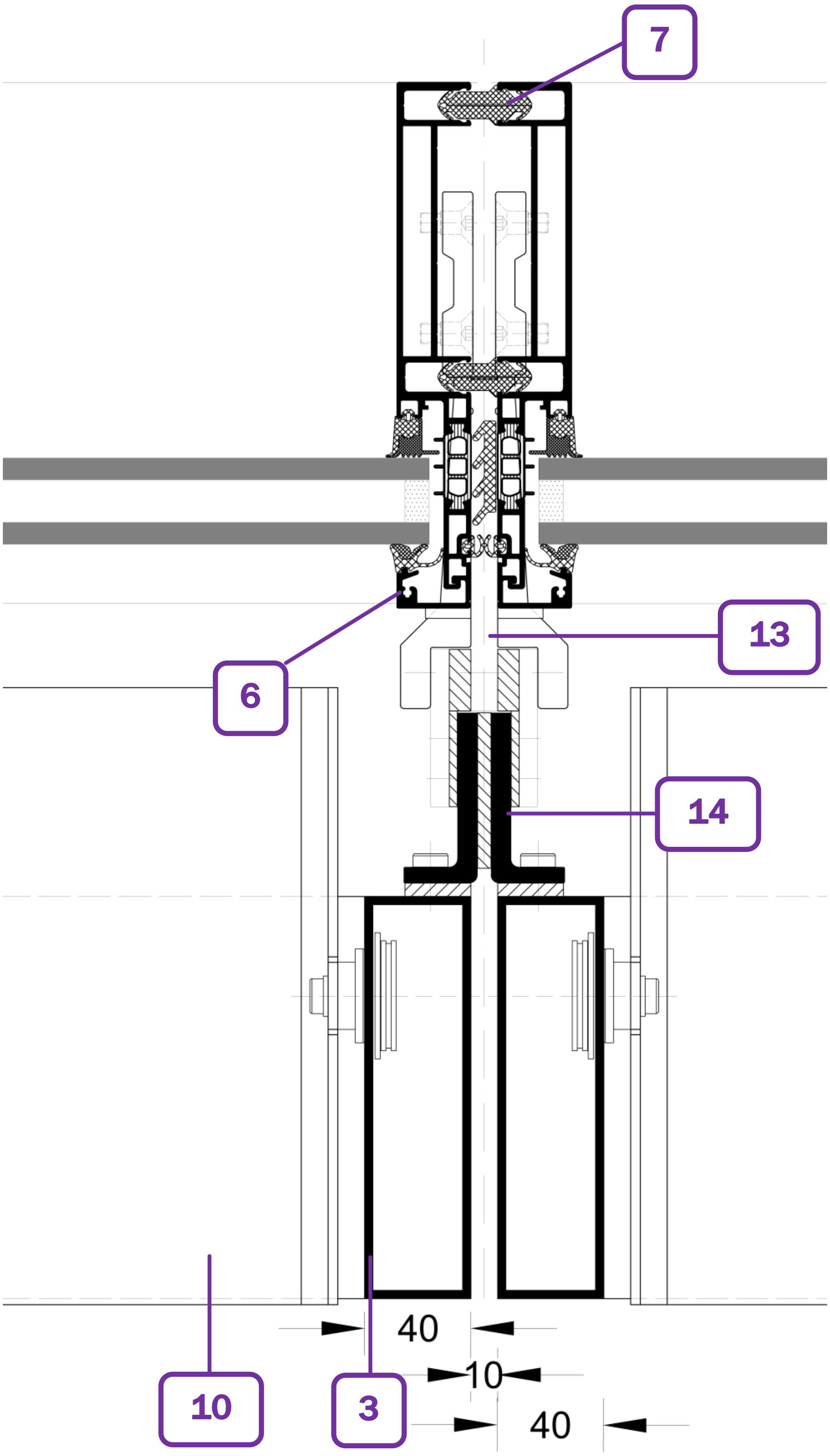
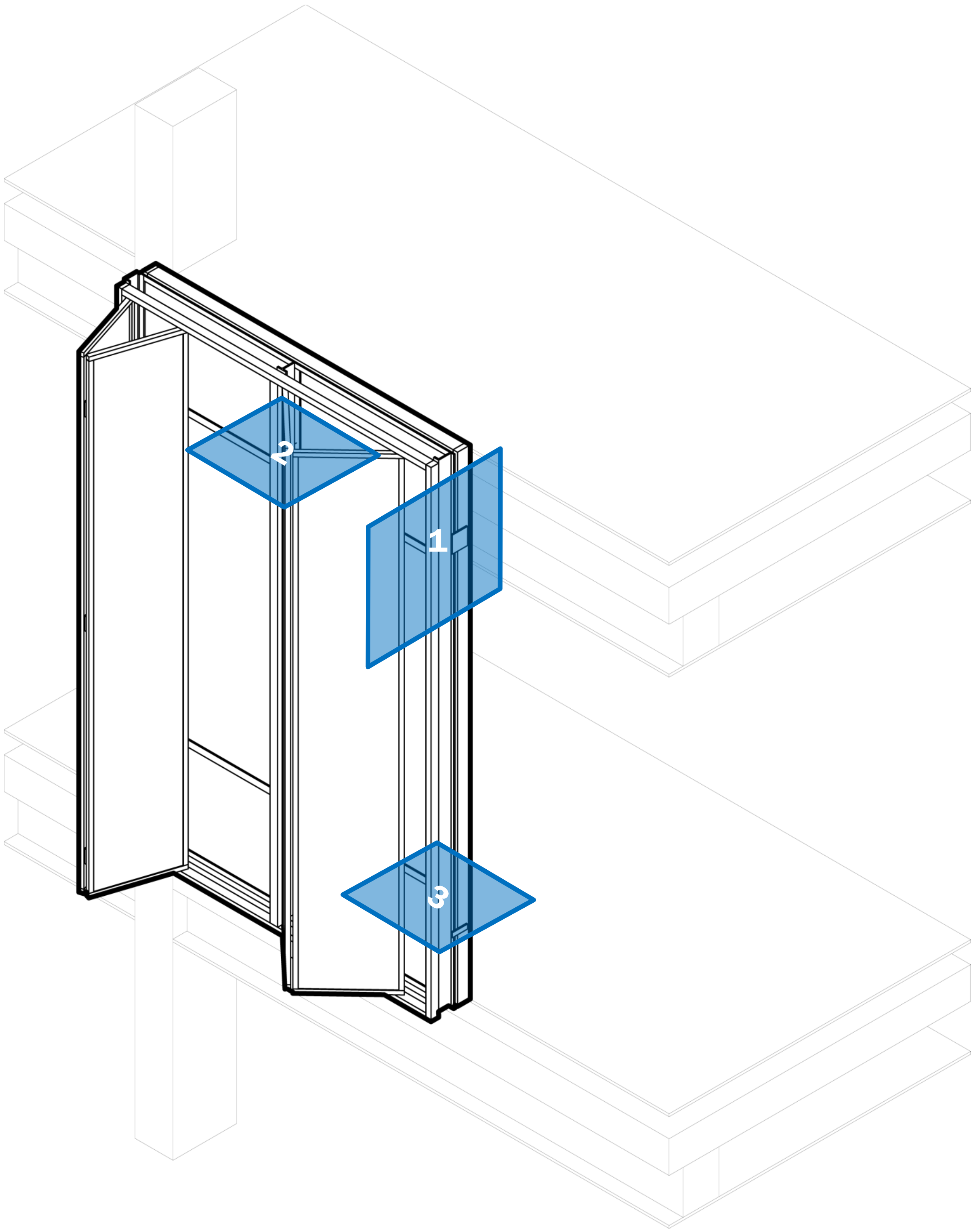
DETAIL 2



