Circular Façade Systems

for Sustainable Building Renovations

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Title

"Circular Façade Systems - for Sustainable Building Renovations"

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Abstract

The building industry accounts for almost 40% of the total carbon emissions that are directly responsible for climate change. So far, we have been following a linear economy model which follows a concept of “take-make-use-dispose” and causes a significantly large burden on the natural environment. For this reason, transition to a circular economy is important to keep the resources in the economy for as long as possible, and thus reduce this burden. With a rising building stock reaching its end of life, the number of renovations in the coming years will increase significantly. They are expected to reach 35 million in 2030. The focus of these renovations will be to make buildings energy efficient. While we have been successful in reducing the operational carbon of buildings, there is still scope to reduce the embodied carbon. This is also the main motivator for circularity goals.

It is estimated that the façade may account for between 13 and 17% of the total embodied carbon associated with a building. There is however not a strategic process to designing a circular facade. The methodology followed is the research-through-design methodology.

This project develops a design framework through studying existing literature, considering existing examples and pilot research projects - Circl Pavilion, CRL. The process uses the 10R strategy - particularly the cases of Reclaim, Recycle, Reuse, Reduce. This is then applied to the case of Building 22 at the TU Delft campus, and 4 options are developed. The evaluation through a life cycle assessment and building circularity approach is conducted on the platform OneClickLCA. It was found that for a circular design, material selection is very important. Overall materials with a lower embodied carbon should be selected. Moreover, materials with a higher volume of reused content should be prioritized first and a higher volume of bio-based content should be prioritized second. There is also a need to document and create more technical information for circular materials.

Keywords - Renovation, Facades, Circularity, Circular strategies, Design process

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01

Introduction

This chapter addresses the context of the research, followed by the problem statement. Consequently, the research objectives, methodology and research questions will be explained, ending with the societal and scientific relevance of the research.

Background Research

Sustainable Development

After the first definition of sustainable development emerged in the late 1980s (WCED 1987), design was recognized as an area of major importance in the journey towards more responsible and sustainable production and consumption models. Sustainable development is an organizing principle for meeting human development goals while also sustaining the ability of natural systems to provide the natural resources and ecosystem services on which the economy and society depends. The desired result is a state of society where living conditions and resources are utilized in a manner that they continue to meet human needs without undermining the integrity and stability of the ecological balance. The evolution of the built environment should avoid impacting the natural environment negatively, and this can be achieved through sustainable development. 'Sustainable development' can be defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Sustainable development is also a core principle of the Treaty on European Union and a priority objective for the Union's internal and external policies. The United Nations 2030 Agenda includes 17 Sustainable Development Goals (SDGs) intended to apply universally to all countries. This is a commitment to eradicate poverty and achieve a sustainable world by 2030 and beyond, with human well-being and a healthy planet at its core (European Commission, 2020). With the SDG policy as foundation, the Government of the Netherlands also proposes to transit towards a 'Circular Economy'. A circular economy holds promise for achieving multiple SDGs, including SDGs 6 on energy, 8 on economic growth, 11 on sustainable cities, 12 on sustainable consumption and production, 13 on climate change, 14 on oceans, and 15 on life on land (UN, 2015). A circular economy offers new ways to create a more sustainable growth model as compared to a linear economy.

Circular Economy

The linear economy model follows a concept of "take-make-use-dispose" and causes a significantly large burden on the natural environment. For this reason, transitioning to a regenerative growth model is essential to keep resource and energy consumption within planetary boundaries. The current linear economy continually increases its demands of scarce natural resources. By using and consuming in a more circular way, we can substantially reduce the impacts of human economic activities on the environment, including the biodiversity of our planet.

By definition, a circular economy is one "that is restorative and regenerative by design and aims to keep products, components and materials at their highest utility and value at all times'". In a circular economy waste and resource use are minimized, and when a product reaches the end of its life, it is used again to create further value (Cheshire, 2016).

The European Commission adopted the new circular economy action plan (CEAP) in March 2020. It is one of the main building blocks of the European Green Deal, and Europe's new agenda for sustainable growth. The EU's transition to a circular economy will reduce pressure on natural resources and will create sustainable growth and new job opportunities. The new action plan announces initiatives along the entire life cycle of products. It targets how products are designed, promotes circular economy processes, encourages sustainable consumption, and ensures that waste is prevented, and the resources used remain in the EU economy for as long as possible (European Commission, 2020).

Circular Economy in the Built Environment

It is well known that the building construction sector is a highly demanding sector both in material and energy consumption. For this reason, applying the circular economy approach in the construction industry is now more necessary than ever. In the built environment, this will be emulated in the form of minimizing waste, recycling materials and reducing energy use in its most general form. Under a circular built environment, landfilling is no longer an option to handle construction and demolition waste, and design for reversibility has a central role. Design for reversibility is a concept in which buildings and products are designed intentionally for material recovery, value retention, and meaningful next use.

A large building stock in the EU was built before 2001. About 85-95% of the buildings that exist today will still be standing in 2050 (European Commission, 2016). These buildings are high consumers of energy, while failing to meet the current standards of user comfort and energy performance (Konstantinou et al., 2017). This means that these buildings will require extensive renovation, to meet future energy and performance goals in the building sector. The extent of impact caused by such a large building stock will be massive unless we adopt smart strategies to reduce demolition waste, and the use of raw materials. This means creating a regenerative built environment that prioritizes retention and refurbishment over demolition and rebuilding. It means that we must design buildings that are able to adapt - reconstructed and deconstructed to extend their life and that allow components and materials to be salvaged for reuse or recycling (Cheshire, 2016). Building retrofit, a growing research area during the last decade, finds its fundament on the urgency of decreasing the harmful effect of buildings in the environment, and improving them as healthier places for occupants.

For these reasons, façade retrofit is rapidly expanding as a research area (Martinez et al., 2015). Moreover, with the principles of circular economy, ideas such as modular and regenerative design, material passports, buildings-as-a service, design for disassembly and material banks are being brought up in the building and construction sector (Leising et al., 2018) (Holland Circular Hotspot, 2018).

Problem Statement

The building and construction sectors together consume 40% of all the materials entering the global economy (Khasreen et al., 2009), and this accounts for 36% of the global final energy use (UN Environment & International Energy Agency, 2017). This consumption has a major impact on the natural environment. More than 220 million building units, representing 85% of the EU's building stock, were built before 2001. With an increasing global urban population, there is a growing need to both construct new sustainable buildings, but more importantly, retrofit old structures (Eline et al., 2018). This means that the building stock will require extensive renovation to meet future energy and performance goals in the building sector. Therefore, it is important to innovate towards a circular construction economy, which encourages judicious resource use and promoted recycling. Building retrofit, a growing research area during the last decade, finds its fundament on the urgency of decreasing the harmful effect of buildings in the environment, and improving them as healthier places for occupants. For these reasons, façade retrofit is rapidly expanding as a research area (Martinez et al., 2015).

Despite an inspirational start in the process of change, we still face many problems in the transition to a circular economy in the built environment. The first problem is that this change is not happening on all levels together. For example, a building product might be using circular materials, but its manufacture does not follow a circular business model. Secondly, there is no developed market for circular materials. For example, materials for reuse might not be available readily. There is also a lack of coordination between all the actors involved in a design project – this emanates from a lack of understanding of overall principles as well as a non-strategic approach for implementation of principles in practical cases. Academically, literature also provides little guidance to designers since it is not comprehensive. Thus, the problem statement can be summarized as -

"There is lack of a clear and strategic approach to designing a circular façade due to factors such as a general lack of awareness and implementation methodology, lack of collaboration between the actors, fragmented market, lack of market readiness, and the complexity of the process due to multiple interconnected aspects constituted."

Scope of Study

The purpose of this research is to encourage circular building design and processes in the built environment. This is particularly related to the technical aspects that contribute to a sustainable building and construction sector. The topics that the research will cover are circularity in the built environment, building renovations, façade design, energy renovations, renovation of office buildings. Since outdoor climate is also an important subject in the research, the study will focus on colder countries - particularly the Netherlands. The research aims to gain an insight on the current practices based on executed projects as well as literature.

Research Question

The research aims to answer the following question -

"How can we implement circularity in façades during the planning and design processes of building renovation projects in the Netherlands."

Further, the subsequent sub questions are as follows –

- What is the state of the art of non-residential building renovations especially for the building facade, in cold countries like the Netherlands?
- What are the design strategies applicable for circular facade design?
- What is the design process to implement circularity during façade renovation projects?
- What steps undertaken in the pre-design and post-design stages of the building renovation process influence the circularity of the façade?

Objectives

The main objective of this research is to develop a framework that can map the planning and design process of a façade in the early stages of building renovation design. The framework will help facilitate circularity in façade systems through the following specific steps –

- Understanding the renovation goals and their impact on the building envelope.
- Identifying circularity principles in the built environment, especially ones that are applicable in façade design.
- Defining a clear and strategic process to designing a circular façade.
- Elaborating the influence of the design stage on other stages of the planning process.

Methodology

The research will be divided into 5 phases which will be conducted sequentially. The stages are (a) Literature review, (b) Case Study, (c) Framework and Conceptual Design, (d) Evaluation and (e) Discussion and Final Design

Phase 1 – Literature Review

In this phase, the major research of the concerned sub-topics will be carried out to identify the gaps and gain insights on the current scenario and future perspectives. Through these topics of facade renovation and circular design, the initial two sub questions will be answered. The literature review will explore academic papers, relevant books, graduation theses, and a precedent study.

Phase 2 – Case Study

In this phase, a building will be selected as a case study. It will be analyzed in detail to determine the existing energy consumption scenario, renovation goals, construction type and material composition. The facade layers as well as components will also be analyzed in order to determine the renovation strategy. The data will be collected through existing architectural reports and documentation, archival drawings, site visits, and interviews.

Phase 3 – Framework and Conceptual Design

In this phase, a design framework will be developed. This framework will be applied to the case study example and will map the design process from site analysis to conceptual design options. The conceptual design options will be based on circular strategies. This phase of the research will also involve a market study to understand the availability of circular materials in the vicinity of building location.

Phase 4 – Evaluation

In this phase, an evaluation tool is selected to assess the design options based on the lifecycle approach. The design options will then be evaluated, and the best performing option for the current case will be selected. The tool will also be used to generate recommendations that can be applied to other building scenarios.

Phase 5 – Discussion and Final Design

In this phase, the final design option will be developed further, and the impact of the design process on other stages for a renovation project will be discussed.

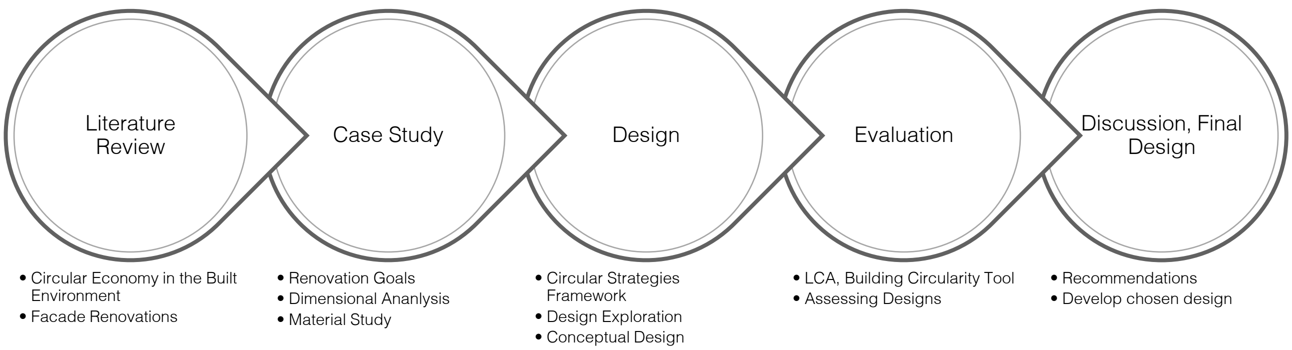


Figure 1 - Methodology of Research; Self

Societal and Scientific Relevance

The project is a major step towards a circular built environment. This step is important because a circular built environment can only be a success if it becomes tangible and measurable. Only then can people implement it in everyday life. However, the present situation still lacks clear steps to undertake this. *Socially*, the built environment is directly connected to humans and touches all aspects of our lives – including wellbeing. This transition will be a learning process that will progressively teach us how to live sustainably, not just because it is ethically correct but also because it will open new opportunities.

Professionally, the results of the graduation project can be used for innovators, entrepreneurs, researchers, and designers. The project aims to understand all the aspects related to making of a circular façade – from the market level to the technical design, and hence can promote further research, project teams in the industry to design and plan for more circular building facades. The project will focus on the renovation aspects but can be applied to for new buildings as well. The project also focusses on non-residential buildings – such as offices, public and commercial buildings, as there is a knowledge gap for them. It will investigate real life examples of circular projects which are executed and relate them to the theoretical literature, so that the construction of such facades and structures can be improved.

Scientifically, this research brings together renovation goals, energy goals, and circularity in the built environment. So far, there is a lack of literature which has combined all these aspects. The research attempts to find business models, applicable strategies in theoretical research and real-life projects to bridge this knowledge gap. It does so by trying to find connections and gaps in both theoretical and practical aspects. Existing frameworks express principled and philosophies but fail to offer specifics on how built environment assets and services must be developed, procured, designed, constructed, operated, maintained, and repurposed. Existing projects only combine a part of these aspects but are good indicators of barriers and challenges. Scientifically, the graduation project will aim to provide a comprehensive answer to the circular economy challenge for the building environment.

02

Facade Renovations

This chapter answers the sub question of the state of the art of non-residential building renovations. It first discusses the motivation for building renovations, and the renovation strategies which can be applied to such projects. Second, it discusses the current state of the building stock in the Netherlands and the building renovation goals in colder countries. Third, it discusses the state of the art in facade design with respect to the renovation goals, building regulation requirements, and the design and construction of a façade system.

Building renovations, a growing practice in the last decade, is centered on the urgent need to reduce buildings' adverse effects on the environment while also making them healthier places to live. As a result, the research field of façade retrofit is expanding. Important initiatives in the U.S. and Europe are also emerging that include the widespread renovation of existing buildings during the coming decades, with the specific aim of significantly reducing energy consumption and related carbon emissions (Martinez et al., 2015).

Building Renovations

Why Renovate?

According to Martinez, the main reason for undergoing renovations was aesthetics or image update, followed by energy performance and remediation. The study also showed that gaining certifications like LEED or BREAM were not as important criterions (Martinez et al., 2015). According to a report by ABN AMRO, in the Netherlands, while the total number of buildings is still growing, the share of newly constructed buildings is falling with respect to the share of renovated and restored buildings, and this had led to a market rise of 50% for restoration and renovation projects (2014). With many existing buildings being marked for retrofitting and renovation, the focus on such projects is increasing and is expected to continue increasing in the coming years.

This rise in the number of renovation projects could be due to several reasons. It could be to keep up with the modern layouts, update safety considerations, boost indoor comfort and productivity, or reduce maintenance and operating costs. All these reasons can be categorized into building immanent factors, legal reasons, or economic reasons. These factors, as presented by (Ebbert, 2010) are summarized below.

Building Immanent Factors

Urban Design	Improvement of the urban and architectural quality, preventing vacancy in a neighborhood to avoid social problems are important factors related to the urban context in which the building is placed.
Architectural Design	Avoid the decay of valuable architectural heritage and construction, update the appearance of the overall building, and change the character to suit the current times.
Function	Transform the building spatially, optimize the spaces as per requirement
User Comfort	Eliminate unpleasant indoor conditions, hygiene, and ventilation problems, avoid sick building syndrome or building related illnesses.
Technical Installations	Reduce the high operational energy demand and maintenance needs
Hazardous Materials	Get rid of hazardous materials if any have been used in the original construction
Building Physics	Eliminate building physics concerns like lack of insulation, wind or water leaks, fire protection deficiencies while planning for climate change and the current climatic conditions.

Table 1 – Building Immanent Factors that encourage renovations; adapted from (Ebbert, 2010)

Legal Factors

Fire Regulation	Introduce compulsory fire safety improvements as per current building standards and regulations
Safety	Avoid danger or damage to third party
Energy Consumption	Meet the current energy consumption standards as per building norms.

Table 2 – Legal Factors that encourage renovations; adapted from (Ebbert, 2010)

Economic Factors

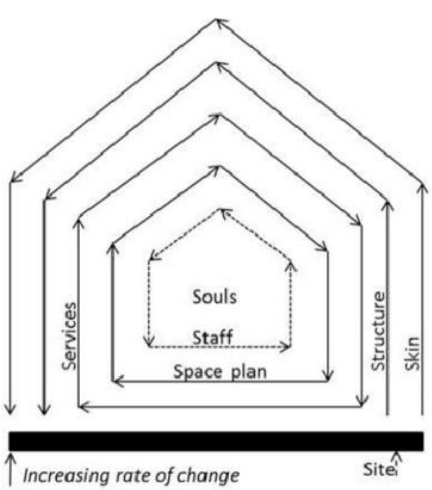
Operational Costs	Avoid the high maintenance costs and high energy demands of building
Lett ability	Bring and vacant building back into the market
Marketing	Users' representation needs
Financial Market	Investment from institutional investors

Table 3 – Economic Factors that encourage renovations; adapted from (Ebbert, 2010)

Renovation Strategies

Layers

It is important to note that buildings are inextricably part of larger systems and comprise of countless interrelated processes that operate in complex configurations. Within themselves as well, they can be considered assemblies of dynamic layers. Frank Duffy and Stewart Brand described these as shearing layers, which are hierarchically listed as per their respective time cycles / life spans. They reduced buildings to six different layers: interior, space plan, services, structure, skin, and site. Each layer is considered to have a different life cycle with the interior having the smallest and the site having the longest (Brand, 1994). This is explained in the Figure 2. While planning for renovations, it is essential to identify the condition of these layers, to effectively plan and carry out maintenance, repair and/or demolition tasks. This can potentially turn problematic in the cases which combine many layers into one.



Shearing layers	Description	Typical lifespan/activity
Site	Location and context	Permanent
Structure	Bones	30-300 years
Skin	Envelope	20+ years
Services	Lifeblood	7-20 years
Space plan	Interior layout	3 years
Stuff	Furniture and equipment	Under 3 years
Souls	People	Daily

Figure 2 – Shearing layers of the building, Source: (Stankovic et. al. 2015); adapted from (Brand, 1994)

Degree of Intervention

Aside from understanding the layers of a building, it is also important to ascertain the degree of intervention required in a building. ‘Renovation’ can cover a range of measures – from cosmetic repairs to the complete demolition of the building. These repairs are summarized by Konstantinou (2014) below.

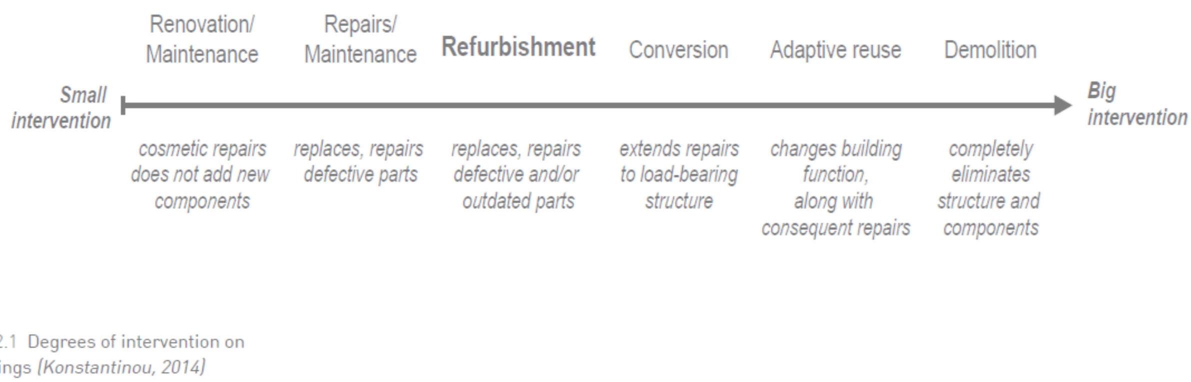


Figure 3 – Degrees of intervention to the building; (Konstantinou, 2014)

Strategies

For the building envelope, there could be three possible renovation strategies that are applicable. The first where additional layers are added within the building, the second where the entire envelope is wrapped in an additional layer, and the third where the existing layers are replaced.

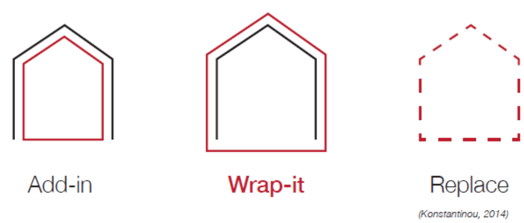


Figure 4 – Renovation strategies; (Konstantinou, 2014; Henry, 2018)

Non-Residential Buildings

The Case of the Netherlands

A report by ABN AMRO, which investigated the current state of the building industry in the Netherlands stated that the total number of vacant residences, retail spaces and offices have increased between 2014 and 2020. The percentage of vacant retail spaces was 9% in 2014, which is an increase of 3% from 2008. The percentage of vacant offices was 17% in 2014, which is an increase of 10% from 2010. The study shows an increasing rate of vacancies in buildings which are caused since the building no longer adequate for the purpose for which it was made. This could be because of the change in function, or high cost of operation, or because it is no longer comfortable.

In the Netherlands, according to the national planning institute, the society has a burden of 8.5 million square meters of vacant office space without a use value (Durmisevic, 2016). This vacancy has been caused by the difference in supply and demand of the building stock, since the existing building stock does not match the continuous and ever-changing market demand (Durmisevic, 2016). This is illustrated in the figure below. Data also indicates that the existing building stock in the Netherlands does not have the capacity to adapt to the changing market requirements. New office buildings are being constructed only because the current buildings do not meet the needs of the end users (Durmisevic, 2016).

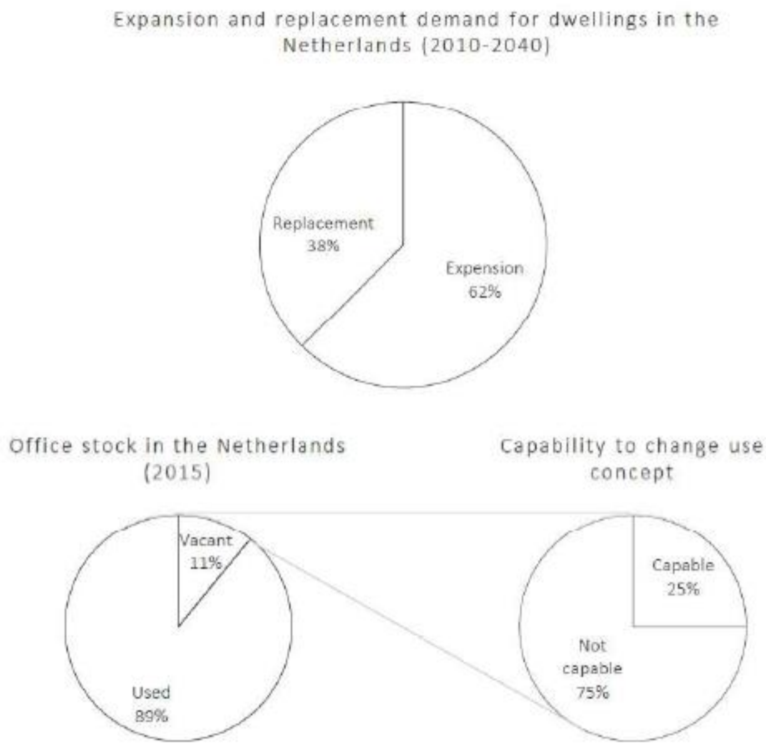


Figure 5 - Demand for the housing and the office sector in the Netherlands, by (Durmisevic, 2016)

Building Renovation Goals

It is found that in building renovations, the primary motivation cited for the various retrofits was aesthetics or image update, followed by energy performance and remediation (Martinez et al., 2015). To better understand the goals of renovation, project reports of similar renovation projects were studied. The renovation of the Maersk office building in Denmark was a project that shared many similarities with the research topic, such as the non-residential function of the building, type of renovation intervention as well as the cold climatic conditions.

The interventions that were documented throughout the renovation process were the installation of new facades, new ceilings, and floors with a higher insulation. The windows were upgraded to be triple glazed windows. A new ventilation system with heat recovery was installed along with heat pumps with 120m deep wells. Additionally, solar thermal collectors and around 170 sqm of PV panels were installed in the building. During the renovation of the Maersk building, various retrofit measures and control strategies were implemented. The measures which directly affected the façade are listed below –

- Installation of triple pane windows. These were changed from double glazed to triple glazed in the North and South façade and resulted in the reduction of the annual heating energy by 8.45%.
- Adding insulation to external walls. The opaque surfaces contributed to 59% of the heat losses from the building. A careful selection of materials to modify the envelope, and addition of insulation could reduce the heating demand significantly.
- Further to these measures, certain other interventions included adding insulation to roof, adding daylight sensors, improving equipment efficiency, installing efficient lights, and modifying heating set-point schedules.

The project had aimed to improve the building energy performance and reduce the heating and electricity consumption of the building (Jradi et al., 2017). Through the project, it is observed that employing renewable energy systems has higher potential in energy use reduction compared to energy efficient measures. It is also more economically favorable. Energy efficiency measures for renovated buildings are also strictly required as per the

EPBD (Energy Performance Building Directive) to save an estimated 30% of energy use in the European Union building stock until 2020 (European Commission, 2016, 2020). Most of the other building standards target new constructions instead of existing buildings.

Even while looking at renovations of the existing building stock, most of the buildings are found to be constructed in the period (1960's – 2000's). The major heat losses in these buildings are attributed to the exterior walls, ventilation systems, and windows. These are all directly a part of the building envelope, and it can be confirmed that the building envelope has an important role to play in saving energy and providing user comfort to the occupants. It is therefore a priority to focus on the façade while dealing with retrofitting and renovations (Jradi et al., 2017).

The documentation of the Maersk office building renovation project was relevant for the purpose of this study, however there were also some renovation projects within the Netherlands that were studied.

However, the results of three renovation solutions realized in the Netherlands have also been investigated through a comparison of the outcomes before and after renovation. In a report by Ritzen et al. (2013), a comparison is made between three buildings which underwent façade renovations. These buildings were DHV office, Amserfoort (The facade was totally replaced, and the interior was preserved largely), WNF office, Ziest (The façade was totally replaced, the building partially demolished, stripped, and refurbished) and Central Post, Rotterdam (Partial replacement of the façade).

The study focused on the energy and the material aspects and concluded that non-bio-based materials like metals need to be recycled as much as possible. Bio-based materials also should have maximum use. Building components should be easy to separate and increase possibilities for reuse and recycling. Some important observations from the research are –

- Operational energy efficient facade renovations result in a decrease of operational energy and an increase of embodied energy in the façade.
- Assessment tools are based on one aspect and hence do not generate insights on lowering the actual total environmental impact.
- Embodied energy is only a small portion of the total energy demand which is over lifespan of 30 years.
- On addition of photovoltaics, the operational energy is reduced in the long run, but the PV material will add to the embodied energy. In this case material consumption would be the determining factor in environmental impact.
- The quantity and choice of materials determine their environmental impact in all situations. in these cases, biobased materials score well in the calculation because of the lower embodied energy and renewability.

Façade Design

The façade of a building has the largest impact on the energy consumption as well as the user comfort of a building, as it is the threshold between the interior and the exterior of any structure. Hence, the key objective in façade design is to reduce the energy consumption of building while maintaining a comfortable indoor environment. A façade serves multiple purposes. It protects the users from the natural elements – extreme temperatures, rain, winds, and provides a barrier to the outdoor noise. It provides security to the users inside and protects the internal skeleton of the building, thus adding to the overall building lifespan. Lastly, a façade defines the appearance of the building and provides a character (Aksamija, 2013).

The development of building envelopes is becoming more complex and is mainly influenced by the following criteria (Knaack et. al., 2009)

- Today's modern and demanding architecture
- Complex geometry of the facades
- New material and techniques

- Increase statutory requirements and standards regarding energy efficiency and CO_2 emissions
- Different demands and requirements in various regions and countries
- Various climatic conditions

In addition to this, when designing and constructing future building envelopes the following demands will have to be considered (Knaack et. al., 2009)

- Increased protection measurements and solar gain
- Overall u-value of facade system to be reduced
- Sun shading devices to meet aesthetic demands of the architect

State of the Art

One of the main building components, which may considerably affect the building sustainability performance is the building's façade. Facade is the building's largest component and plays a major role in heat conductivity between the indoor and the outdoor environments. Selection of suitable facade material from a vast number of alternatives is a complex decision requiring a large amount of information and input from the design team (Moussavi Nadoushani et al., 2017). Various comparative research has been conducted to understand the difference in environmental impacts of different facade systems. These studies attempt to evaluate using the life cycle costing and the lifecycle assessment approach, However they only incorporate the environmental and economic aspects of facade systems, overlooking the social impacts (Moussavi Nadoushani et al., 2017).

A survey conducted by (Martinez et al., 2015) resulted in multiple answers that resulted in aesthetics as the main motivation to renovate a façade (74%), followed by energy performance (65%), and remediation (56%). However, code compliance and green standard compliance (i.e., LEED, Energy Star, Living Building Challenge, etc.) were surveyed separately and resulted in 15% and 14% of the total responses for motivations. According to the goals, more than half of the projects had durability, energy consumption and occupant's health and comfort as main goals. (Martinez et al., 2015). This translates into factors such as good daylight, high view factor, improved indoor thermal and acoustic performance, while consuming less energy.

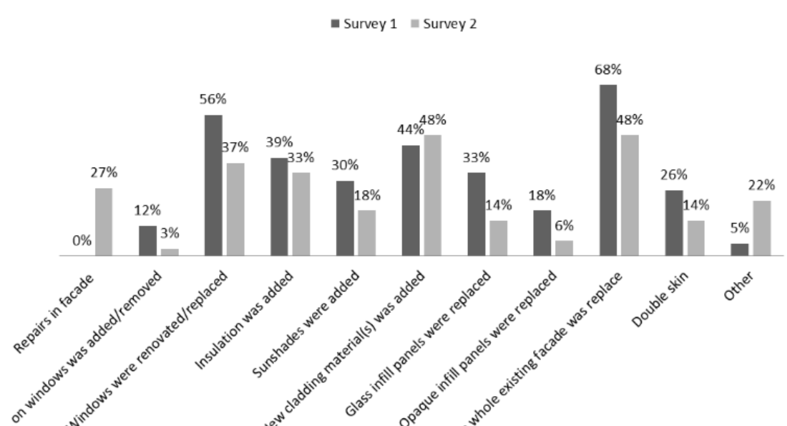


Figure 4: Scope of façade retrofit projects reported in both surveys (results add to more than 100%)

Figure 6 – The scope of façade retrofit projects from Survey by (Martinez et al., 2015) Page 939

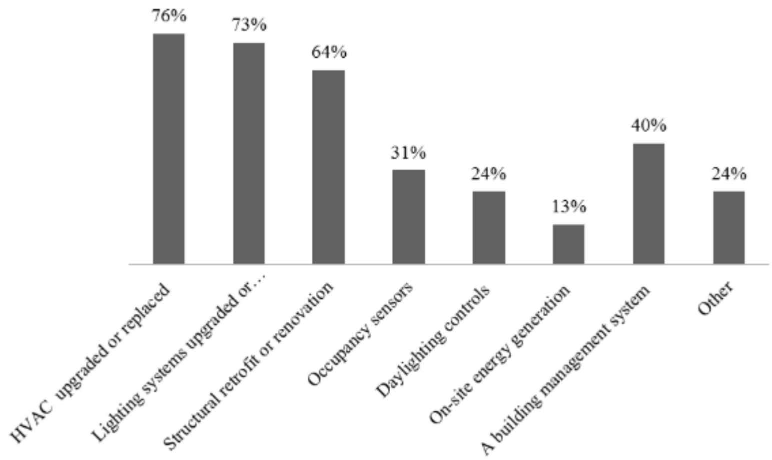


Figure 5 Systems being retrofitted in conjunction with the facade

Figure 7 – Other systems being retrofitted in conjunction with the façade by (Martinez et al., 2015) Page 940.

Building Regulations and Standards

Building standards define benchmarks or standard values and are important for regulating façade performance. The benchmarks that directly impact façade performance are elaborated below.

Energy Performance

The energy calculation method for new and existing buildings is defined in Standard NEN 7120 that is in line with the CEN standards. This calculation of the primary energy consumption of a building is based on monthly climate data that is adjusted for physical processes with a shorter timeframe, e.g., solar gains and heat accumulation. The calculation of the thermal quality of the building envelope includes thermal bridges, ventilation and air infiltration, hot water use, efficiency of heat and cold generators, renewable energy used both in and near the building, and the contribution of passive energy, lighting, and daylighting. Shading caused by the building itself is included in these calculations. Shading by other buildings is not considered. The quotient of a building's calculated annual primary energy needs to the allowed primary energy performance provides the energy performance coefficient.

Building Typology	**Required maximum values for the energy performance coefficient (new buildings)**
Day-care centres	1.1
Prisons	1.0
Healthcare buildings with bed area (hospitals)	1.8
Healthcare buildings (other than with bed area)	0.8
Office buildings	0.8
Accommodation in lodging structure (hotels)	1.0
Accommodation not in lodging structure (conference facilities)	1.4
Educational buildings	0.7
Sports buildings	0.9
Retail buildings	1.7
Residential buildings	0.4
Mobile homes	1.3

Table 1. Required maximum energy performance coefficients for new buildings since 1 January 2015 and, after cost-optimal studies, for non-residential buildings since 1 July 2015.

Figure 8 - Required maximum energy performance coefficients; (van Eck, 2018)

Thermal Performance

Since the oil crisis in the 1970s, The Netherlands applied minimum requirements for the thermal quality of the building envelope. In 2011 and 2012, a study has been carried out, to establish cost-optimal minimum requirements for existing buildings. These requirements came into effect in 2013-2014. The minimum requirements for individual building components are listed in the table below for major renovations (25% envelope) (van Eck, 2018).

Minimum requirements for the thermal quality of the building envelope by 1 January 2015 for new buildings and major renovation (> 25% envelope).	
Roofs	R-value ≥ 6 m^2.K/W
Floors	R-value ≥ 3.5 m^2.K/W
Façades	R-value ≥ 4.5 m^2.K/W
Transparent façade sections	U-value < 65 W/m^2.K
Individual structure	U-value < 2.2 W/m^2.K

Figure 9 - Minimum Requirements for building components for new buildings and major renovations; (van Eck, 2018)

Other Benchmarks

There are several other measures, such as the acoustic performance, daylight penetration, views, and thermal comfort. Although no set benchmarks for these have been defined for the scope of this project, it is important to maintain a balance while designing for optimum user comfort. The steps taken to ensure this a elaborated in the 'Design Process' chapter.

Making of a Façade

Construction / Prefabrication

Since the beginning of civilization, humans have tried to perform their basic tasks in a repetitive way to reduce the amount of effort required to do them and increase precision. Thus, industrialization has been a fundamental solution to achieve this goal. Prefabrication represents one of the main fields of construction industrialization. While there is a more conventional alternative to construct a building envelope – which involves construction and assembly on site, it is not preferred as it is time consuming, there is lack of quality and precision, and it is highly customized for a single scenario. Prefabrication overcomes these shortfalls and offers better results in achieving a high performing building envelope. It is defined as "a set of construction techniques that are based on the production of construction elements outside of their final places of definitive setting, on site or in an external production unit, which are afterwards connected and assembled on site." (Abrantes et al., 2016). As observed, prefabrication requires a high level of modular dimensional coordination. This means that while designing for prefabricated elements in architecture, the dimensions must be multiples of some standard sizes. This ensures that the assembly and connections take the minimum number of resources and happens in an economical and efficient manner.

Composition / Components

As discussed earlier, the building can be divided into many layers – or building systems. Within this, the façade is one such system. Beurskins and Bakx further identify the components as exterior façade components, primary façade frame, secondary façade frame, infill façade components, interior façade components, intermediate façade components. These components will have elements which serve the purpose of support, finish, control, or integration. These elements can be further divided into materials, which can be further divided into raw materials. This breakdown of components, elements, materials is illustrated in the figures below.

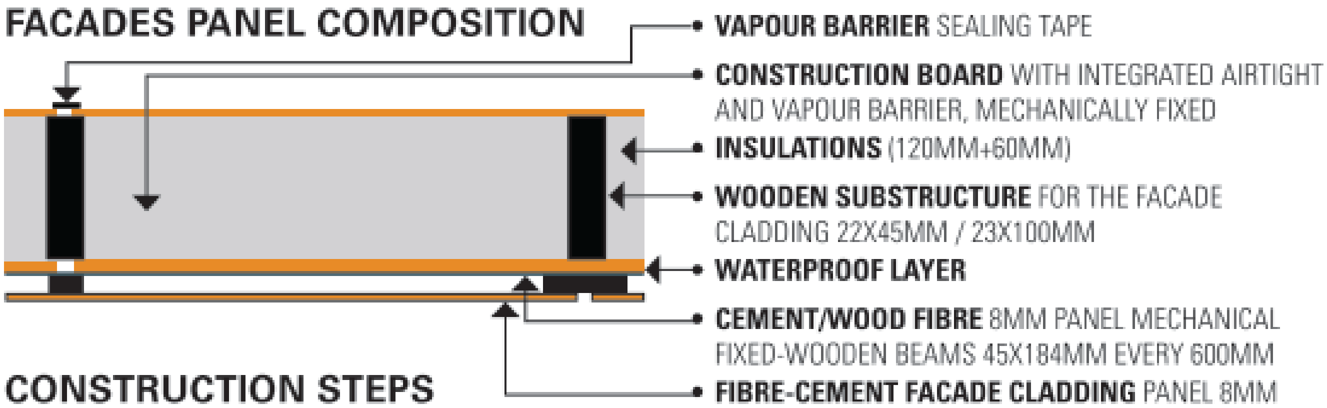


Figure 10 – Façade layers composition, (Brussels Environment & Building Research Establishment, 2019), Page 70

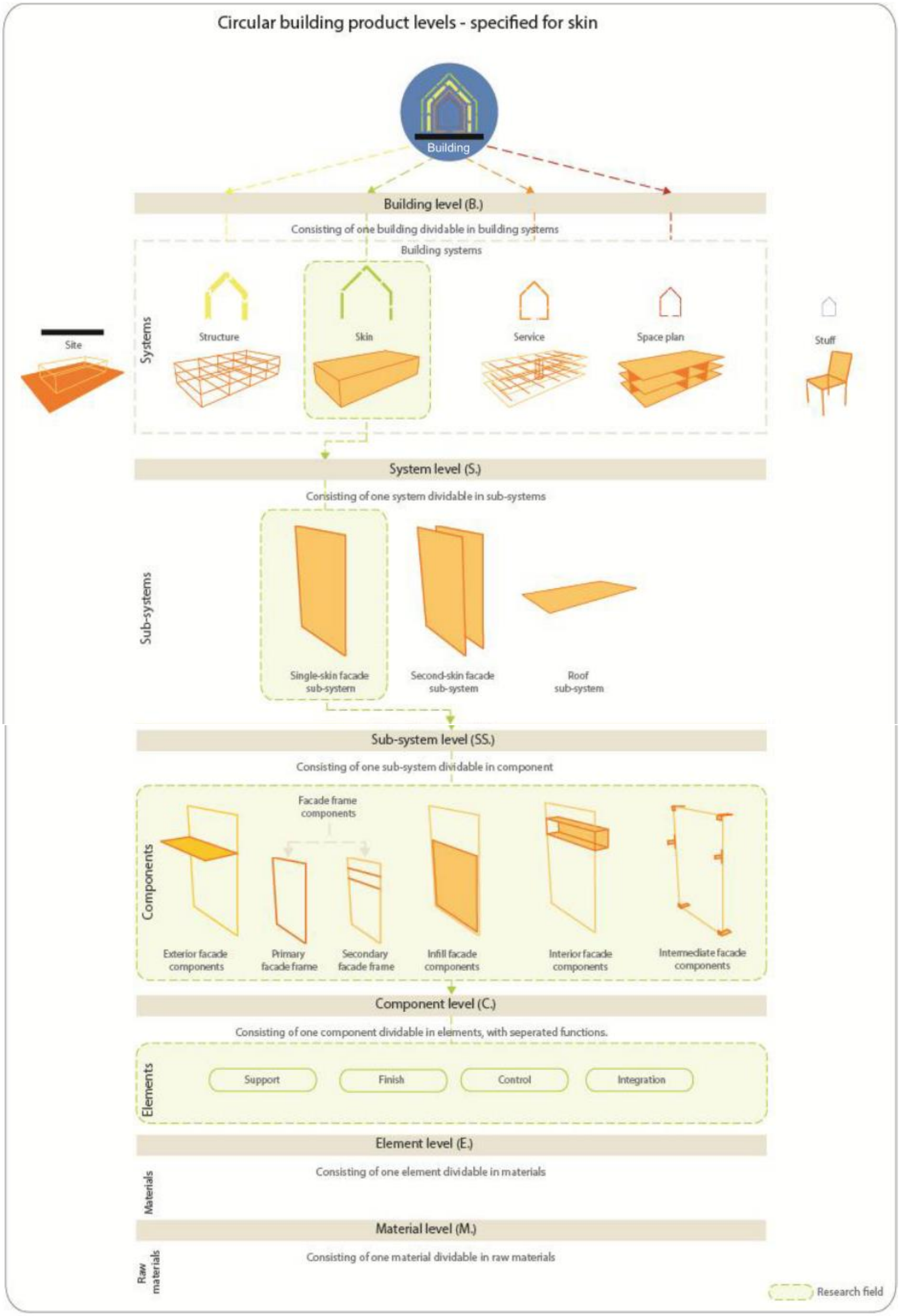


Figure 11 - Circular building product levels, (Beurskens & Bakx, 2015)