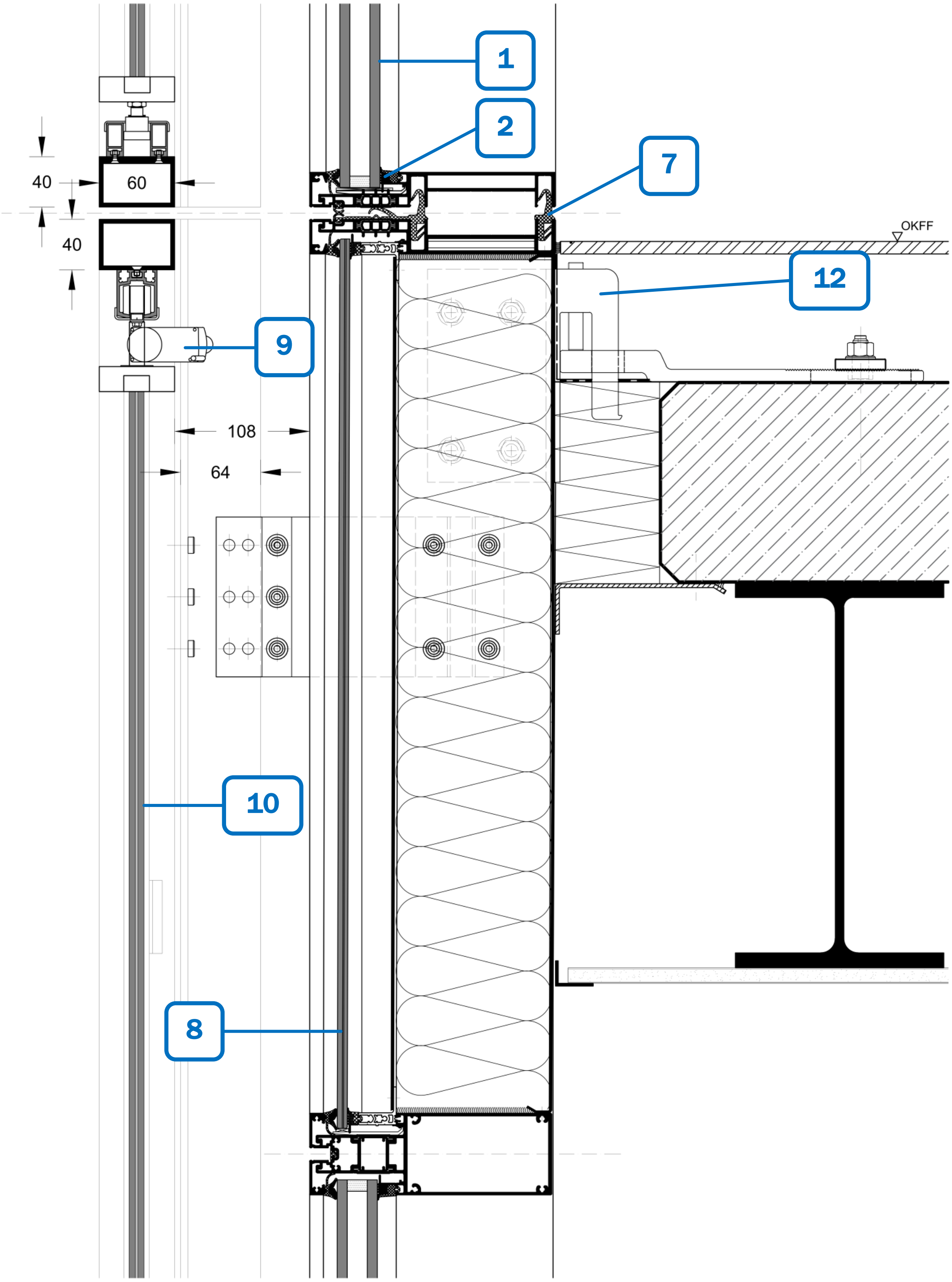
DETAIL 3



ADAPTIVE CONCEPT F1 – Horizontally Folding Panels



DETAIL 1



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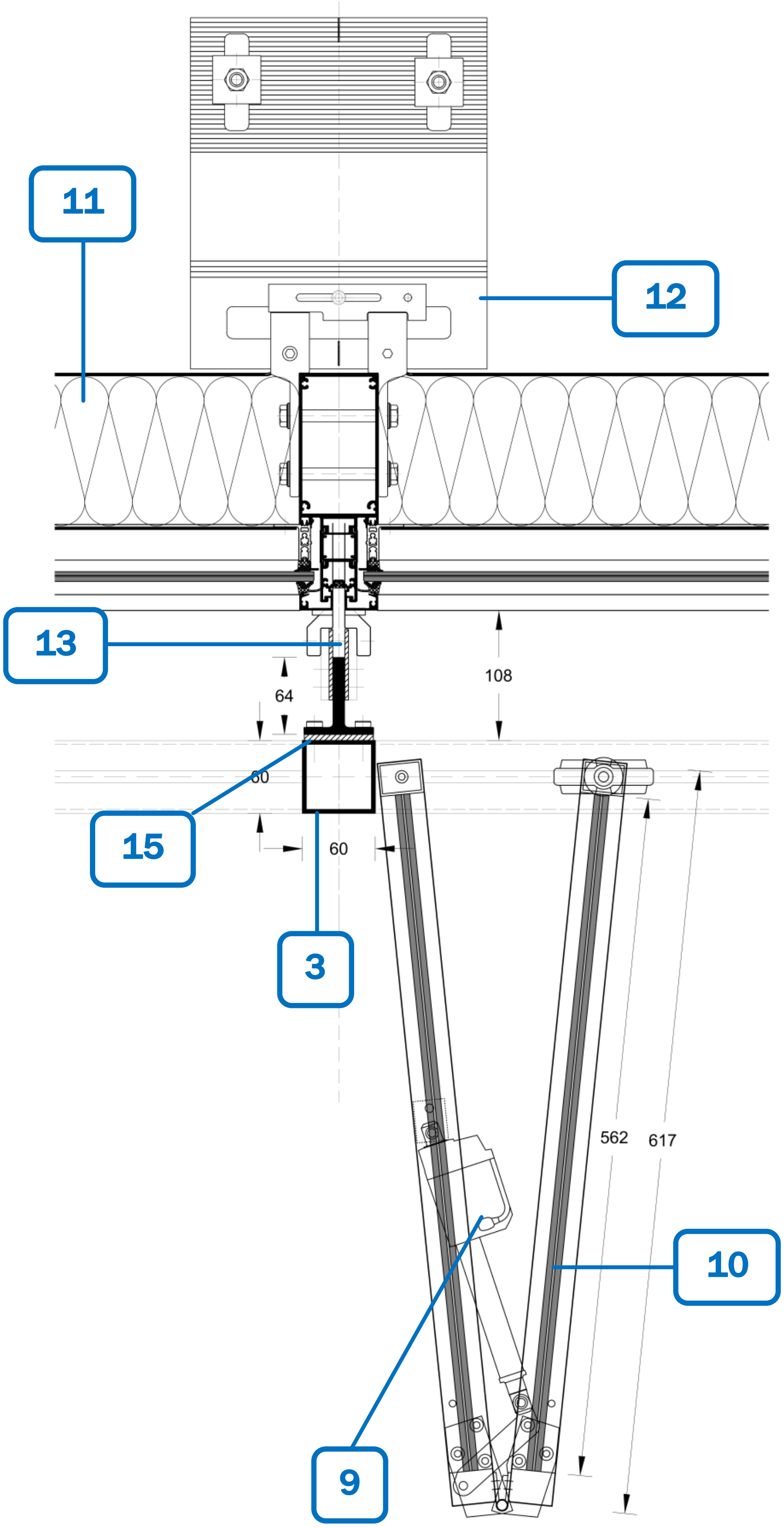