Chapter Summary

There are many factors that motivate building renovations, such as building-imminent factors or legal and economic factors. These could range from improvement in user comfort and technical installations to updating fire and safety regulations or trying to reduce operational costs. A building renovation can be strategically planned by determining which building layers (skin, structure, services) need to be renovated and what is the degree of intervention required (small repairs, refurbishment, or adaptive reuse). In the Netherlands, a large percentage of vacant building stock exists, which needs to be renovated soon to match the current requirements off the end user. This is particularly the case for office and institutional buildings. These buildings were constructed 30 to 40 years ago and are currently reaching the end of their life. They are observed to have major heat losses which are attributed mostly to windows and exterior walls. This is reflected in recent renovation examples, where changes have been made to the facade and building insulation, leading to an overall improvement of the building envelope and subsequently thermal performance. There has also been an increase in recycling of materials and extension of product use, as well as the use of bio-based materials. It is observed that the facade has the largest influence on the previously mentioned factors, and therefore facade design is increasingly becoming more complex. The façade for office typologies must not only meet aesthetic and functional upgradation, but also meet the current building standards of energy performance, thermal and acoustic performance, daylight and view factors, and indoor comfort. To efficiently design a complex facade system, it can be broken down into further components such as exterior cladding, primary façade frame, infill elements, interior finish etc. Further, these components can be broken down into elements, materials, and lastly raw materials. To efficiently construct a complex facade system, prefabrication has proven to be economically efficient, high performing, less time consuming and better quality than non-industrialized approaches. It however requires a high modular dimensional coordination, and clear hierarchy within the facade components.

03

Circular Design

This chapter answers the research question of what design strategies are applicable for façade design. It first discusses the various strategies related to circularity in the built environment. Then it looks at the challenges to circular façade designing. Second, some precedents in the building and construction industry are described and how they are relevant to this research.

Circular Strategies for the Built Environment

At its essence, the circular economy represents a new way of looking at the relationships between markets, customers, and natural resources (Lacy & Rutqvist, 2008). Several countries have promoted initiatives and programs to shift from a linear to a circular economy. In the building sector, this is particularly relevant since it is the highest producer of waste (Giorgi et al., 2022).

Much literature (frameworks, systematic reviews, project reports, roadmaps) also describe various strategies for a transition to a circular built environment. Giorgi groups these strategies within three key fields of application. These are – resource and waste management, design for reversible buildings and business models in the construction value chain (2021).

Resource and Waste Management

This strategy focuses on improving the management of material inflow and outflow during the construction process. This can be achieved through improving waste identification, processing quality, and waste management to reduce waste generation during the construction phase and at the end of life. Other scientific contributions concern material and information traceability systems, which use digital technologies to track geometric and mechanical characteristics of components, location, residual value of materials, age, and expected life cycle, to allow knowledge of potential components to be reused in a new project. Expert conducted pre-demolition audits have been identified as valuable tools for establishing material compositions and enhancing the accuracy of material tracing calculations, as well as enabling the evaluation of alternative demolition/recovery options (Giorgi et al., 2022). Thus, these strategies can be summarized as below –

- Avoidance of resource consumption
- Avoidance of materials landfilling
- Reuse of building elements
- Traceability systems for materials waste
- Use of pre-demolition audit

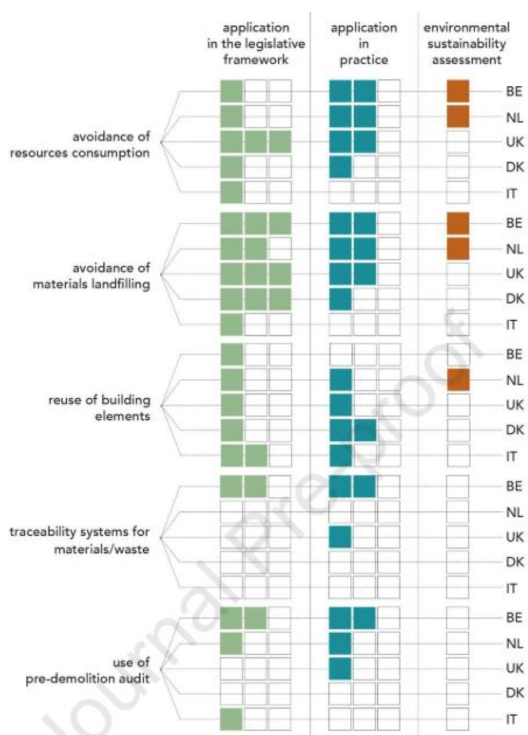


Figure 12 - Strategies for Resource and Waste Management, (Giorgi et al., 2022)

Design for Reversible Buildings

The second set of solutions focuses on modifying the design and construction process to create buildings that are flexible, adaptive, and easy to disassemble, conceived as 'material banks'. The use of prefabricated and modular elements, dry technologies, mechanical connections, off-site constructions, and high durability products are among the construction technologies for a reversible building that allow for easy construction reversibility and the reuse of spaces and components, thereby extending their useful life. BIM is regarded as an enabling tool in this industry for monitoring resource use throughout the life cycle, sharing information across operators, and modelling the reuse potential of materials in various types of designs early in the project. Furthermore, BIM software facilitates the use of material passports, which are useful tools for keeping track of all construction materials over time and conserving their value (Geldermans et al., 2019). It is also possible to know the quantity and location of materials stocked in urban mining using a common material passport system. Additionally, sustainable building certification systems have been recognized as a technique for promoting circular design (Giorgi et al., 2022). Thus these strategies can be summarized as below –

- Design for reversibility
- Use of BIM software for design
- Use of materials passport
- Use of sustainability certification

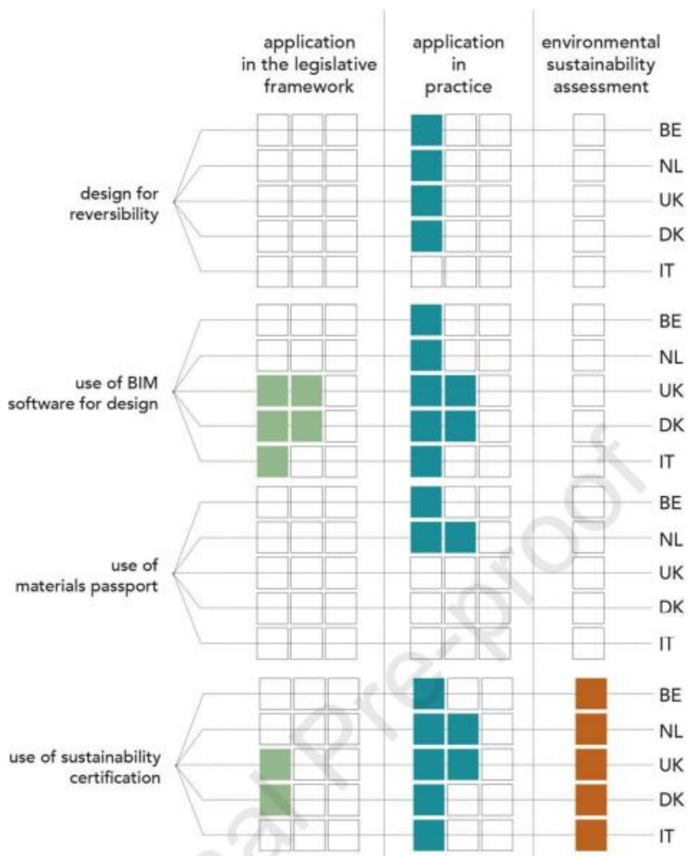


Figure 13 - Strategies for reversible buildings; (Giorgi et. al., 2022)

To elaborate on 'Design for reversibility', a key subject for the current research, Durmisevic also defines some guidelines for building design solutions that can guarantee a high reuse potential of the building, systems, products, and materials, and can be called 'reversible'. This reversibility can be further broken down into some design aspects that have an influence on the decision making (Durmisevic, 2018). These are –

- Functional Decomposition: the functional breakdown of the structure is vital to consider when planning a building for disassembly; whether two or more functions are incorporated into one architectural component or whether functions are split into multiple components. Functional separation can be used to generate structural independence, which is favorable for reversible design.
- Systematization: In terms of DfD, clustering building pieces into subsystems based on their life cycle performance is helpful since it prevents too many sequences during (dis)assembly on-site.
- Relational Pattern: The relations between different elements in a system can be hierarchical and graded on one hand, or more interconnected on the other hand. The hierarchical systems decrease the dependencies and make the system more dynamic, whereas the interconnected systems increase the dependencies and make the system more static.
- Base Element: Each cluster of elements must have a main or ‘base’ element which integrates all the surrounding elements and connects them to the base element of the next cluster.
- Geometry: This aspect deals with the interface design or the geometry of the product edge which can be open or penetrating geometry. Open geometry is preferred for reversible design since elements can be disassembled in both directions.
- Assembly Sequence: This is the way a building is assembled, and this sequence determines the number of dependencies within building elements. For an easily reversible design, the sequence should be simple and efficient.
- Connections: When the connections allow disassembly, each building component becomes replaceable, and each material becomes recyclable. The type of connection defines the degree of freedom of each of the elements.
- Life Cycle Co-ordination: The elements with a shorter life cycle should be grouped and allowed to disassemble first. The elements with a longer life cycle should be grouped and designed to be disassembled last.

Business Models in the Construction Value Chain

The third set of strategies focuses on developing new effective service-oriented business models (e.g., Product Service Systems, Pay-per-Use, Buy-back-based, Leasing or Rental/Ownership-based) to shift product ownership and responsibility, as well as improve product maintenance and reuse during use and recycling at the end of life. This emphasizes the significance of creating new organizational and management structures, stakeholder networks, and green deals along the construction sector value chain. As a result, establishing digital collaboration tools to enable new business models and collaborative and dynamic networks based on circular materials is critical. As a result, in recent years, instruments for accelerating the adoption of a circular economy in the construction industry have been developed. There are now examples of platforms for exchanging materials and creating collaboration for 'circularity' of materials towards the end of product life, as well as platforms for pursuing collaborative processes and networks among various actors.

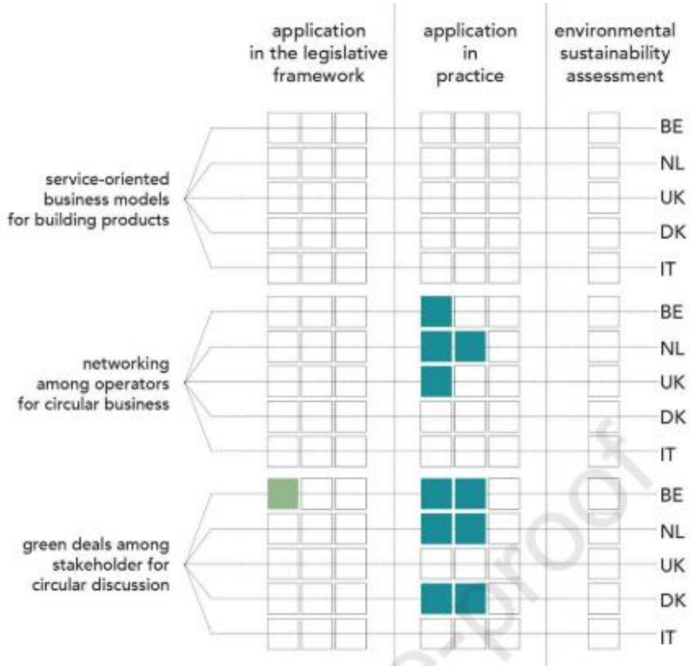


Figure 14 - Business models in the construction value chain, (Giorgi et al., 2022)

Circular Façade Design

In the design of circular products, all design strategies can be categorized into three main types. These are (a) Design strategies

In the research on building circular facades, (Bakx et al., 2016) ascertain the following points –

- A building façade can be made circular by disassembly and adaptability in the early stage of design.
- Disassembly can be facilitated by making a disassembly plan so that on-site labor can readily access and recognize components and connections.
- Adaptability can be facilitated by simple standard design and reversible connections.
- The level of circularity can be quantified based on building level and element level indicators.

Materials

Circular Materials are plastics, natural fibers, metals, etc., that have been recovered from their first/prior use-phase. They have been successfully collected, sorted, reprocessed and are ready for the next life cycle, in a new product.

- Biobased materials
- Technical materials

Components

- Indirect with additional fixing device
- Indirect via independent third component
- Indirect via dependent third component
- Direct with additional fixing device
- Indirect with third chemical material
- Direct between two pre-made components
- Direct chemical connection

Assembly Order

- Parallel/open assembly
- Stuck assembly
- Base element in stuck assembly
- Sequential base element

Challenges in Circular Façade Renovations

The building industry faces many challenges during this transition towards circularity. These challenges have across on many stages of the design and construction process of a building. An investigation of various case studies, analyses of barriers and drivers, and tools related to circularity helped identify the main challenges to building renovations. These are listed below –

In the early stage of building renovations, there is a lack of knowledge on how circular building design will be different from traditional building design (Kanters, 2020). Applying the principles of circularity to the redesign is considered 'nice' to do, and not necessary.

In the preparation and planning phase, there is a high number of stakeholders involved and therefore high complexity (Kanters, 2020) and difficult to motivate every team to be wholeheartedly involved in circularity (Ellen MacArthur Foundation, 2016). The building industry is conservative and requires more conventional roles of stakeholders which requires capacity building (Kanters, 2020). There also needs to be improved communication and combination of information to arrive at an integrated design (Ellen MacArthur Foundation, 2016).

While designing, the use of new and unconventional materials such as biomaterials, or recycled materials is rising, for which there is a lack of information on application (Ellen MacArthur Foundation, 2016). There is also a lack of upgraded skill set in architects, and design tools are not fully developed (van Stijn & Gruis, 2020) which can help architects and designers make informed decisions about a project.

In the technical / detailed design of the components of a building, there is a lack of incentive to design products for EOL, and also in innovatively designing to be able to separate each material at EOL (Adams et al., 2017).

In the production and construction stage, there lacks a waste management plan for the demolition waste, as well as a lack of availability of a storage space (Ellen MacArthur Foundation, 2016) to be able to keep materials for next use. This is aided by the fact that there is no mindset yet to preserve these materials in a usable state.

Documentation wise, there is an absence of application of an integrated system to gather knowledge about materials used (Ellen MacArthur Foundation, 2016) like a material passport or digital twin, and also shortfall in understanding the costs and values of materials in relation to the building's lifecycle (Ellen MacArthur Foundation, 2016).

For the end of life of the building, there still remains a lack of a developed market for reused materials (Kanters, 2020), as well as a lack of a system to take back these materials.

Precedents

While considering circular buildings, one can see how distinctly the circular economy principles are applied to each project. Some projects use secondary reused and recycled building materials, such as the Alliander Office in Duiven. Some projects use biobased materials which are sustainably sourced, such as the Circl Pavilion by ABN AMRO. Some projects such as the City Hall at Venlo are made of technical materials that have multiple reuse and recycling possibilities at the end of their functional life. There are also projects which use DfD principles such as the Temporary Courthouse in Amsterdam. There are also pilot research projects that combine many of the circular economy aspects. In this section, some of these precedents are elaborated further.

Pilot Research Projects

Research Projects	Type	Renovation Project	Façade
REHAB (TU Delft)	Prototype	x	x
CRL Circular Retrofit Lab (Vrije Universiteit)	Residential	X	x

Table 4 - Overview of Pilot Research Projects, (author)

<u>REHAB Project</u>
By: TU Delft, AMS
Type: Prototype

Buildings consist of various components, such as facades, kitchens and bathrooms. The housing stock can be gradually made circular by replacing these components with more circular components through natural maintenance and refurbishment periods. The 'REHAB' project focuses on developing two circular building components for residences – the Circular Shell and Circular Extension. This is being developed in co-creation between TU Delft, AMS Institute, housing corporations and construction partners. The project will also develop circular design and assessment tools within this project. Both the variants are not only more sustainable but also offer opportunities to accelerate the energy transition. They also allow a step-by-step approach to design energy-neutral homes. In 2019, the design variants were developed (also illustrated in the figure below) based on the following strategies:

- Construction from reclaimed materials, Variant 'Reclaim'.
- Construction from sustainable and biodegradable materials, Variant 'Bio-Skin'.
- Construction of high-quality building products with easy disassembly and reassembly, making the building products easy to reuse, Variant 'Bank'.
- Construction of a modular façade, made of building blocks, making the façade element easy to adjust and reuse, Variant 'P&P'.
- Construction of an easily disassembled façade, Variant 'P2P'.

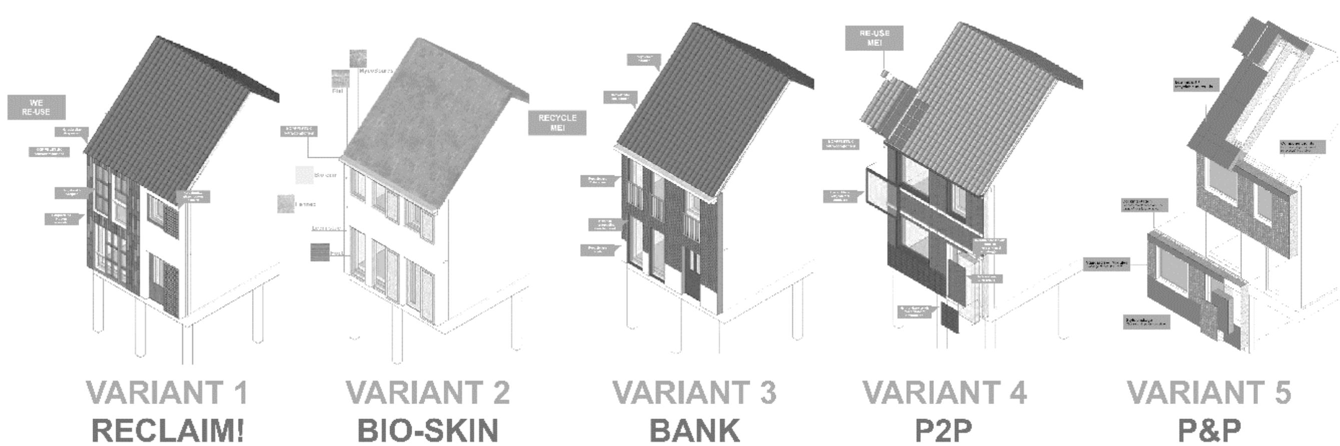


Figure 15 - Variants that were prototyped in the REHAB project; (van Stijn, n.d.)

As per the research by van Stijn (n.d.), it was found that a modular design which allowed partial replacements were most circular. Materials with a long lifespan which had a low impact, non-virgin, re-usable and bio-based should be preferred. The design should minimize the use of materials. The design should be made 'as efficient as possible', with components that support multiple life cycles. The components itself should be used for as long as possible. Moreover, the modular system should offer the possibility to adapt – which when not required can be disassembled and reused elsewhere. This project was relevant to develop the concepts in a preliminary stage of building renovation design.

<u>CRL – Circular Retrofit Lab</u>
By: Vrije Universiteit, Brussels
Type: Renovation

In the research by BAMB (2019), various scenarios were tested and implemented for the reuse and restoration of a prefabricated student accommodation on the VUB Campus while generating minimal waste. Internal and exterior transformations, as well as the module's functional reconfigurations, have been explored in the project. For maximum waste reduction, the circular refurbishment tested dismountable, flexible, and reusable solutions. Throughout the (re)design, (re)build, (re)use, repurposing, or teardown phases, the pilot created a co-creative process. During the early development phase, this entailed close collaboration with all value network stakeholders and potential users. The CRL lab integrated the reversible solutions for internal walls and façades. The use of modular, prefabricated, and kit-of-parts design methods not only increased assembly flexibility and production efficiency, but also sped up the implementation process. In this regard, the team collaborated with industry partners to implement cost-effective operating solutions, such as the use of dry, resilient, and reversible technical solutions, as well as materials that could be reused several times without being damaged.

As a result of the project, the façade panels which were designed were demountable from the inside and the outside. It was possible to upgrade the insulation layer of the façade without changing any other element. The assembly process was simple and straightforward – it did not require additional skill development and needed only slight changes to the existing systems. The building also used durable and robust building materials which were not entirely dependent on each other – and could be relatively easily separated. The assembly and disassembly were accelerated in the process due to prefabrication. Moreover, the quality of the product was uniform throughout and there was minimal waste generation. However, it is observed that the façade panels were dimensioned and customized for this building case but might need to be modified for other buildings. This project was relevant in understanding the breakdown of components, materials and connections that are applied in the making of a façade.

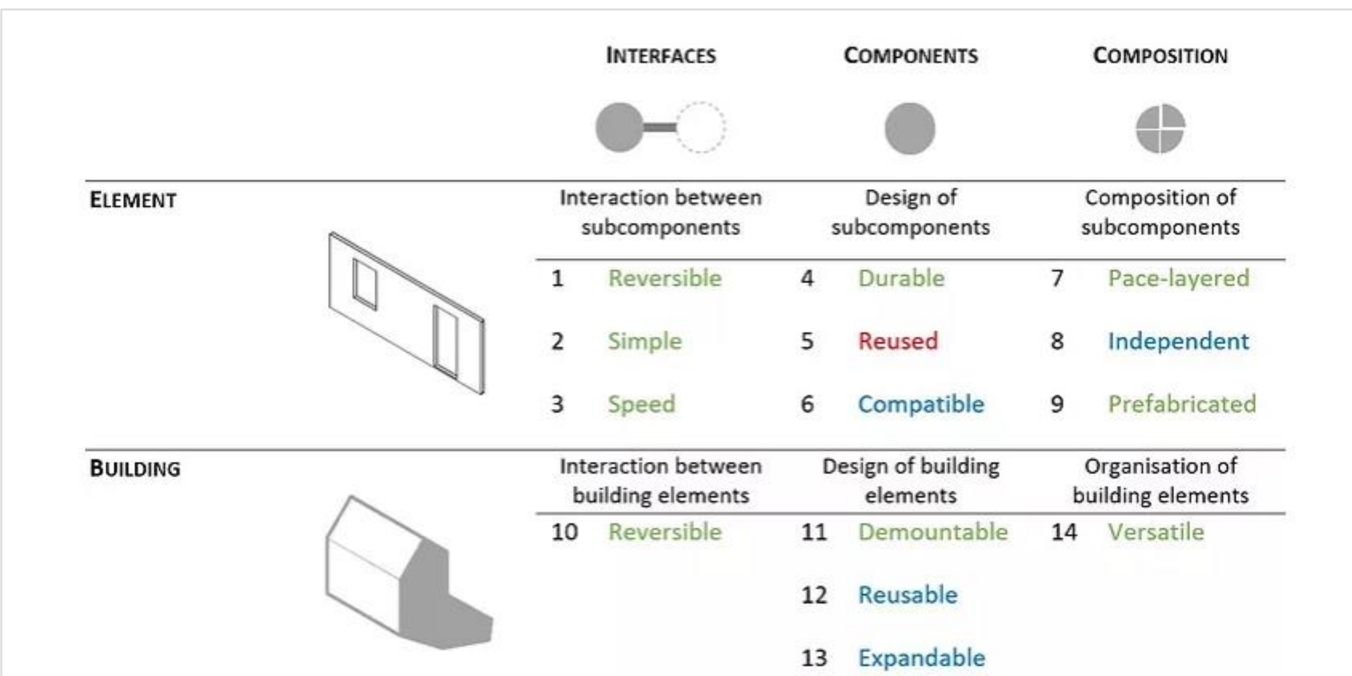


Figure 16 – Evaluation of the end result of CRL based on the design and connections; (BAMB, 2019)

Practical Examples / Case Studies

Case Studies	Type	Renovation Project	Façade
Circl Pavilion, ABN Amro	Mixed Use		x
Windeshein Campus	Educational	x	x

Table 5 - Overview of Practical Examples, (author)

Circl Pavilion
By: de Architekten Cie.
Type: New Construction

ABN Amro recently built a new circular pavilion in front of their headquarters in Zuid Amsterdam. According to a report by Architekten Cie., the pavilion is designed to function as a living laboratory that can adapt to changes in use, environment, and technology advancements. The pavilion's design is adaptable, according to architect Hans Hammink, because it uses fixed component measurements and allows for disassembly. As a result, the design can accommodate functional modifications without requiring the building's partial demolition. The building is mainly made of wood and consists of 35% of secondary material overall. This is especially seen on the insulation, which is made from recycling 16,000 pairs of old jeans. The indoor partitions are reclaimed window frames harvested from an old Philips office in Hilversum. The balustrades, sidewalk tiles and cable trays are also reused materials, that have been extracted from demolished buildings by the company New Horizon (BAM Bouw en Techniek, 2017). The structural layer of the pavilion is completely demountable – with connections of screws and steel plates to hold columns and beams together. The columns also use fine finger joinery to connect shorter wood elements. With this, they avoid the use of sealant and glue. This project was relevant to understand the potential and applications of recycled and reused materials in building design.

Figure 17 - Joint and connections in the structure of CircL Pavilion; (author)

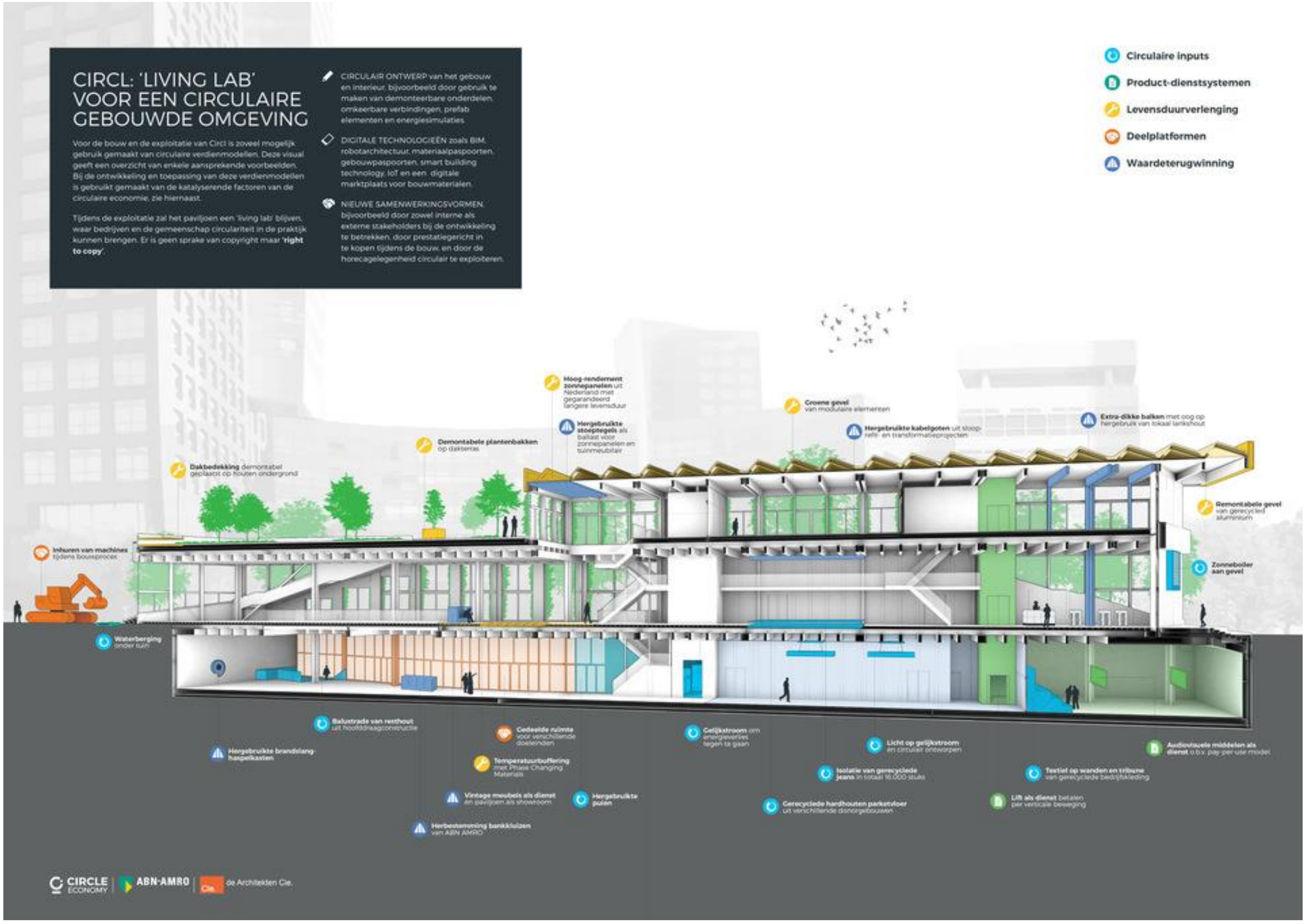


Figure 18 - Circl Pavilion Detailed View, (ABN AMRO, 2017)

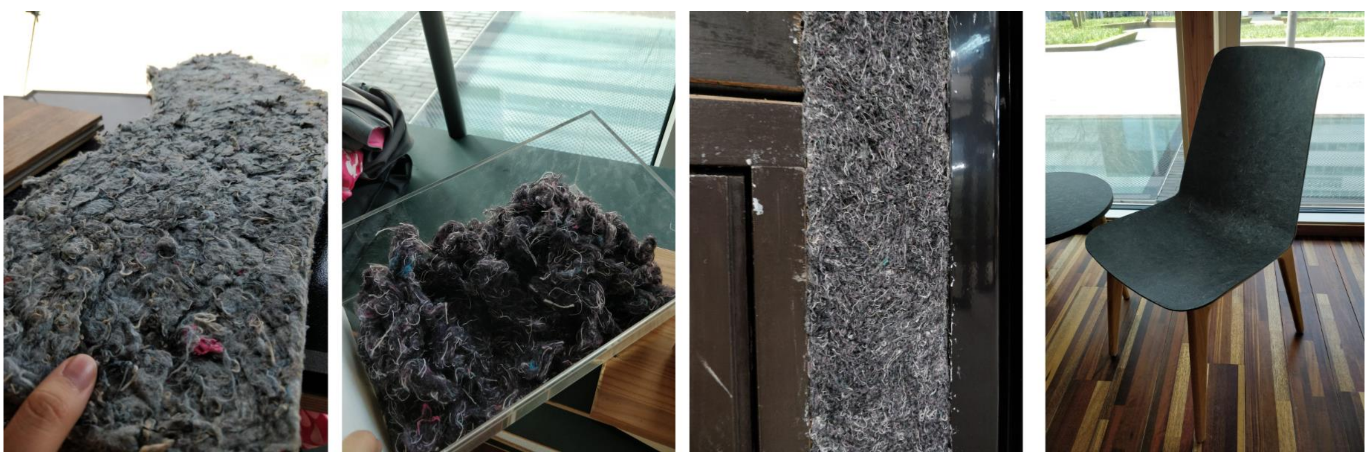


Figure 19 - Use of recycled textile insulation and boards in the CircL Pavilion, (author)

<u>Building B and C, Windesheim Campus, Zwolle</u>
By: LIAG
Type: Renovation

The renovation project of the buildings B and C in the Windesheim Campus involve the design of a circular façade which integrates services within a modular and interchangeable façade system. According to a report by LIAG (2020), the existing façade is largely preserved – and in this way reduces the construction and demolition waste generated in the entire process. While choosing the materials, reused materials have been given a preference –

however the quantity of material available was proven to be a challenge. It was therefore used for a small part of the building – the canteen. Other than this, factors such as lifespan, origin and end-of-life have been considered while selecting materials. While designing the connections, the accessibility of connections has been considered an important factor. The façade plays an important role in realizing the circular ambitions of the project – the elements within the façade are designed in such a way that they can be assembled with a limited number of form elements, and is reversible in design which allows for easier maintenance / replacement. The removed elements can then be recycled (LIAG, 2022). The project was also benchmarked and evaluated the design periodically using the Building Circularity Index tool which was linked to the BIM model of the project. This project was relevant to understand how renovations are undertaken in real life scenarios with sustainable strategies as a main goal. For office and public buildings, it is important to achieve a sustainable goal for the sake of image despite additional costs.

Figure 20 - Facade renovation of Windesheim Campus; (LIAG, 2022)

Chapter Summary

There are three main strategies identified for a circular built environment, these are resource and waste management, design for reversible buildings, and business models in the construction value chain. Resource and waste management, as the name suggests deals with avoiding resource consumption, reducing materials landfilling, and reusing of building elements. The design for reversibility deals with using disassembly techniques, modular and standard dimensions, impermanent connections, use of materials passports. The business models deal with new service-oriented models such as product service systems, pay per use etc. After identifying the strategies, the literature also discusses challenges while undergoing circular facade renovations. Some critical challenges are that the market is not yet developed for the new circular materials, and there is also a lack of developed skillsets and as well as tools for the designer – which are not being used in majority of the practices. Lastly, circular practices in construction are not yet made necessary to do. To gain an insight into practical applications of circular strategies, some real-life projects and executed research and pilot projects were studied as well. The projects CircL Pavilion, renovation of Windesheim campus, Circular Retrofit Lab and REHAB helped gain an understanding of how to develop the different conceptual design strategies, applications of new circular materials, breakdown of connections and assemblies, principles of designing for circularity and sustainability considerations in building renovations, design considerations such as modularity and standardization, as well as giving a direction to the process of design. Finally, through this study of practical examples and the literature, the key aspects of materials, connections and assemblies were identified as highly impactful to façade design and therefore elaborated.

04

Case Study Analysis

In this chapter, a building is selected to apply the knowledge gained from the literature review. The building history, architecture, layers, and materials, are analyzed in detail as well as the climatic context of the location – the Netherlands.

Background

The project chosen is the Applied Physics building at the TU Delft campus. The building is in the pool of building stock which is 30-40 years old, outdated and no longer meets the requirements of the users as well as the building regulations and standards. The structure was built in 1960's and has not undergone any major renovation since the time of construction. According to a study by Blom and van den Dobbelsteen, the primary energy consumption of the building is high with a poor indoor environment (n.d.).

History

The post war era saw a major growth in the building and construction industry. The use of architectural precast concrete became very popular, especially in the early 1960's. The Applied Physics building itself was constructed in 1963 and utilizes architectural precast concrete in almost the entire façade. These precast panels were preferred over in-situ concrete due to the benefits of reduced construction time, high quality fabrication and reduction in costs. The resulting construction costs were 10-15% less, and the construction time was half or 1/3rd the standard. Moreover, the Ministry of Housing and the public service housing societies in the Netherlands also encouraged the use of precast concrete. Functionally, architectural precast concrete offered many options of use. It could be applied on buildings as small panels attached to loadbearing structural frames, as large loadbearing wall panels, as parapets of balconies, as well as insulated sandwich panels used in exterior cladding. Aided by a high demand and the post war development of the building industry, the precast concrete industry was modernized and mechanized.

Construction

The APC could be designed and constructed as flat panels as well as curved 3D forms. While residential projects of the era used flat panels to reduce costs, public buildings often exploited the three-dimensional possibilities of architectural precast concrete. In the case of the Applied Physics building, the façade is non-loadbearing and most likely fixed using protruding reinforcement bars during the construction of the skeleton itself. The figure below illustrates how the construction of the building skin could have been possible (van de Voorde, 2012).

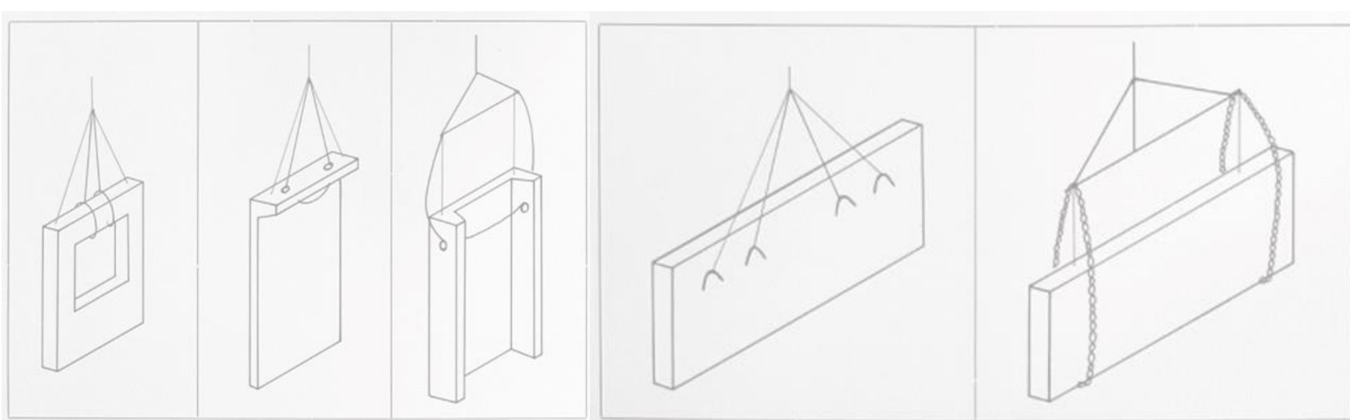


Figure 21 - Assembling 3D façade panels during construction, (van de Voorde, 2012)

Carbon Goals

According to CO2 roadmap study done by Blom & van den Dobbelsteen (n.d.), the building should have an 80% less heat demand to meet the future climate goals. An average energy consumption by the buildings in campus is shown in the figure below, where the Applied Physics building is (highlighted) consumes 200-250 kWh/m^2 of energy. To successfully achieve a lesser heat demand, the only solution is to renovate the building, which involves the renovation / replacement of the skin as well as the services.

Figure 22 - TU Delft map of CO2 emission per building, (van den Dobbelsteen, n.d.)

Renovation Goals

A plan for the renovation and maintenance of the Applied Physics building – Building 22 was created in 2015. To understand the goals of the project better, an interview was conducted with a representative of DGMR (sustainability experts for project) Ms. Merlijn Hubbers, who was the sustainability consultant at the company during the time of the project. The most important task identified was to reduce the primary energy consumption of the building. Architecturally, there was also a need to create spaces within the building. As for sustainability, there were no concrete goals, and the company was given freedom to achieve sustainable goals by any means suitable. For the project, however, DGMR prioritized energy efficiency and better indoor comfort, while also facilitating the use of materials that contributed to better health and wellbeing of the users. Before proceeding with the planning and design process, a detailed façade study of the building was conducted. With the study, the exact material composition and construction technique was identified. This was done by making a hole horizontally through the façade. The findings are elaborated further in the next section.