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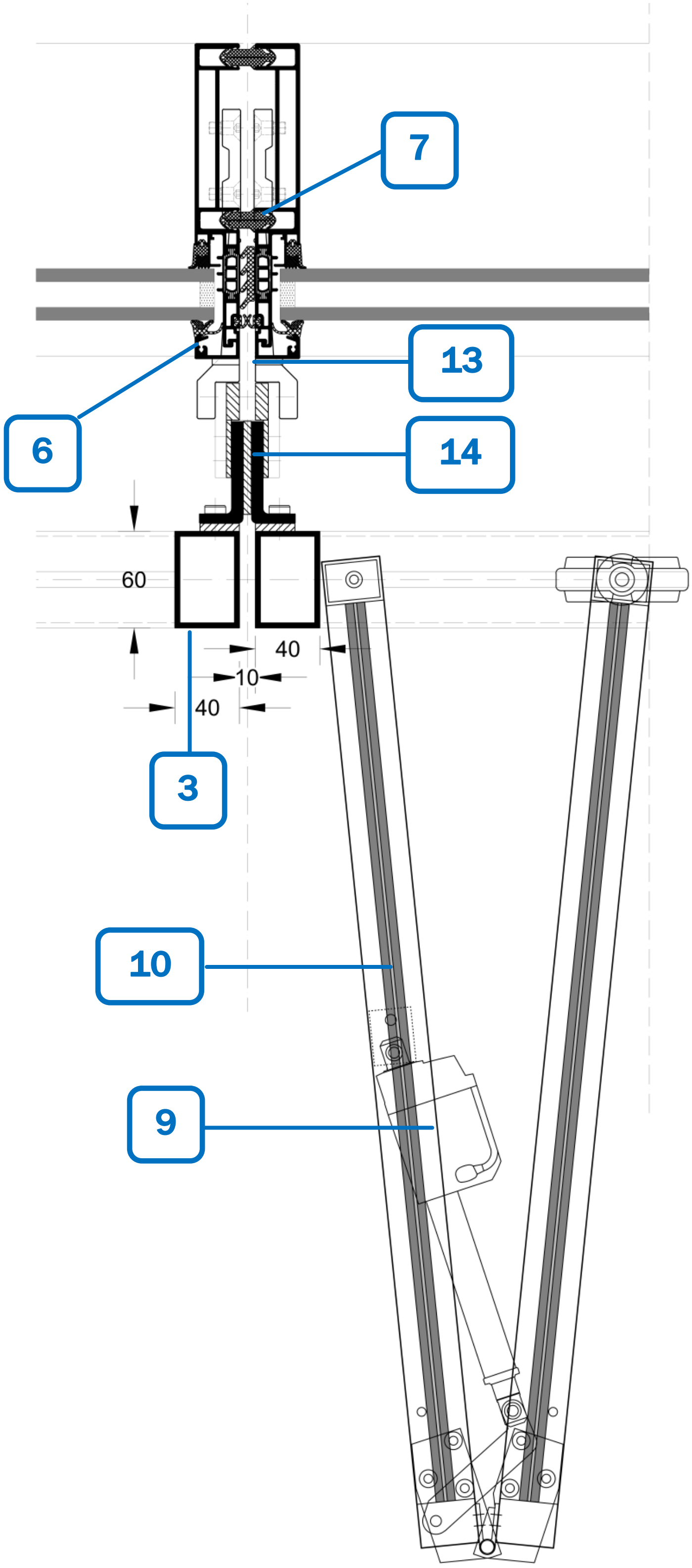
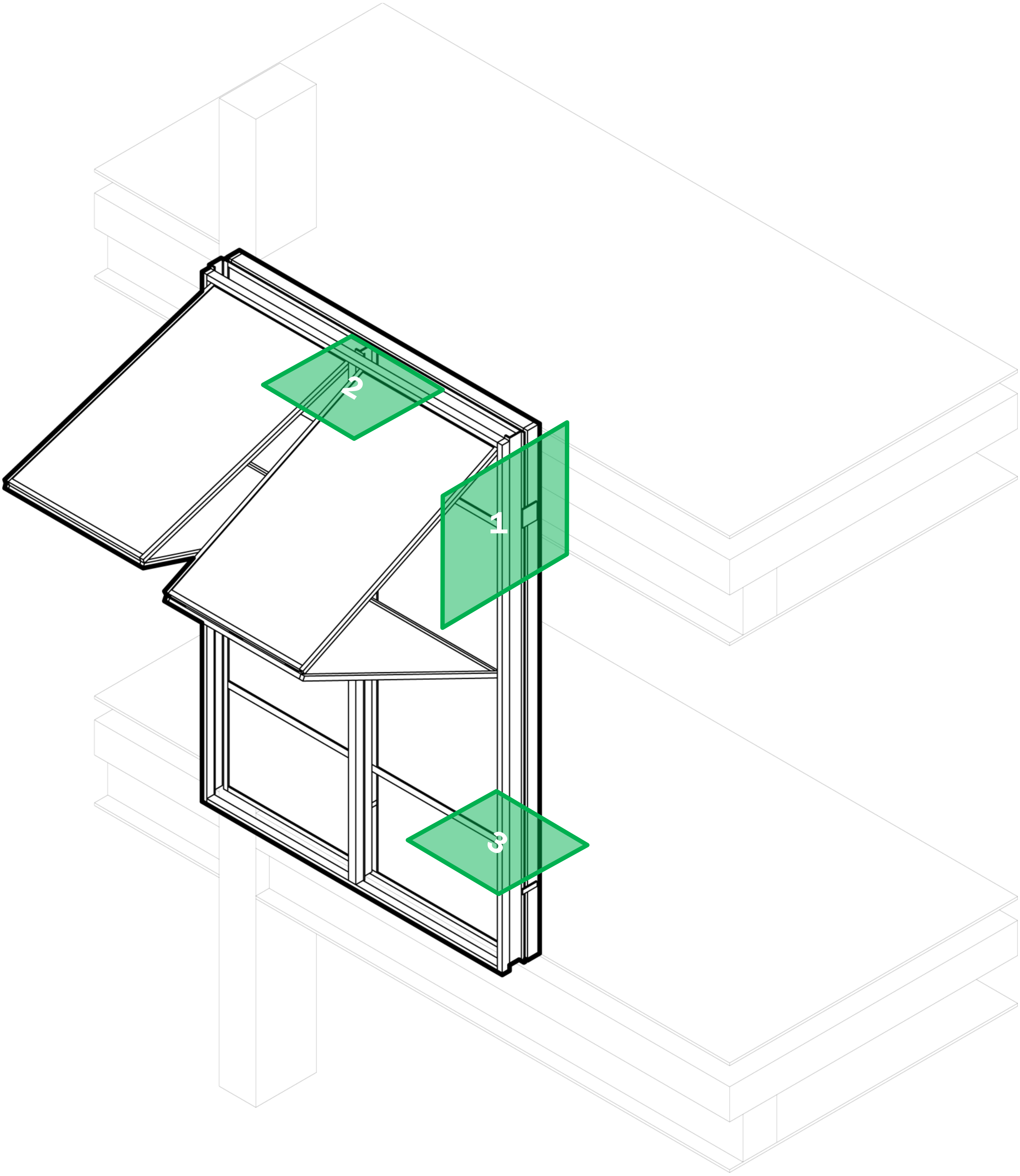
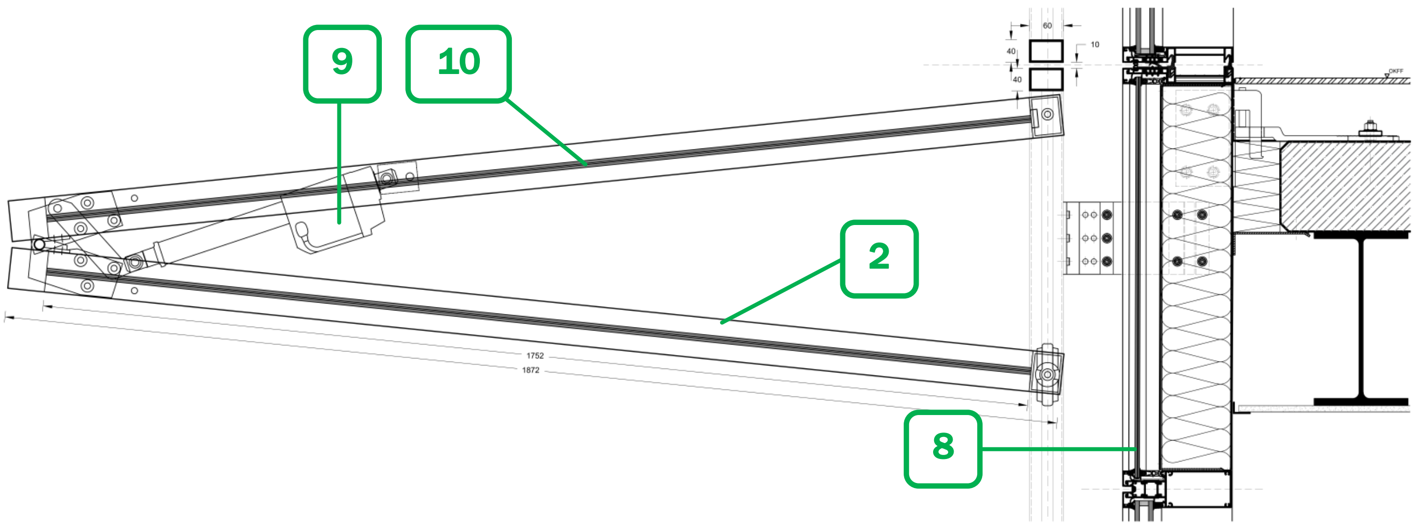