Analysis

Building Grid Analysis

The structure is 175 meters long and has a total of 5 stories including the ground floor, with an average floor height of 3.5 meters. The maximum height of the building is 17.5 meters. The construction follows a rigid grid internally and externally. The building is modular, with a constant spacing between the columns as well as the façade elements. This is illustrated in the images below. Within the front façade, there are 4 divisions space distribution wise, each of length 35m, separated by an atrium of 7.2m. Within the façade panels itself, there are three sizes used, 1800 x 450 [mm], 1350 x 2550 [mm], and 450 x 2550 [mm]. These generate centerlines of 1800 [mm] vertically and 3000 [mm] horizontally.

Length	Front Façade	175 m
Height	Storey Height Number of Storeys Maximum Height	3.5m 5 17.5 m
Surfaces	Footprint Gross Floor Area Front Façade	~ 9735 sqm ~ 48,675 sqm ~ 961 swm
Windows	Average Window Area Number of Windows in Front Façade Area of Windows in Front Façade	2.3 sqm 418 961 sqm

Table 6 – Basic Building Dimensions and Areas, (author)

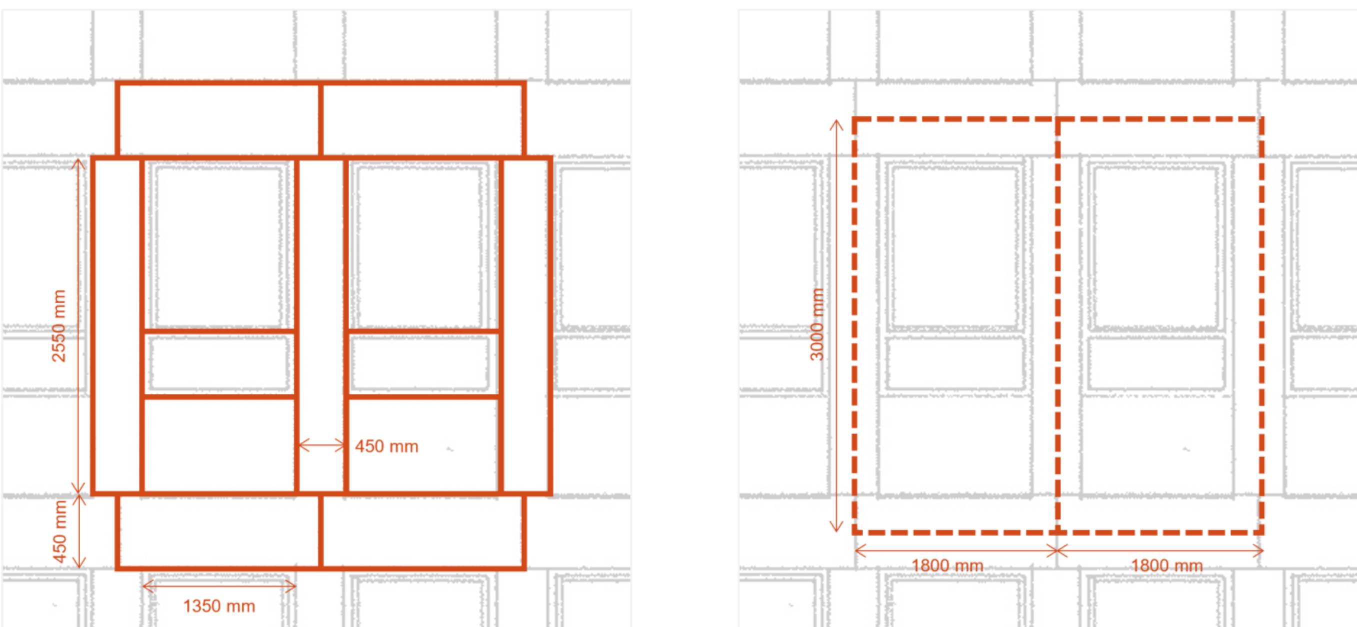


Figure 23 - Building grid, (author)

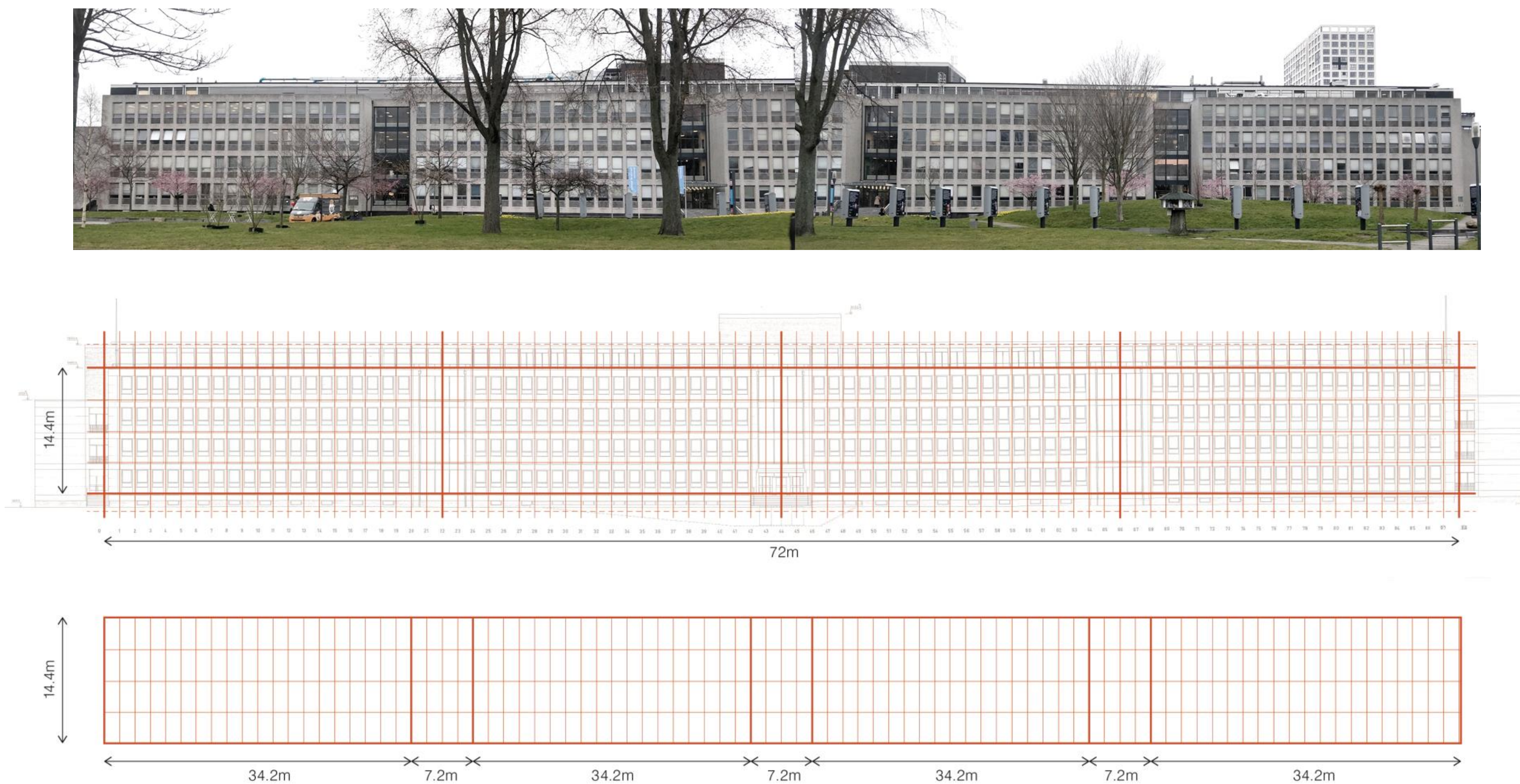


Figure 24 – Front façade of the Applied Physics building, (author)

Building Layer Analysis

The building layers of the skin, structure and services are not dependent on each other, but are very permanent in terms of construction.

Structure	Reinforced concrete structure
Skin	Masonry and prefabricated concrete panels
Services	Heating, Ventilation (internal and separately installed)

Table 7 - Building Layers (author)

Within the layer of the 'skin', following the division by Bakx (2016), the break-up of components, elements, and materials of the existing structure can be expressed as shown below.

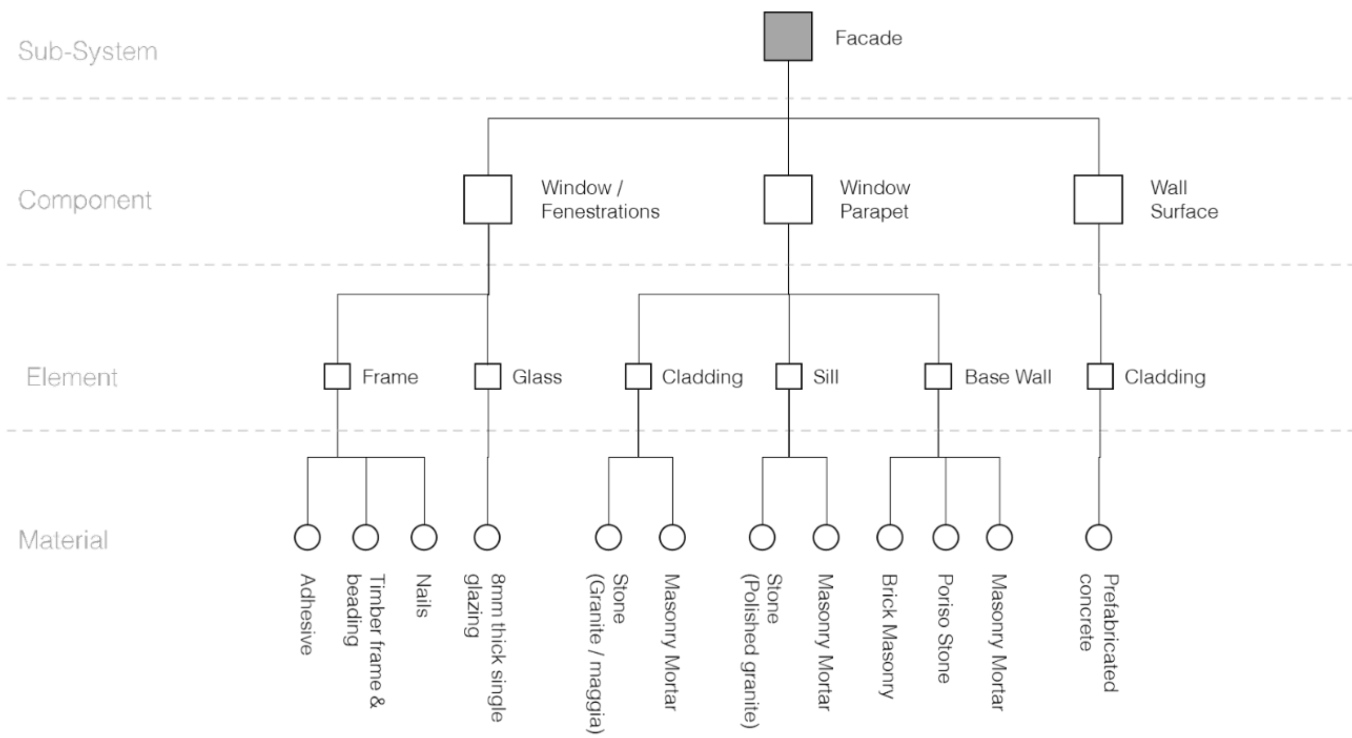


Figure 25 – Break up of the materials, elements, and components within the sub-system of 'Façade' (author)

However, to follow a standard system for the new design, a layer-wise distribution is adopted. The façade component is divided into 6 layers, based on their function. These are the exterior finishing, window/fenestration, insulation, sheathing, structural frame, interior finishing, and illustrated below.

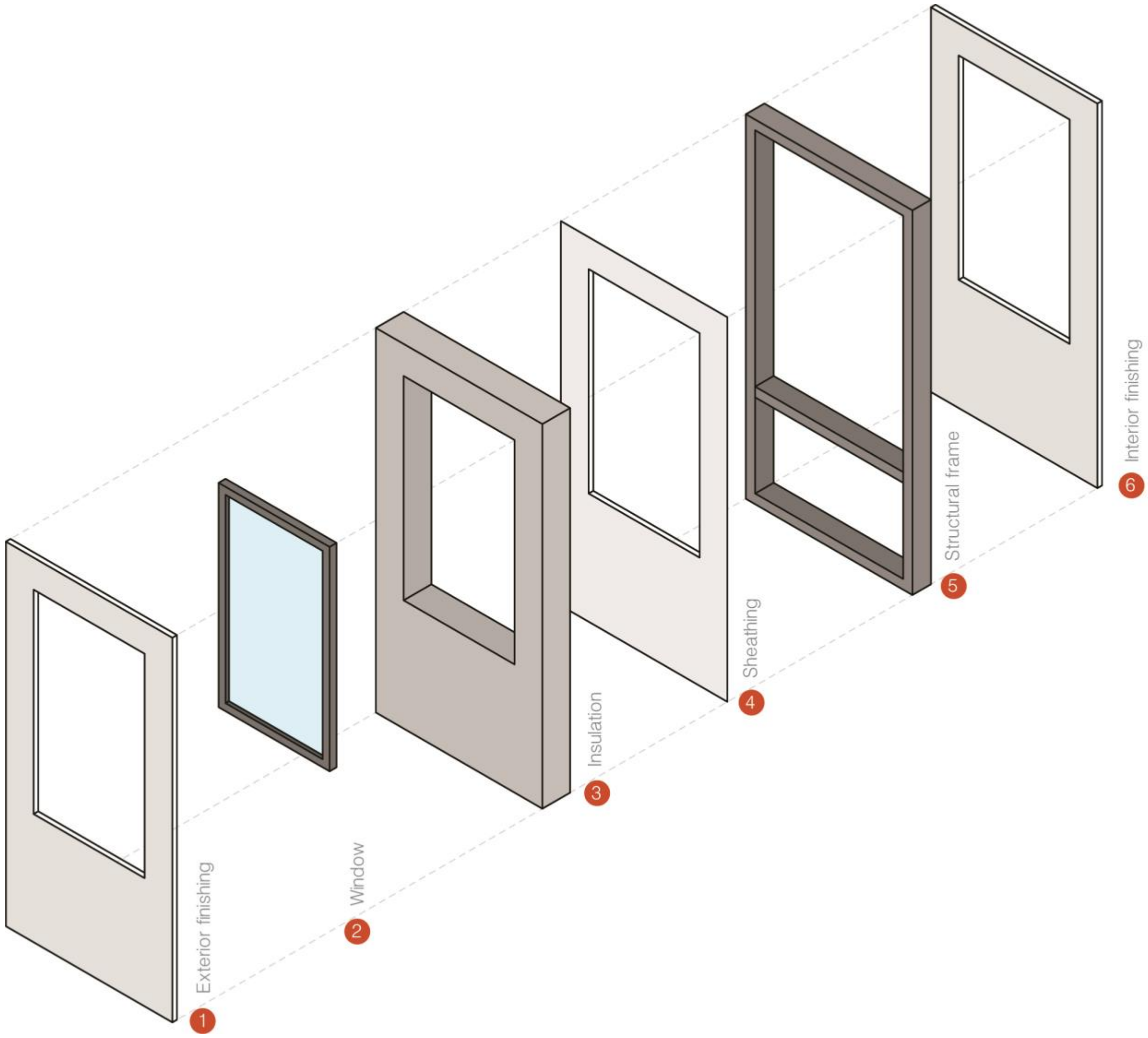


Figure 26 - Layers of the façade, (author)

Building Material Analysis (Façade)

The building utilized 183,000 cubic meters of concrete in construction and was the largest concrete building in the Netherlands at the time of its completion in 1963. As mentioned before, the building structure, which includes the beams, columns and floors are made of reinforced concrete. The internal walls are made of brick masonry and poriso stone which is assembled using mortar. The concrete skeleton of the building is clad using 4700 prefabricated concrete panels, and this forms a major part of the facade.

Facade	Internal Walls	110 mm thick Masonry walls, made using masonry mortar 90 mm thick Poriso stone
	Façade Cladding	Prefabricated concrete panels with embedded smooth stones (marble, basalt, natural feldspar, Bavarian green) Stone panels (Maggia stone) - possibly connected to extruding reinforcements
	Windows	8 mm thick Single glazed windows with wooden frames

Table 8 - Building material specifications, (Macel et. al.,1994), (Hubbers, 2022)

A typical façade panel in architectural precast concrete used in the building consists of two layers: first a decorative layer, at least 10 mm was cast, followed by a layer of regular concrete. The panels used are approximately 7 cm thick and up to 2.50 m long. The ends of the panel have ridges that provide more structural stability. The sealing joints on the exterior are watertight and approximately 12-18mm wide. The gap between the precast concrete panel and the masonry is not filled with any insulating material in this case. The exterior layer was made of concrete mixed with 9 natural stones that are ground smooth. Basalt, natural feldspar, bavarian green, marble (Macel et al., 1994). The parapet under the windows is cladded with maggia plates with a rough surface finish.

Figure 27 - Exterior images of the building skin, (author)

The windows are single glazed windows with wooden frames. They have manual blinds for sun protection and are only partially openable. The schematic sections of the solid and glazed part of the façade are illustrated below.

Figure 28 - Exterior and Interior images of the building skin, (author)

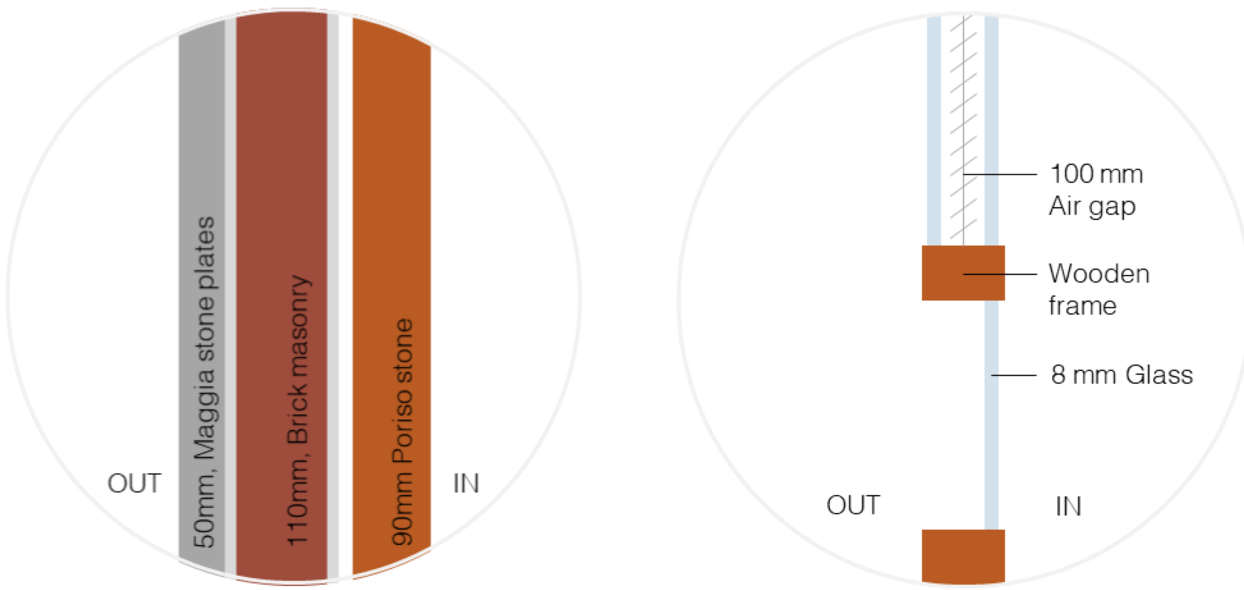


Figure 29 - Schematic section of (a) solid facade and (b) window

The detailed section, as designed originally for the building is attached in the appendix.

Figure 30 - Facade elements and connections, (Peutz DGMR, 2015)

Overview

The façade is found to be in a good condition and is watertight. There is also no corrosion on the metal elements and no concrete rot. It is also expected to deteriorate in the next 2 decades at least (Peutz, DGMR, 2015). Also, if partly demolished, the materials that will be extracted will only likely become gravel. It will not be possible to reuse them in the current state, and the only option is downcycling.

Figure 31 – Analysis of the physical attributes of the building, (author)

Chapter Summary

The first step to a building renovation is to analyze the building and the current scenario, as well as determine the end goals for the renovation project. The building selected for the case study was the Applied Physics building at the TU Delft campus. It was constructed in 1963, during a major growth phase in the construction industry and is a concrete framed structure cladded with prefabricated concrete panels. A detailed analysis of the building materials and the dimensional grid was made to be better informed while choosing strategy for renovation. It was found that the building has a rigid structure with a constant grid. This is particularly reflected in the window and panel sizes – which are the same throughout the façade. An analysis was also made for the connections and materials used within the façade.

05

Design Process

This chapter highlights the scope of the thesis project and describes the design process followed to achieve a circular façade during a building renovation. This is done through developing a design framework, then developing design options based on varying material and connection choices.

Design Considerations

As specified in the previous chapter (overview as shown below), there are multiple steps to achieving a circular design while planning for a renovation. The framework for the design of components is divided into 4 major steps. The first is type of intervention – this is related to the type of renovation intervention that is best suited for the building in question. The second is the choice of materials between technical, bio-based materials or both. The third is the choice of connections. This is to an extent dependent on the material choice. It could range from an indirect connection which can be disassembled completely to a direct connection which is a permanent connection. The fourth is the end-of-life scenario of the combined components.

To be able to systematically follow a set process of design and evaluation, the following 4 steps have been identified and elaborated.

Interventions on Existing Building

Design decisions about interventions to the existing building are informed from the analysis of the building done as prior to the design stage. For this building, the intervention chosen is to renovate and improve the performance of the building envelope, leaving the other layers of the building intact. This is done through two strategies 'repair/maintenance' and 'refurbish'. The refurbish strategy involves completely replacing the façade. This maintains a similar quality of construction through all the design options. However, we see that the façade is in a good condition. For this reason, the 'repair' strategy is also considered in an option.

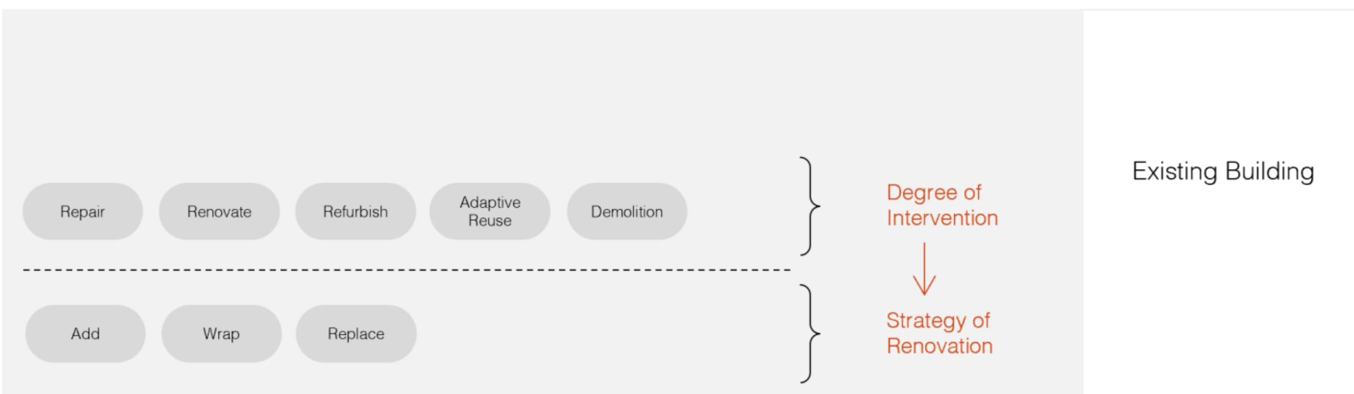


Figure 32 – Interventions on existing building

New Design Decisions

These decisions are informed by the knowledge of circular strategies. These will influence the material choices, the type of connections within the component and assembly order of the layers within the components. These three are briefly explained below.

<u>Type of Materials</u>
The materials can be of two types, (a) Bio-based materials; those materials which are produced from natural sources with minimal carbon emissions, can be easily renewed and are bio-degradable are bio-based materials, or (b) Technical materials; which are common processed materials like metals, plastics etc. The production of a material depends on the raw material feedstock, which could comprise of virgin materials, or reused materials, or recycled materials. Further, the end-of-life scenarios of each material could range from reuse in exact form to incineration for energy generation.

For the materials that are applied in the new design, the following considerations are made -

- Single use materials (that go to landfill at EOL) are not selected

- For reclaimed and reused materials, the priority given to harvested materials from the site itself.
- Locally available (or available at closest destination to location of building) are preferred.
- Materials with a virgin feedstock are considered.
- Materials which are toxic / generated using toxic raw materials are not considered.
- Materials that have the end-of-life scenario as landfill are not considered.

Connections

Connections between various elements of a component are important as they decide the degree of freedom of each element. This affects the recyclability of a component directly. From existing literature, connections can be categorized within three types – indirect (or accessory), direct (or integral) and filled connections. Indirect connections require one or more additional pieces to combine 2 elements. These types of connections are more favorable for reversible design. Direct connections depend on the geometry of the elements to be combined, such as overlapping or interlocking. The filled connection requires a third material which chemically joins the two elements, such as welding and concrete filling. This type of connections is the most unfavorable for reversible design (Durmisevic, 2018; Henry, 2018).

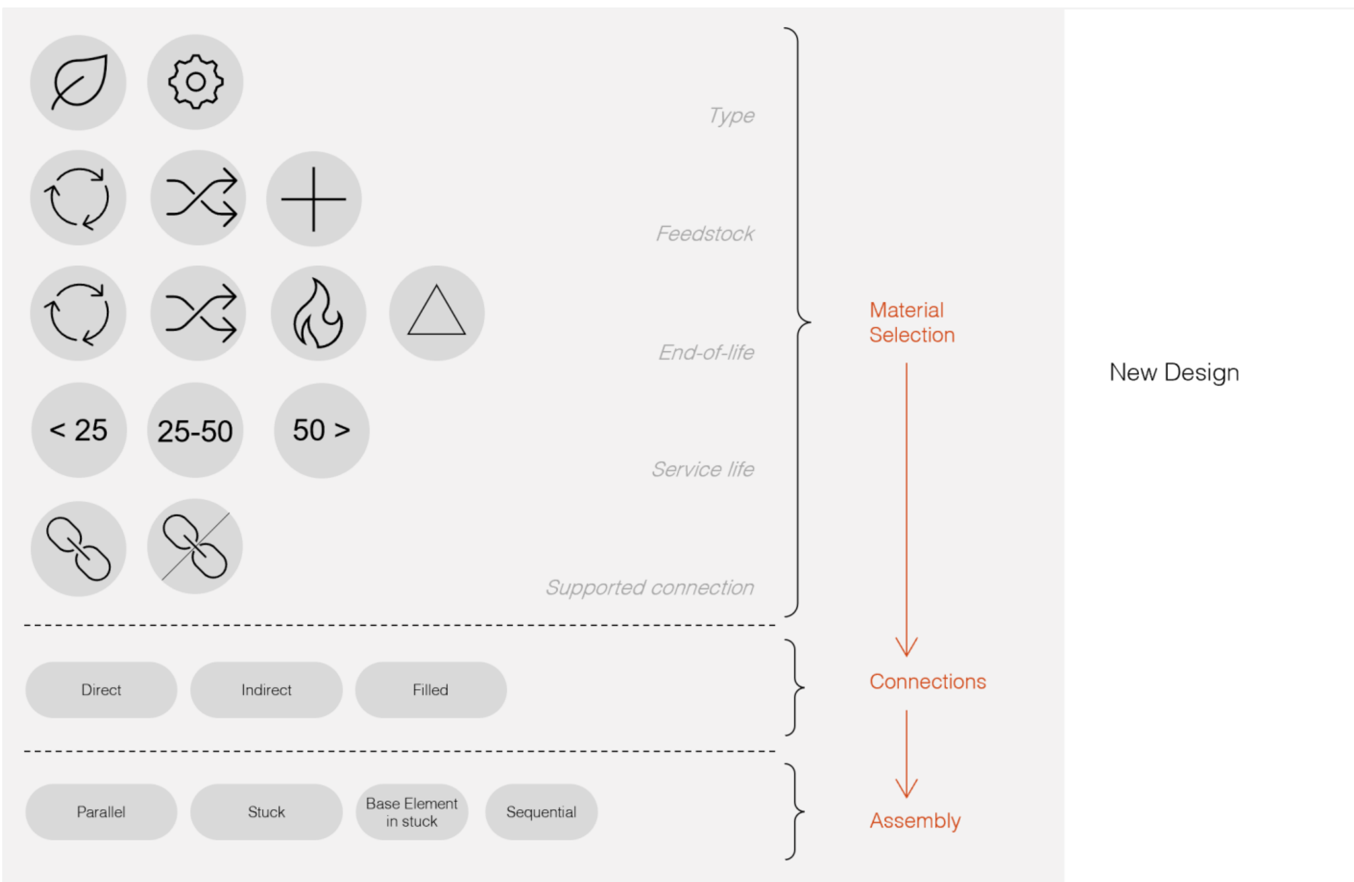


Figure 33 – Strategies for circularity in the built environment

Fixed Performance Criteria

While developing the design, there are two kinds of performance indicators – fixed and variable. For the purpose of testing the circularity, all the indicators that affect the circularity directly are considered variable. The indicators which affect the general design of a renovated façade such as the minimum required thermal performance, etc. are considered as fixed. These performance indicators are listed below. They remain of largely the same values within all the design options. For this design exercise, the Ubakus tool was used to determine thicknesses and R values of entire construction. The R value of façade = 5 [m^2W/K], is considered as base requirement.

a) Thermal Performance - The design options all meet a standard value of R=5 [m²·K/W], or u=0.2 [W/m²·K] for the solid construction. It is assumed through the process that their thermal performance is comparable. The windows are double glazed with nearly the same glazing properties.
b) Energy Performance - The function of building, occupancy schedule, HVAC schedule and lighting schedule is considered constant. As mentioned above, the insulation value also remains constant.
c) Acoustic Performance - The area of solid surface to glass is kept constant. The interior finishing layer of each option is considered to be of comparable acoustic properties.
d) Daylight, Views - The window to wall ratio and type of window (double glazed) remains constant throughout the options.
e) Thermal Comfort - The indoor comfort is expected to remain largely the same for all the options since the thermal performance of the solid and glazed envelope.

Appearance

This criterion is subjective, however, for the purpose of this exercise, the most basic factor such as total thicknesses of façade composition is considered.

Conceptual Design

Circular Design Strategy

There are many definitions of circularity and many different visions, frameworks, strategies for circular design in the built environment. To be able to directly translate these into architectural concepts can be a challenge. To facilitate this, the 10R framework was chosen. This gives a general direction for material and product selection decisions especially targeted in the early design phase of the building. The advantage of this is that it is directly applicable for the small scale – the design, manufacture of products, components as well as the large scale – building design itself. The selected strategies are 'Reduce', 'Renew', 'Re-use – or Reclaim' and 'Recycle'. These also party rely on the concept of slowing closing and narrowing material loops. This is elaborated further in the next section.

Refuse	prevent raw material use
Reduce	decrease raw material use
Renew	redesign product in view of circularity
Re-use	use product again
Repair	maintain and repair product
Refurbish	revive product
Remanufacture	make new product from second-hand
Repurpose	reuse product with a different function
Recycle	salvage material streams with highest possible value
Recover	incinerate waste with energy recovery

Figure 34 - 10 R Model, and what is relevant for this design scenario

Design Exploration

Many façade design concepts were developed architecturally. These varied in sizes, composition, and form. They were then assessed based on principles like modularity and checked if they would support standardization of individual components. An overview of the options is represented below. Out of these, 1,5 are preferred since they support modular dimensions. 6 also supports modular dimensions within the panel design but not while considering the entire façade. Eventually, the square shape is selected as it supports standardization and modularity within the panel design as well as the entire façade.

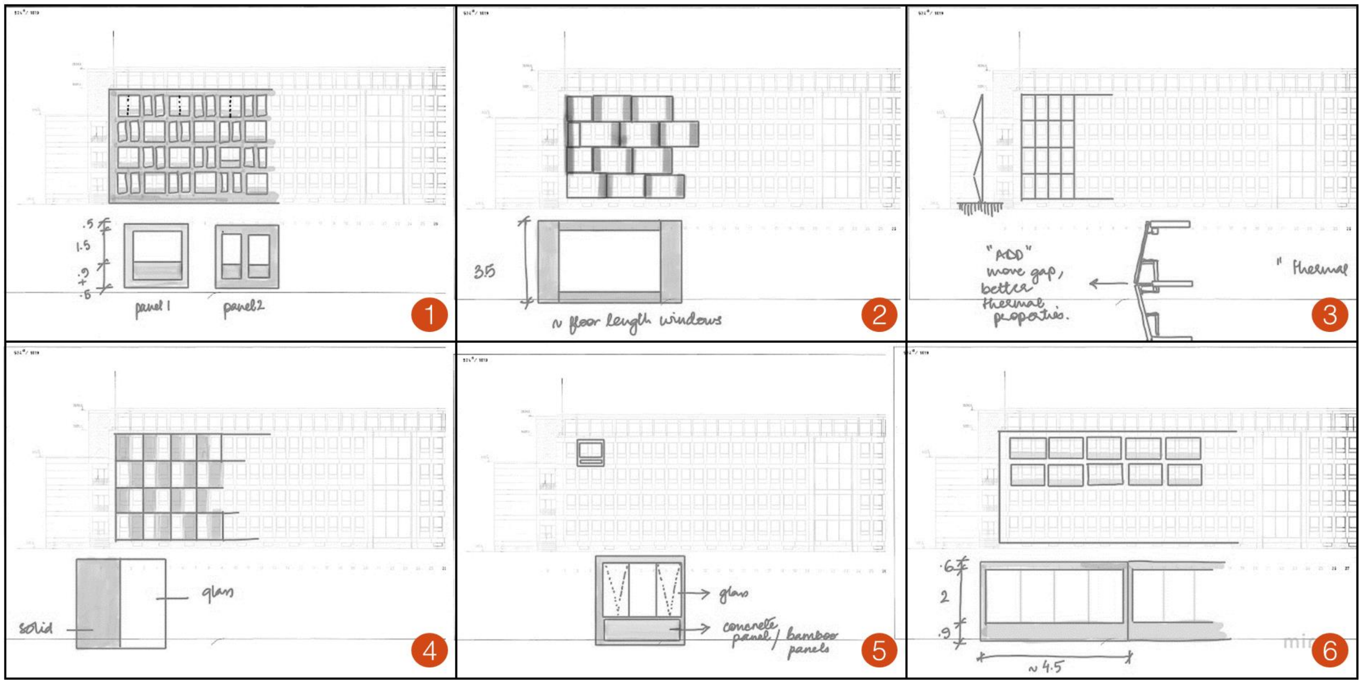


Figure 35 - Initial design options

Material Exploration

The material selection for the options is based on certain criteria such as availability, sustainability, etc. These criteria are (a) the materials should have a low embodied energy during production and minimal CO_2 emission overall, (b) materials that already have a scaled production and are readily available in the market are preferred, (c) materials and products that are locally available, or within a certain permissible radius of the building are preferred. This means that materials that are still being researched and could potentially be used in the next few years are not considered. Materials and products that are processed and manufactured outside of Europe are also not considered for the design. Furthermore, materials which cause any kind of discomfort or are toxic are also rejected. The information about the materials through the selection process is gathered through product specifications available on the manufacturer's websites or through EPD's available in product databases.

Within the layers of the façade element, the materials are explored layer-wise. Especially the layers of 'exterior finish', 'insulation', 'structural frame' had many material options available in the market. Most new projects also utilized circular materials within this layer. The major materials explored were reclaimed bricks, composite cladding panels in the exterior finish layer, textile, straw and wood fiber insulation in the insulation layer and cross laminated timber, reclaimed timber and aluminum for the structural frame layer. These are represented in the figure below.

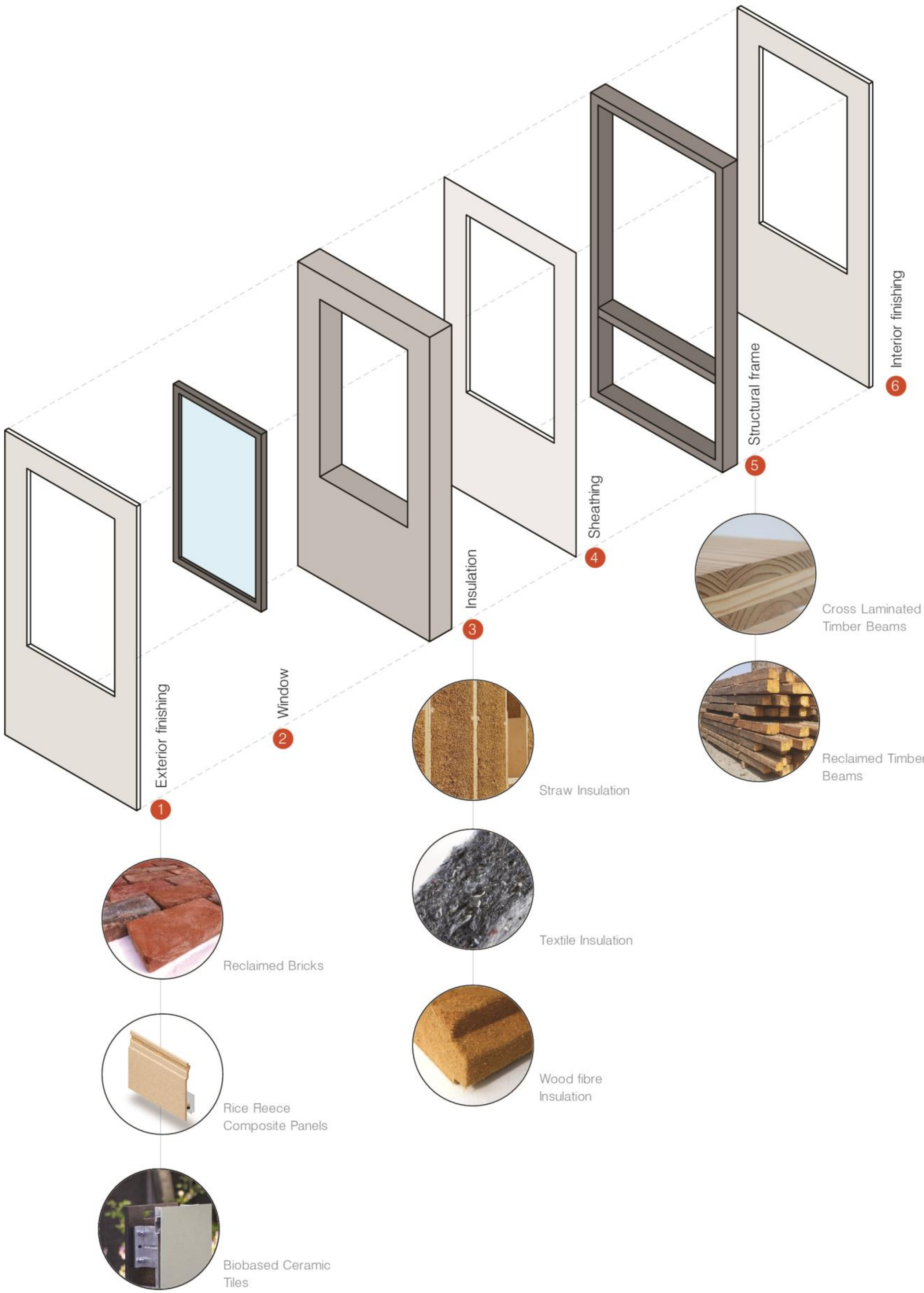
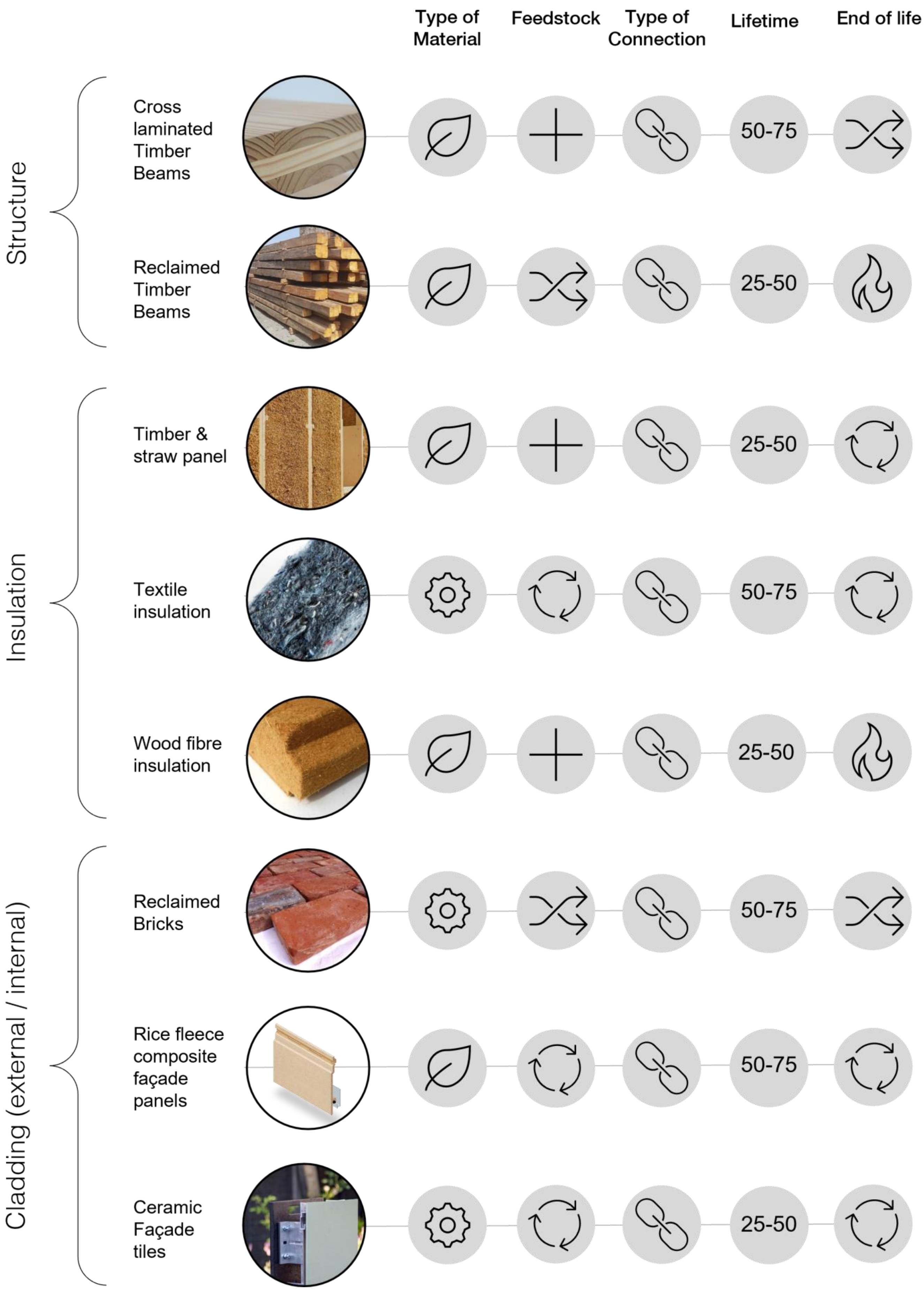