ADAPTIVE CONCEPT F2 – Vertically Folding Panels



DETAIL 1



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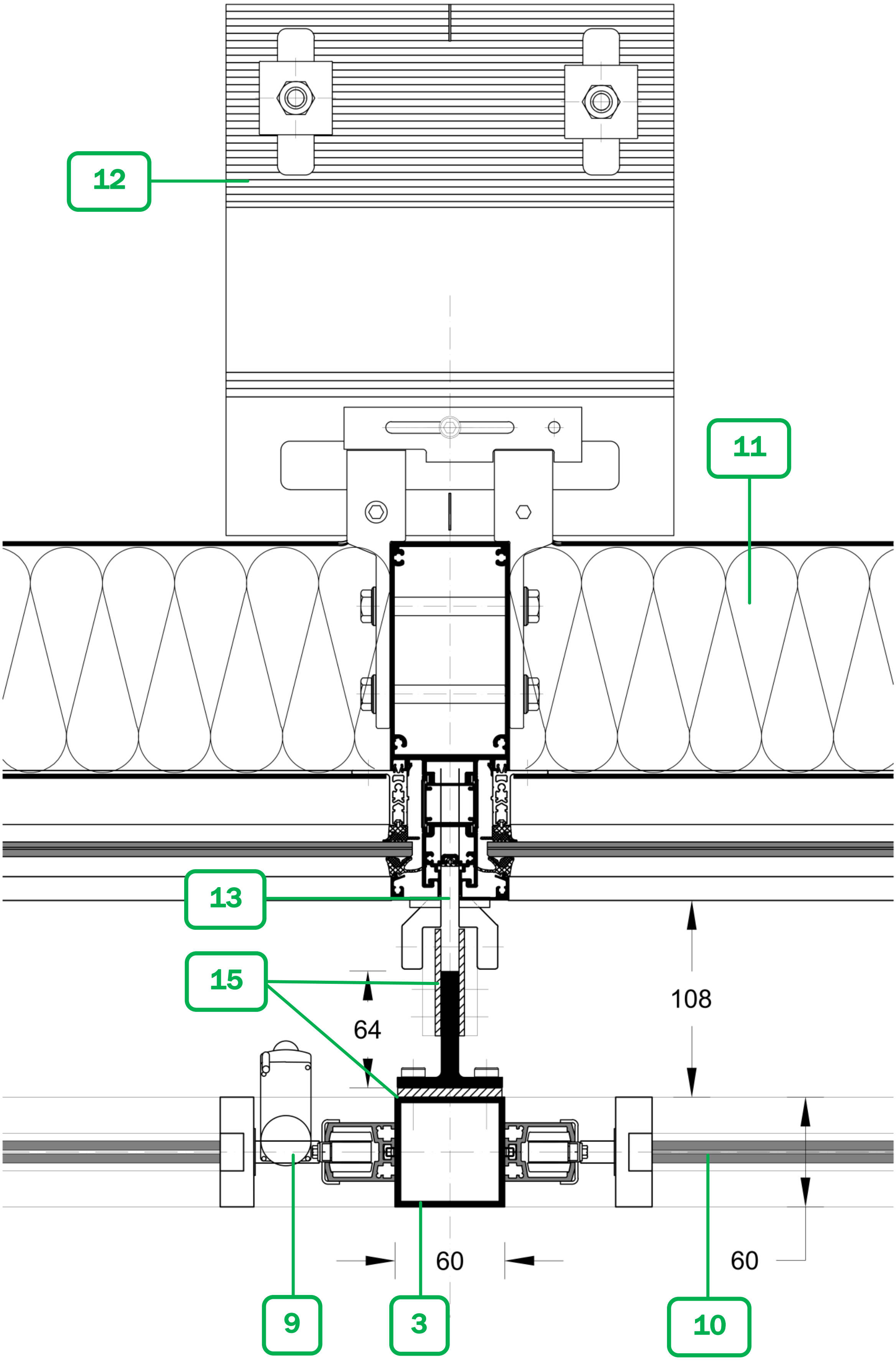
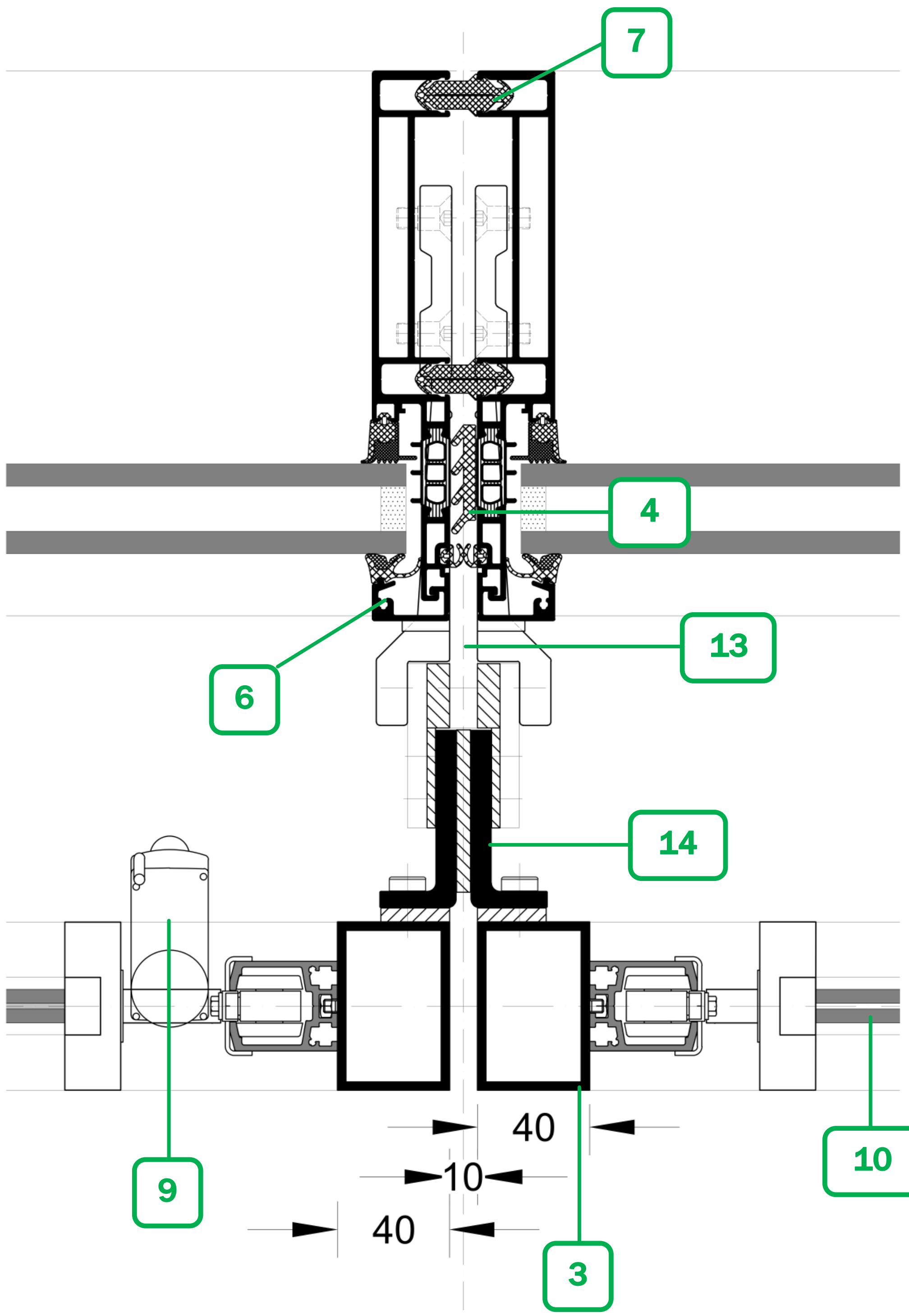
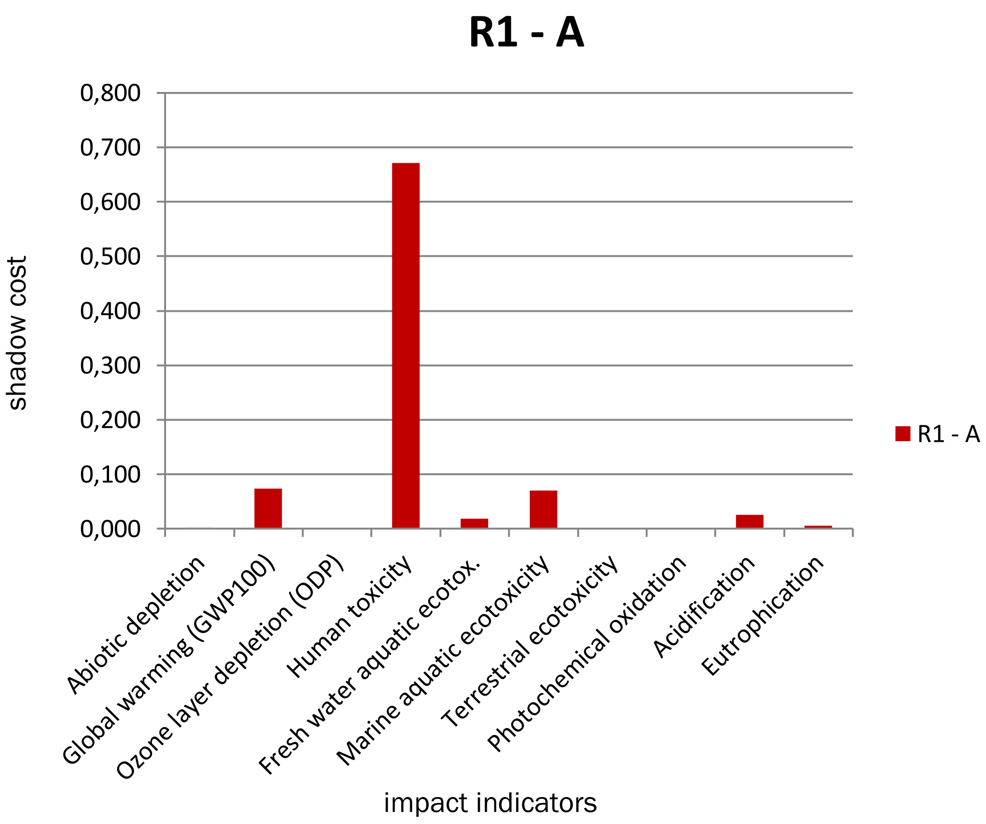