Figure 36 - Materials selected as per the layers of the façade



Type of Material
Feedstock
Type of Connection
Lifetime
End of life
Structure
Cross laminated Timber Beams
50-75
Reclaimed Timber Beams
25-50
Insulation
Timber & straw panel
25-50
Textile insulation
50-75
Wood fibre insulation
25-50
Cladding (external / internal)
Reclaimed Bricks
50-75
Rice fleece composite façade panels
50-75
Ceramic Façade tiles
25-50

Developed Design Options

Option 1: 'Reclaim'

This strategy is mainly to do with 'slowing loops' and involves using reclaimed products which are sourced from from various sites – these could be directly sourced from external sites, such as buildings being demolished in the region, or indirectly, such as through material harvesting companies and associations that extract materials from buildings and store them. While the direct approach requires knowledge of local trends and ongoing projects in the region, the indirect approach is more centralized and accessible. This can be accessed through documented databases available on company websites. Two such websites are used for the purpose of selecting materials for this project – Restado (Germany) and New Horizon (Netherlands). Both the companies feature the quality and quantity of the harvested materials. It was found that the materials available were mostly robust materials that are relevant for the exterior cladding (clay tiles, bricks), and structural frame layer (timber beams). Materials ideal for use in the insulation layer, or 'finished' materials suitable for the interior finishing layer were not available easily.

Within the designed option itself, the materials are sourced from external sites as there are no components within the façade that can be harvested and used again. Also, all the layers do not use reclaimed materials since they were not available through the aforementioned sources. In the design, the internal finish layer (reclaimed timber cladding), structural frame layer (reclaimed timber beams), and the external finish layer (reclaimed bricks) consist of reclaimed materials. The sheathing, insulation and window layer are made of recycled materials. This scenario is specific to the case of this building and can change for another building (for eg, a smaller building might have be offered a greater availability of materials due to a lesser quantity).

After the selection of materials based on combination & type of connections, the 'u value' was calculated using the took 'Ubakus'. The total width of the composition was calculated to be 422 mm and the u-value as 0.21 W/m^{2}K.

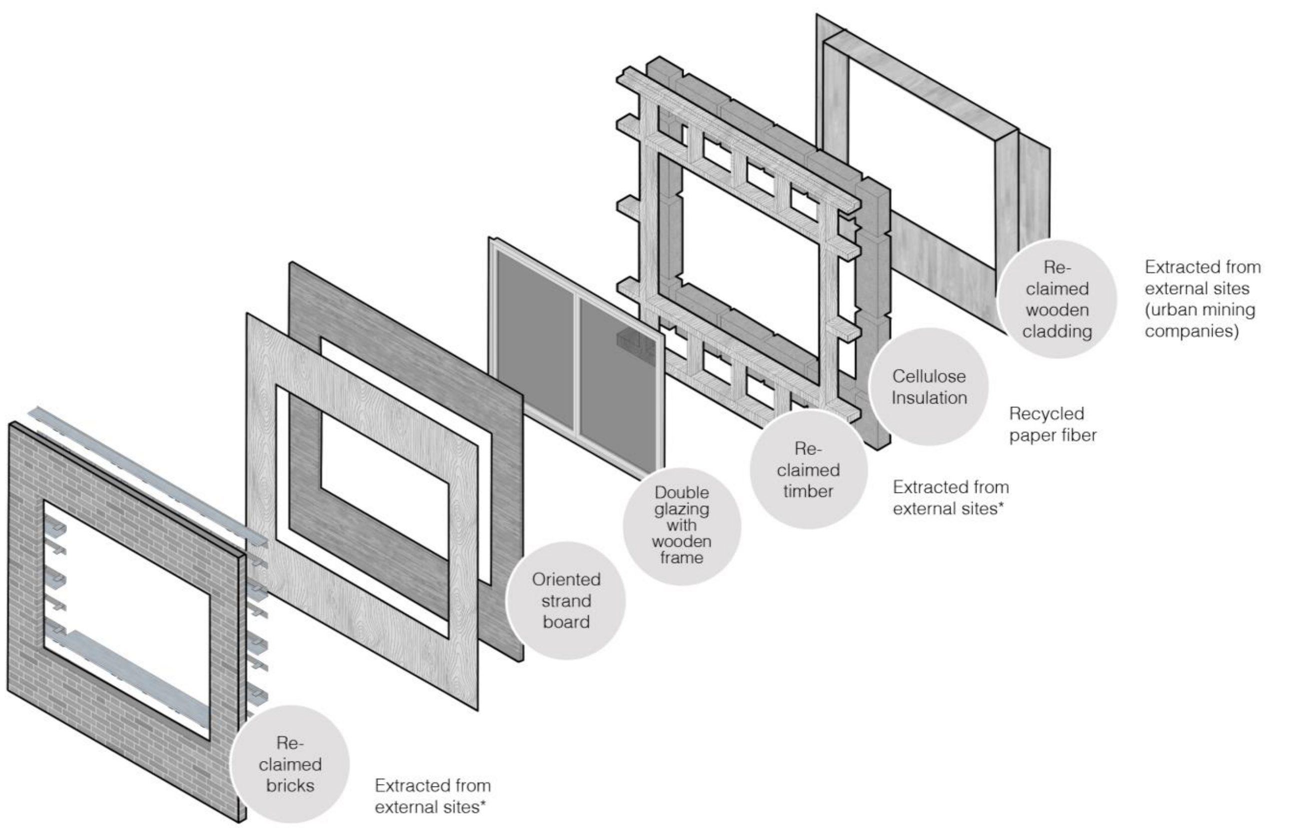


Figure 37 - Exploded views of layers of 'Reclaim' option

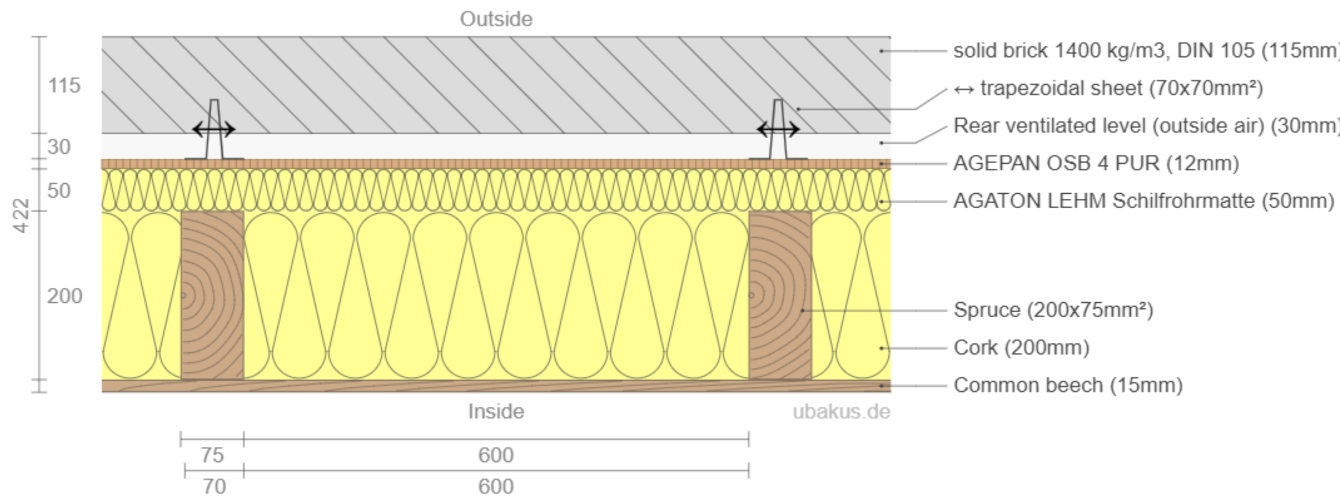


Figure 38 - Schematic section of 'Reclaim' option

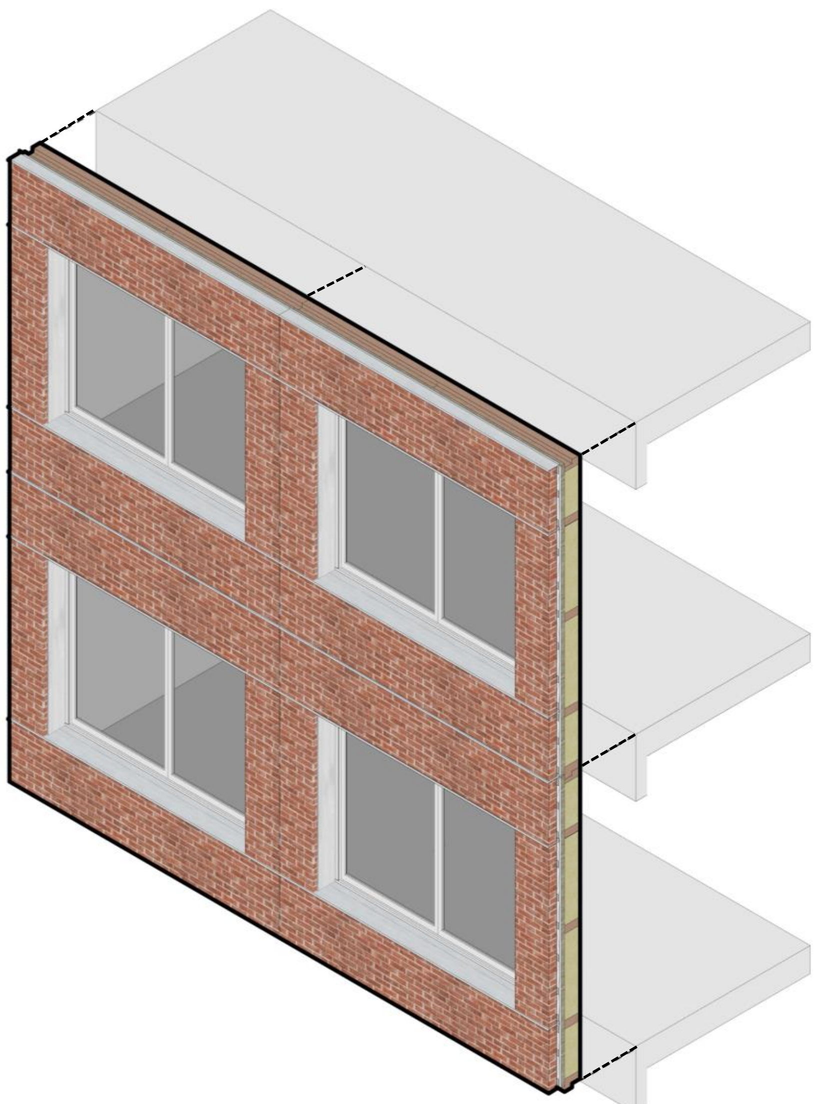


Figure 39 - Isometric view of 'Reclaim' option

Option 2: 'Renew'

This strategy is mainly to do with 'narrowing loops' and uses materials that are sourced from nature and have a lower environmental impact. These nature-based, or bio-based materials are renewable in nature as the raw materials for these are abundant in nature. They help to design for a circular environment in the following ways. First, they sequester carbon dioxide during the growth phase. They also produce less carbon dioxide emissions in the production phase, thereby leading to overall a lower embodied carbon benchmark. Second, these materials can be easily found locally, especially rural regions. The wide availability reduces the energy and costs involved in the transportation. Third, these materials can be reused (cellulose flakes, seaweed) as well as recycled (hemp mats, sheep wool), and at the end of life, materials such as straw, hemp, sheep wool, can be composted.

In the design of the façade option, it is recognized that bio-based materials might never be able to replace metals and minerals. For this purpose, the design cannot completely rely on bio-based materials, especially while considering fixing, connection mechanisms such as screws and/or sealants and adhesives. For the design of this option, products that are currently available in the market are explored. One such product is Ecococoon, which is an assembly of a timber frame and straw insulation, with an additional layer of fiberboard. This product is mainly comprising of the layers of structural frame, insulation and sheathing. The panels are made of 98% renewable materials and vapour open, with no thermal bridges. The product can be finished with plaster, or other materials inside as well as outside.

After the selection of materials based on combination & type of connections, the 'u value' was calculated using the took 'Ubakus'. The total width of the composition was calculated to be 262 mm the u-value as 0.24 W/m^{2}K.