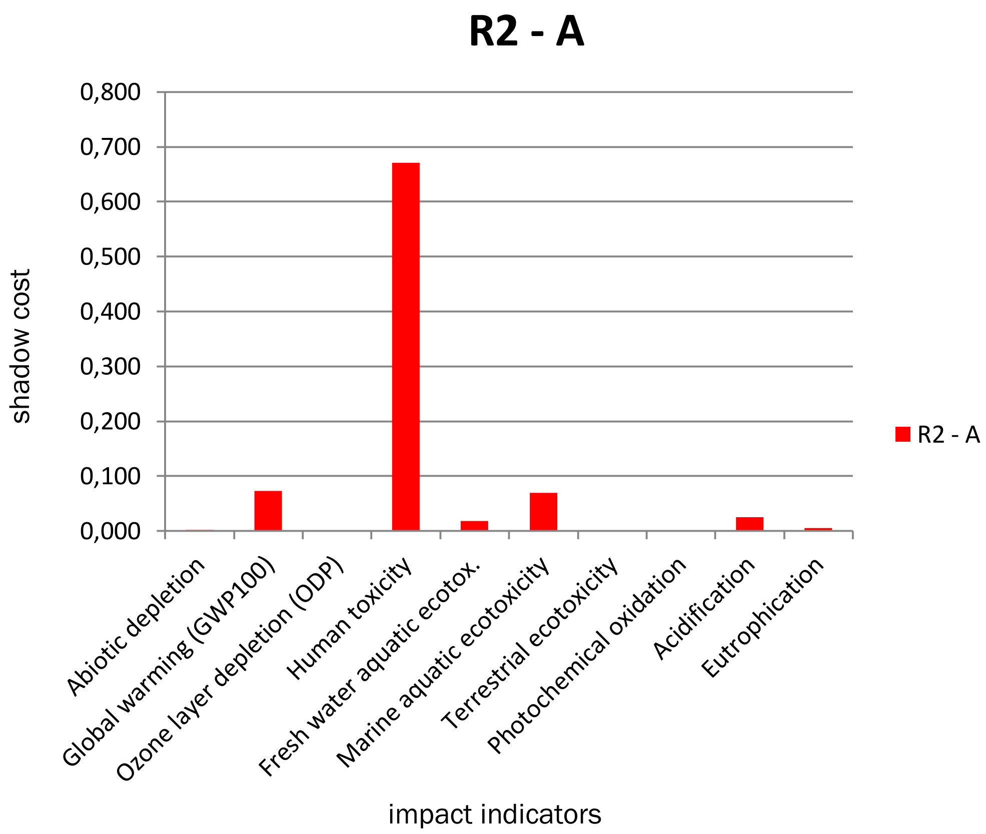
DETAIL 3

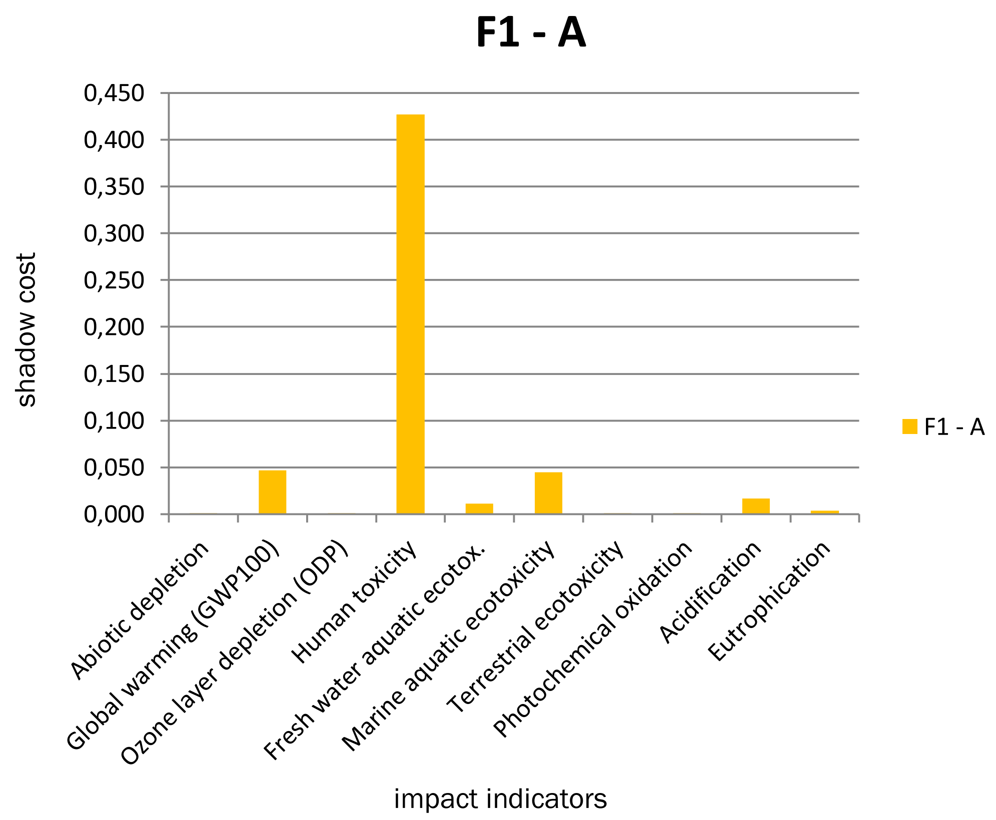


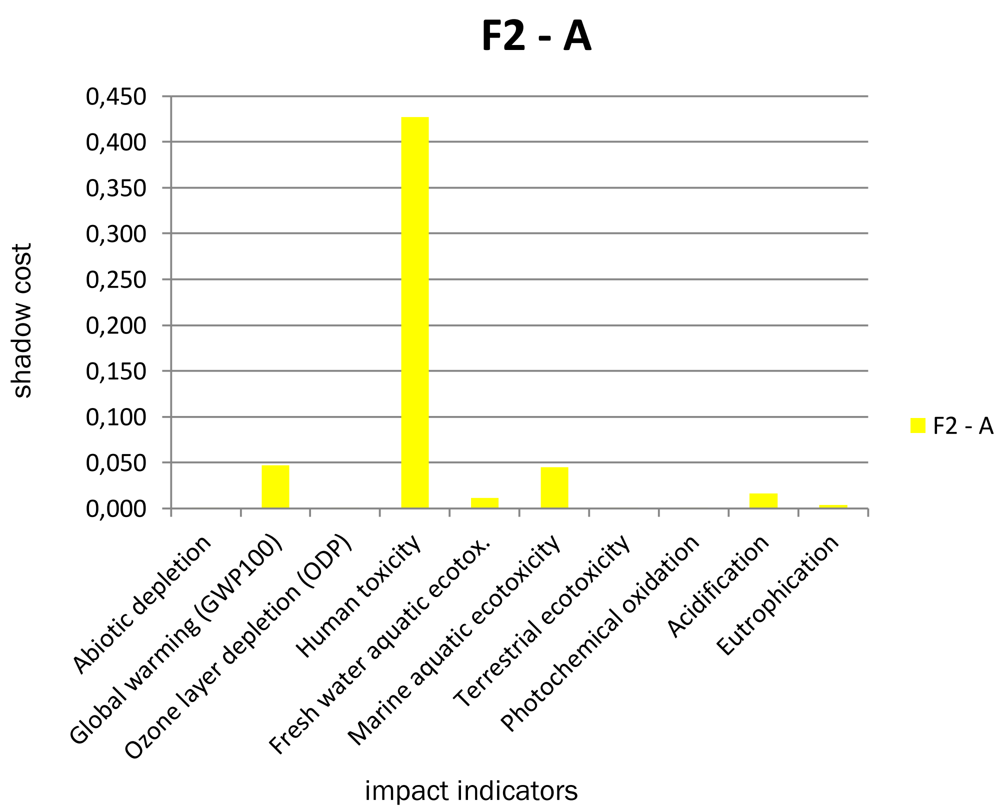
APPENDIX B

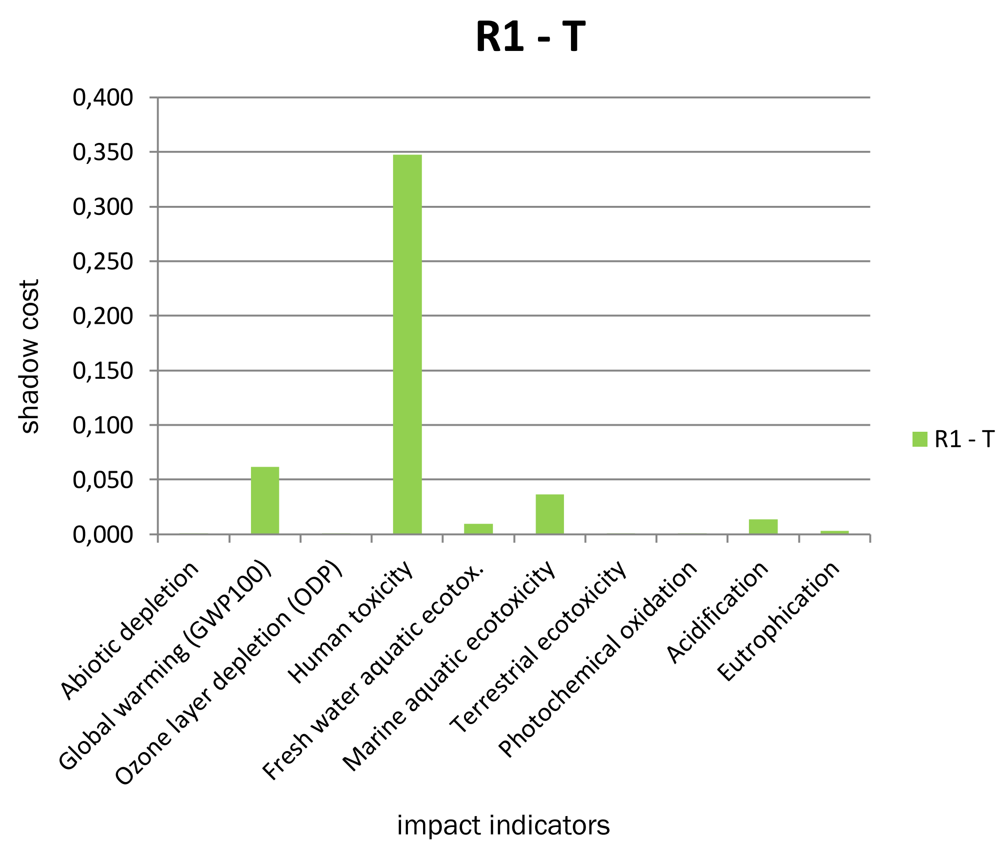
EPD RESULTS

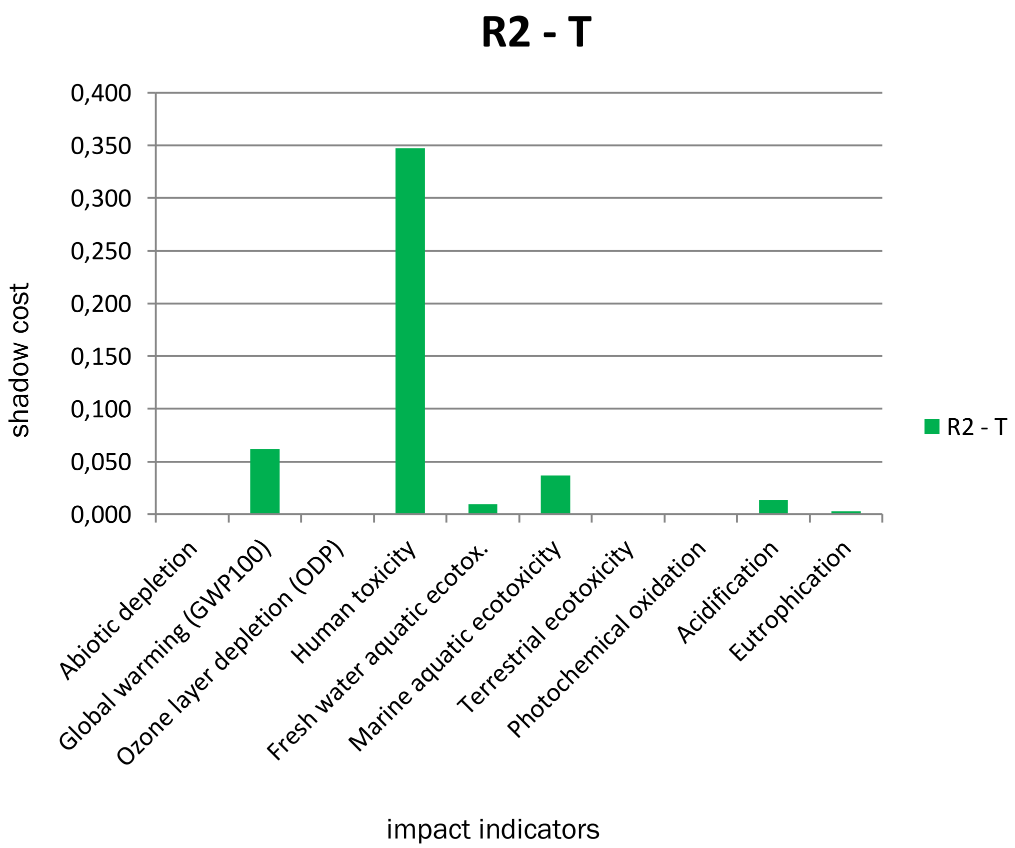

R1 - A
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
shadow cost
R1 - A
Abiotic depletion
Global warming (GWP100)
Ozone layer depletion (ODP)
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Acidification
Eutrophication
impact indicators

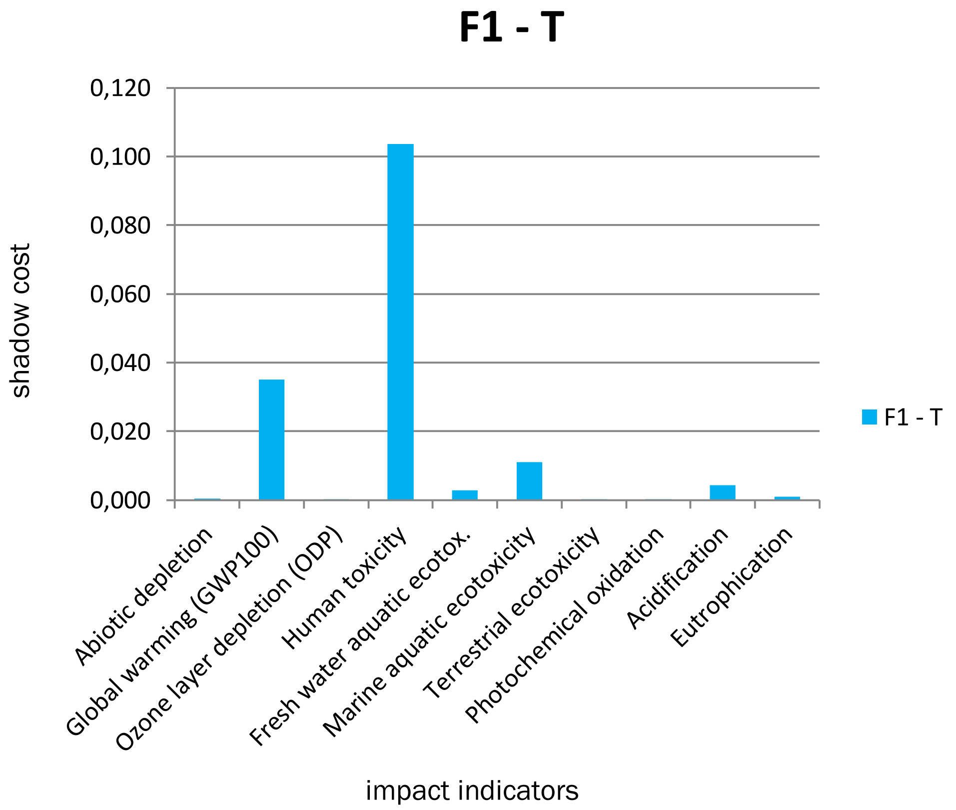

R2 - A
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
shadow cost
R2 - A
Abiotic depletion
Global warming (GWP100)
Ozone layer depletion (ODP)
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Acidification
Eutrophication
impact indicators


F1 - A
0,450
0,400
0,350
0,300
0,250
0,200
0,150
0,100
0,050
0,000
shadow cost
Abiotic depletion
Global warming (GWP100)
Ozone layer depletion (ODP)
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Acidification
Eutrophication
impact indicators
F1 - A

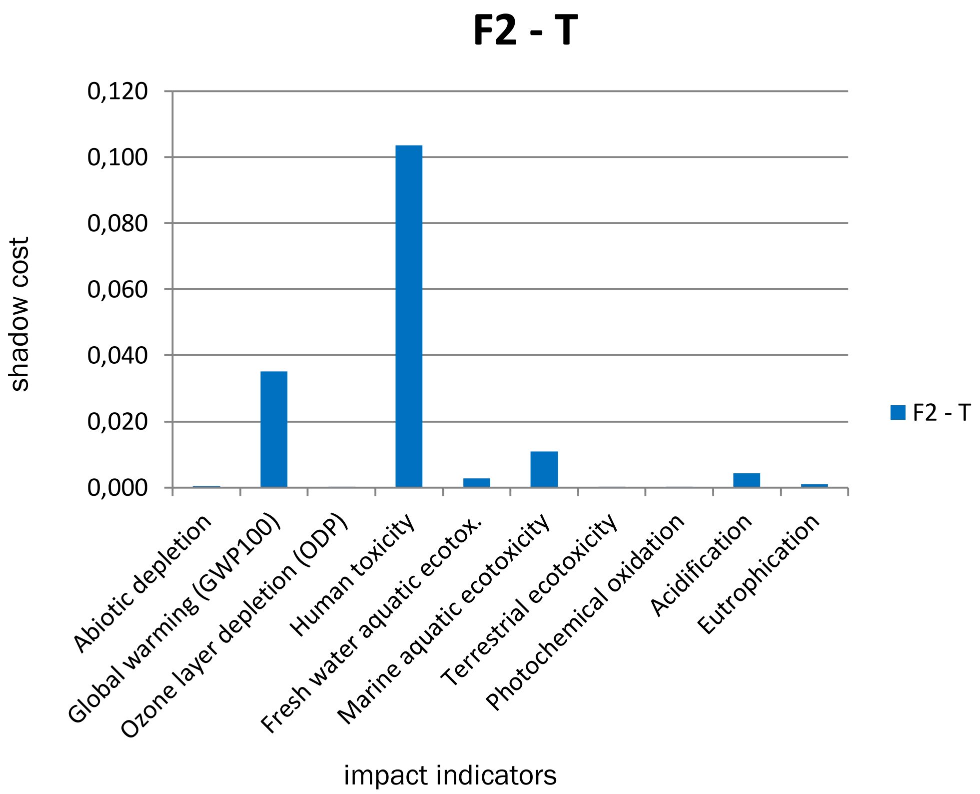

F2 - A
0,450
0,400
0,350
0,300
0,250
0,200
0,150
0,100
0,050
0,000
shadow cost
Abiotic depletion
Global warming (GWP100)
Ozone layer depletion (ODP)
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Acidification
Eutrophication
impact indicators
F2 - A


R1 - T
0,400
0,350
0,300
0,250
0,200
0,150
0,100
0,050
0,000
shadow cost
R1 - T
Abiotic depletion
Global warming (GWP100)
Ozone layer depletion (ODP)
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Acidification
Eutrophication
impact indicators


R2 - T
0,400
0,350
0,300
0,250
0,200
0,150
0,100
0,050
0,000
shadow cost
R2 - T
Abiotic depletion
Global warming (GWP100)
Ozone layer depletion (ODP)
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Acidification
Eutrophication
impact indicators



F1 - T
shadow cost
0,120
0,100
0,080
0,060
0,040
0,020
0,000
Abiotic depletion
Global warming (GWP100)
Ozone layer depletion (ODP)
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Acidification
Eutrophication
impact indicators
F1 - T



F2 - T
shadow cost
0,120
0,100
0,080
0,060
0,040
0,020
0,000
Abiotic depletion
Global warming (GWP100)
Ozone layer depletion (ODP)
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Acidification
Eutrophication
impact indicators
F2 - T

APPENDIX C

TABLES

TABLE C.1: CONNECTIONS

concept	name	connection type	amount nr.	reversibility yes/no	complexity 5: simple	accessibility 5: accessible
R1	**glass rotator**	bolts	16	yes	4	3
R2	**glass rotator**	bolts	48	yes	4	3
F1	**slider top**	bolts	4	yes	3	2
	slider bottom	bolts	4	yes	3	2
	hinge top+bot.	bolts	4	yes	3	2
	alu hinge (rotator)	screws	24	yes	5	4
	totals	2 different	36	yes	3.50	2.50
F2	**slider**	bolts	8	yes	3	2
	hinge	bolts	4	yes	2	2
	alu hinge (rotator)	screws	16	yes	5	4
	totals	2 different	28	yes	3.33	2.67