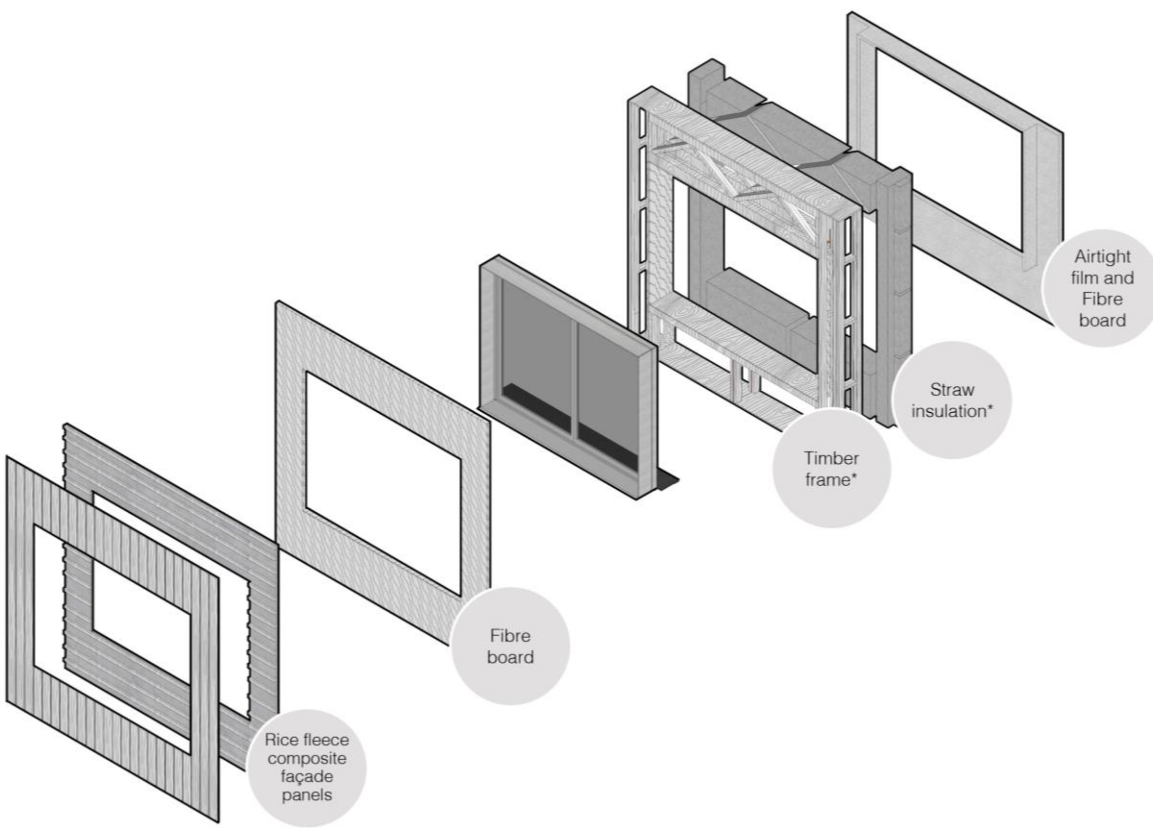


Figure 40 - Exploded views of layers of 'Renew' option

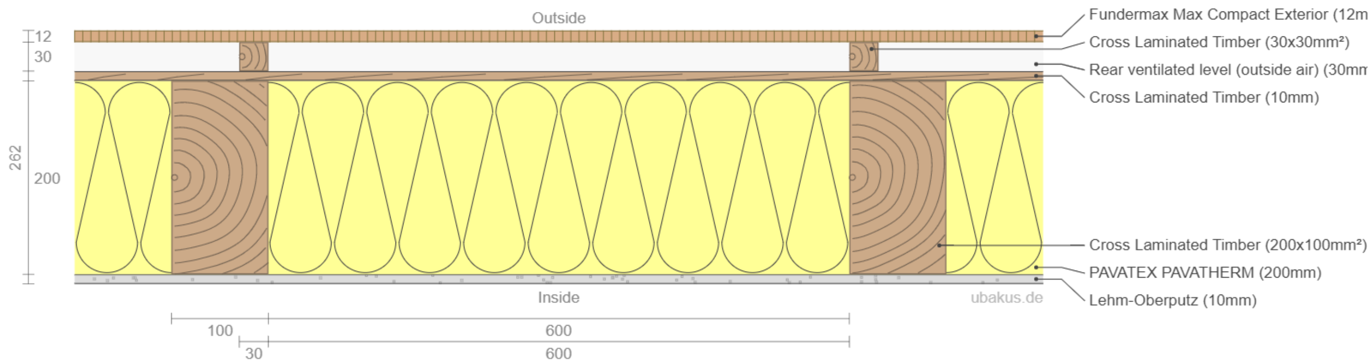


Figure 41 - Schematic section of 'Renew' option

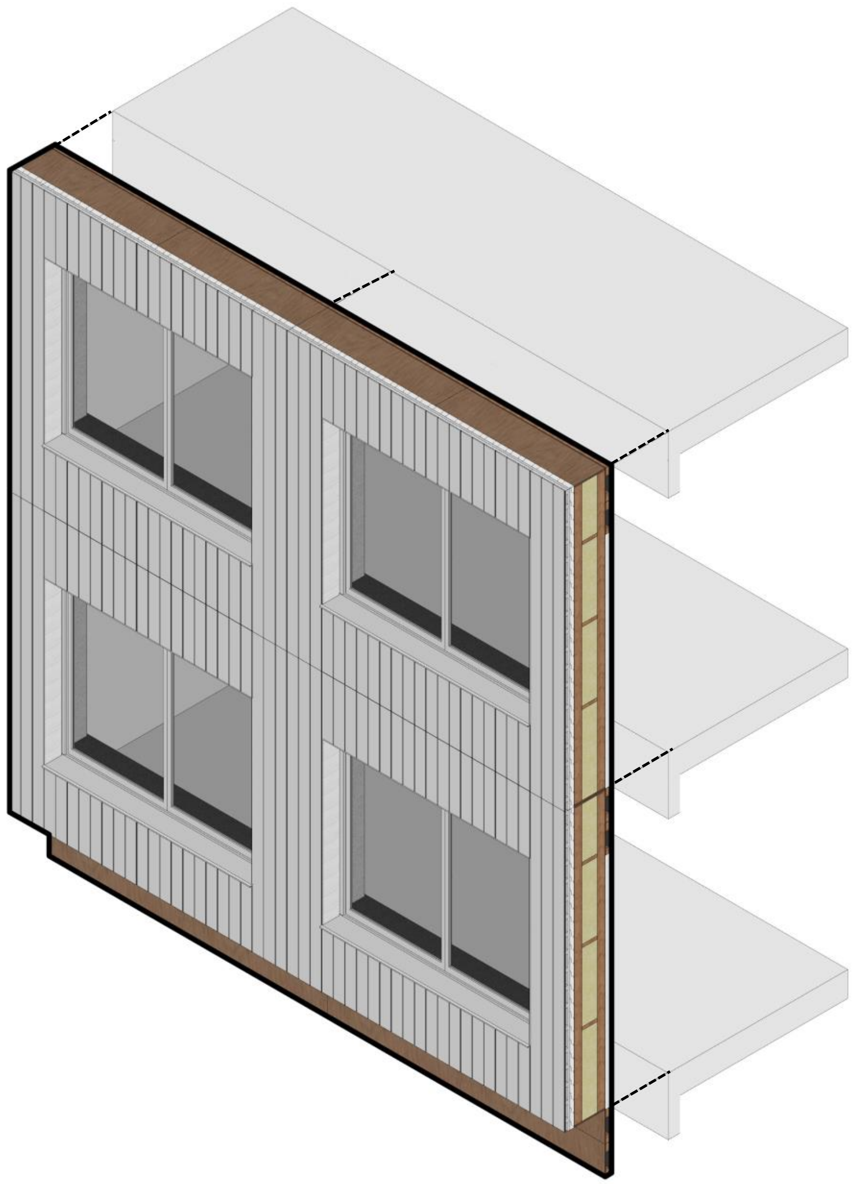


Figure 42 - Isometric view of 'Renew' option

Option 3: 'Recycle'

This option is based on 'closing loops' and follows the assumption that using products which are endlessly recycled in an ideal environment. Therefore, the option majorly uses moderate to high-end recycled products that are robust, have a long life and at the end of their life can be recycled. This strategy helps in two ways. First, it reduces the amount of raw materials being extracted from the natural environment. Second, it reduces the construction demolition waste that is created at the end of product/building life.

In this design option, the recyclable materials used are primarily in the structural frame layer, insulation layer, the interior, and the exterior finishing layer. The main frame is made of aluminum, which can be recycled endlessly. This recycling process saves 95% of the energy used in its production from raw materials. The primary insulation is made from textile (jeans), and the secondary, more rigid insulation is made from fiberboard. The exterior cladding comprises of residual material fibers from pruning waste and natural materials – which is combined together in the natural ceramic façade tile by 'Kerloc'. These tiles can be taken back at end of life and fully recycled for the manufacture of new tiles.

After the selection of materials based on combination & type of connections, the 'u value' was calculated using the took 'Ubakus'. The total width of the composition was calculated to be 283 mm and the u-value as 0.23 W/m^2K.

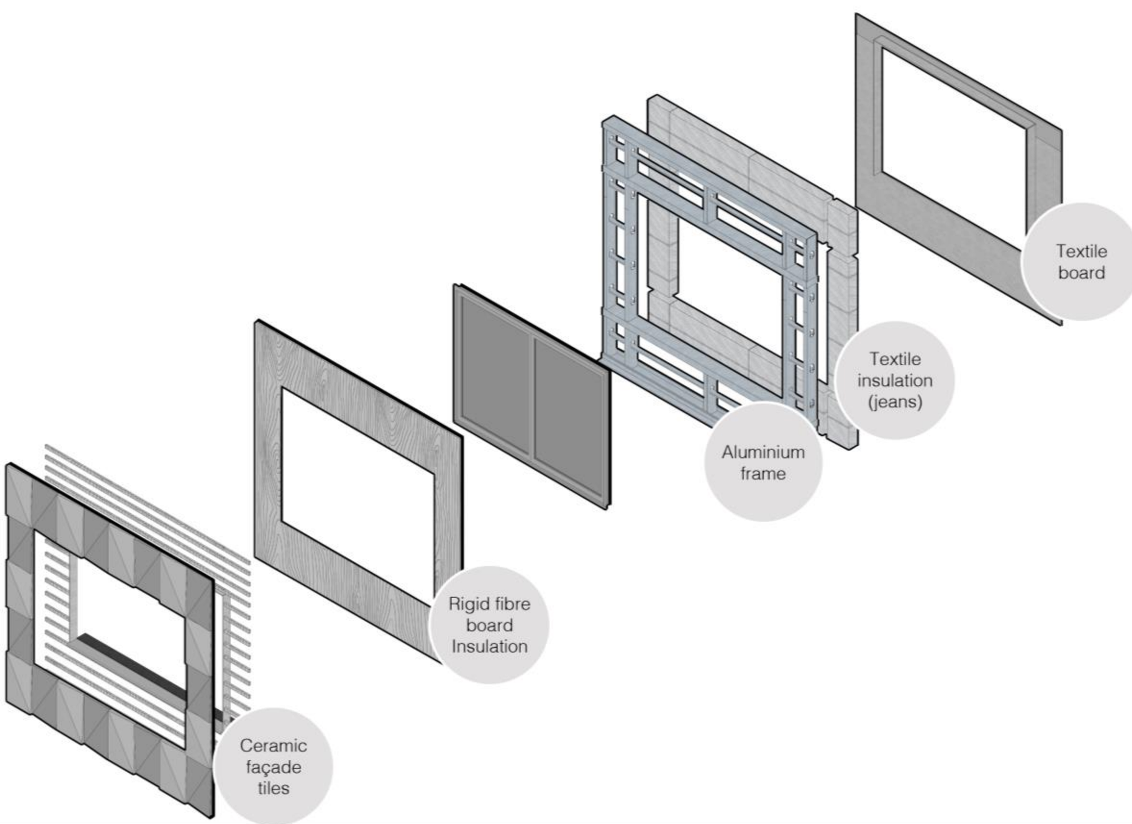


Figure 43 - Exploded views of layers of 'Recycle' option

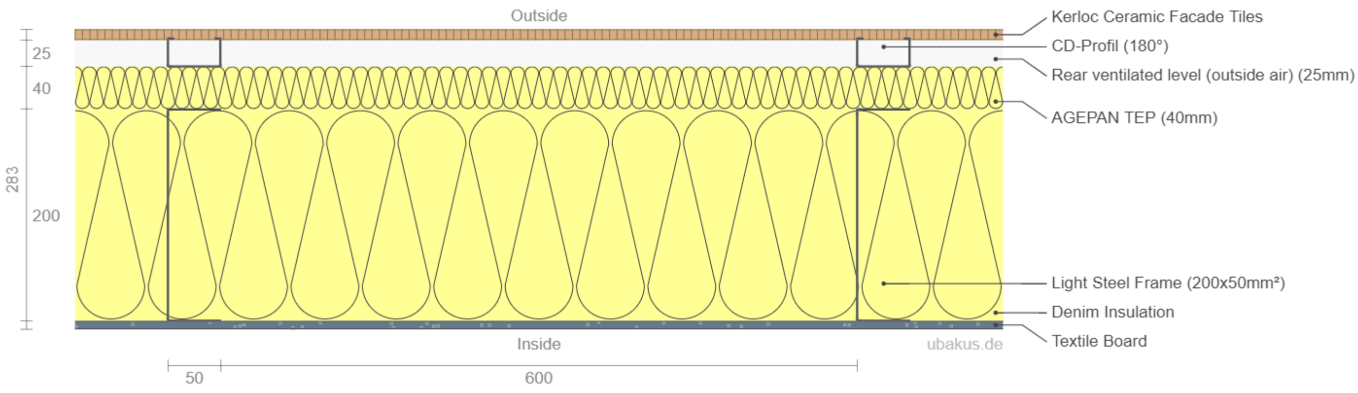


Figure 44 - Schematic section of 'Recycle' option

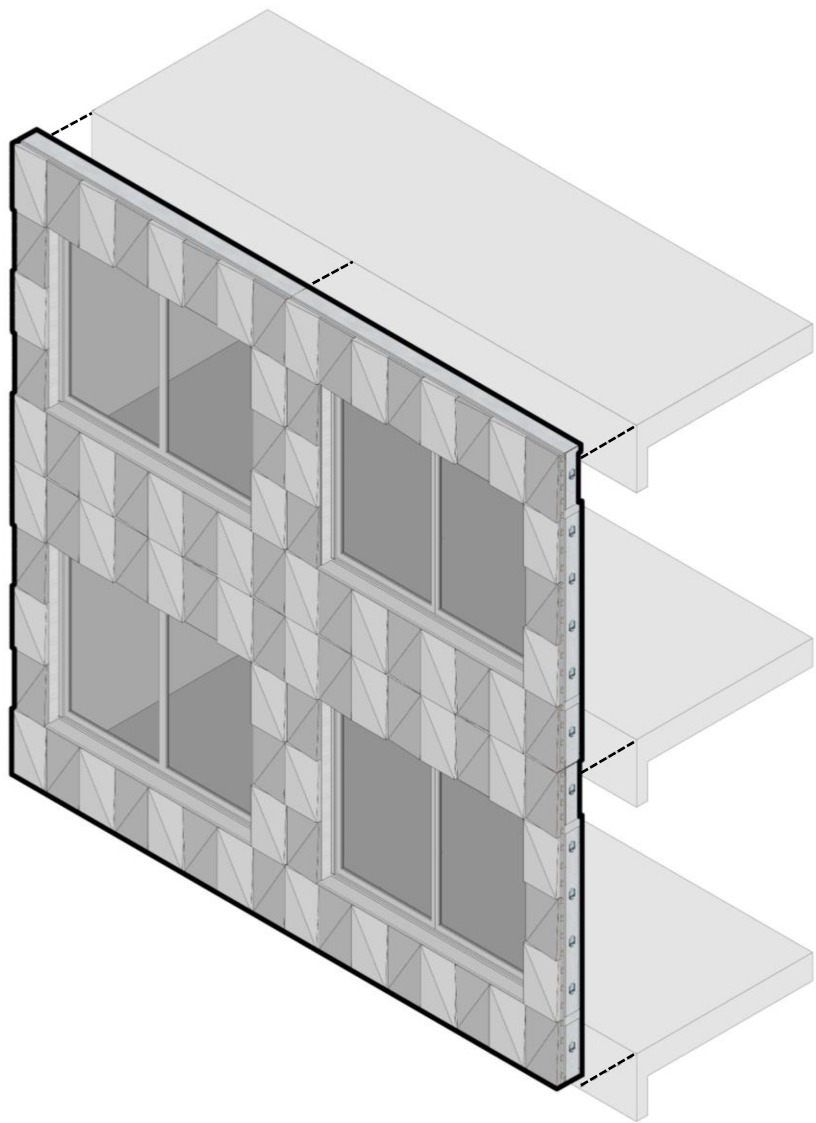


Figure 45 - Isometric view of 'Recycle' option

Option 4: 'Reduce'

This design option is based on the strategy of 'narrowing loops' which means using fewer resources per product. This option is very specific to this building since it has an overall good quality of the existing façade (DGMR, Peutz, 2015). As explained in the previous chapter, it was found that there is no concrete rot observed in the building. There is also no corrosion in the metal components which were used to fix the façade panels on the structure of the building. Such degradation is also not foreseen in the coming two decades. The watertightness of the building is good but not the airtightness. It was also found that the windows and parapet for this building are not connected to hull of the building and can be replaced easily. This study of the quality of the façade led to the decision that it would be possible to replace the window frame, glass and the parapet leaving the rest of the façade intact. This will reduce the amount of new materials being applied on the façade as well as the overall construction demolition waste generated.

In the project, the main layers targeted are the insulation, exterior and interior finishing. The new exterior finishing is kept the same as the existing as they are perfectly cut sizes of stone panels. The new materials used are wood fiber insulation and the structural framing on reused timber.

After the selection of materials based on combination & type of connections, the 'u value' was calculated using the took 'Ubakus'. The total width of the composition was calculated to be 255 mm and the u-value as 0.23 W/m^2K.

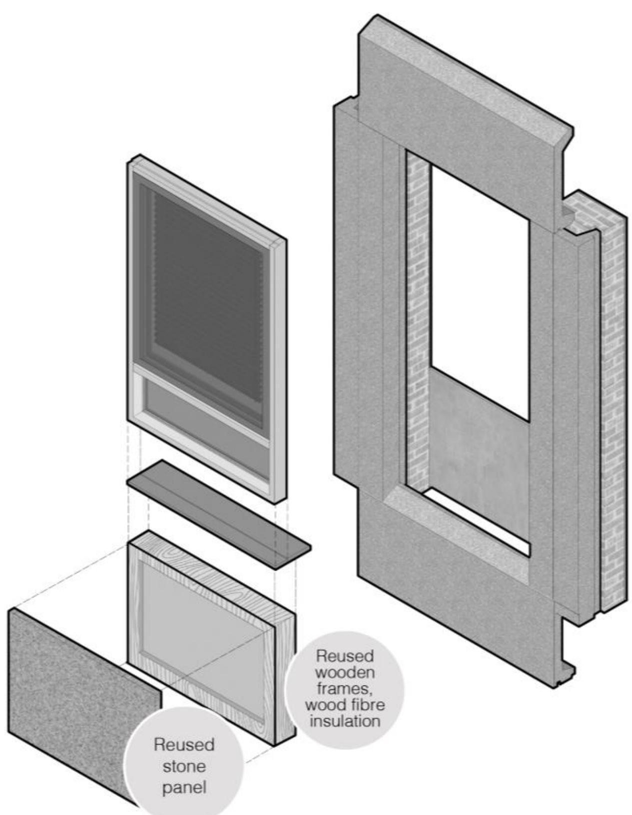


Figure 46 - Exploded view of layers of 'Reduce' option

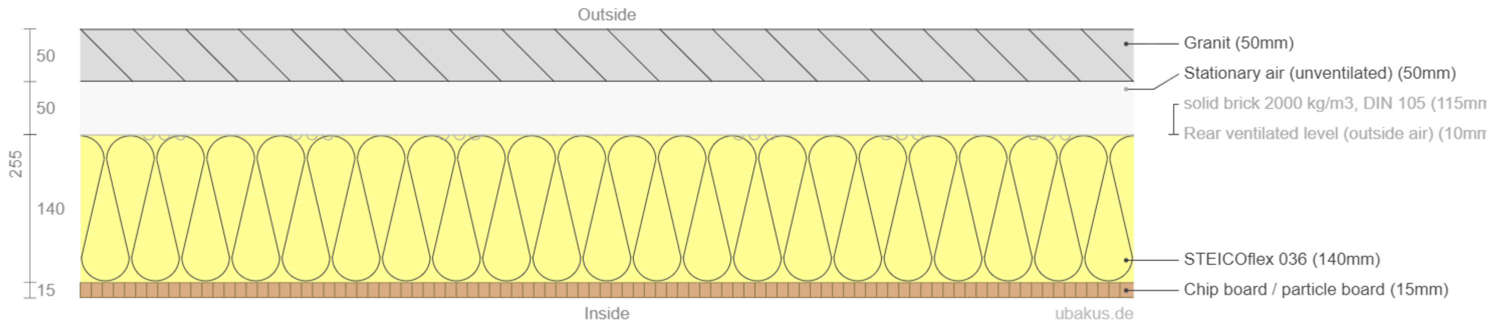


Figure 47 - Schematic section of 'Reduce' option

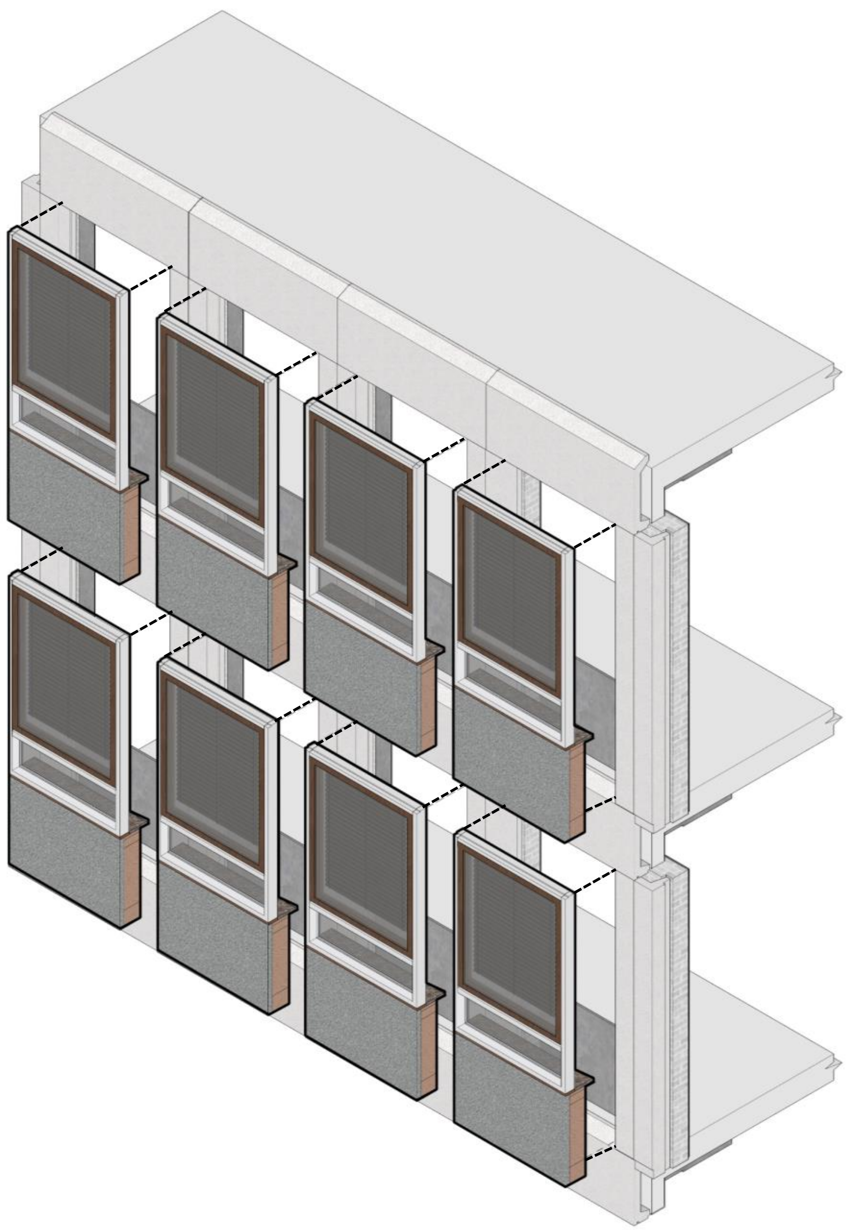
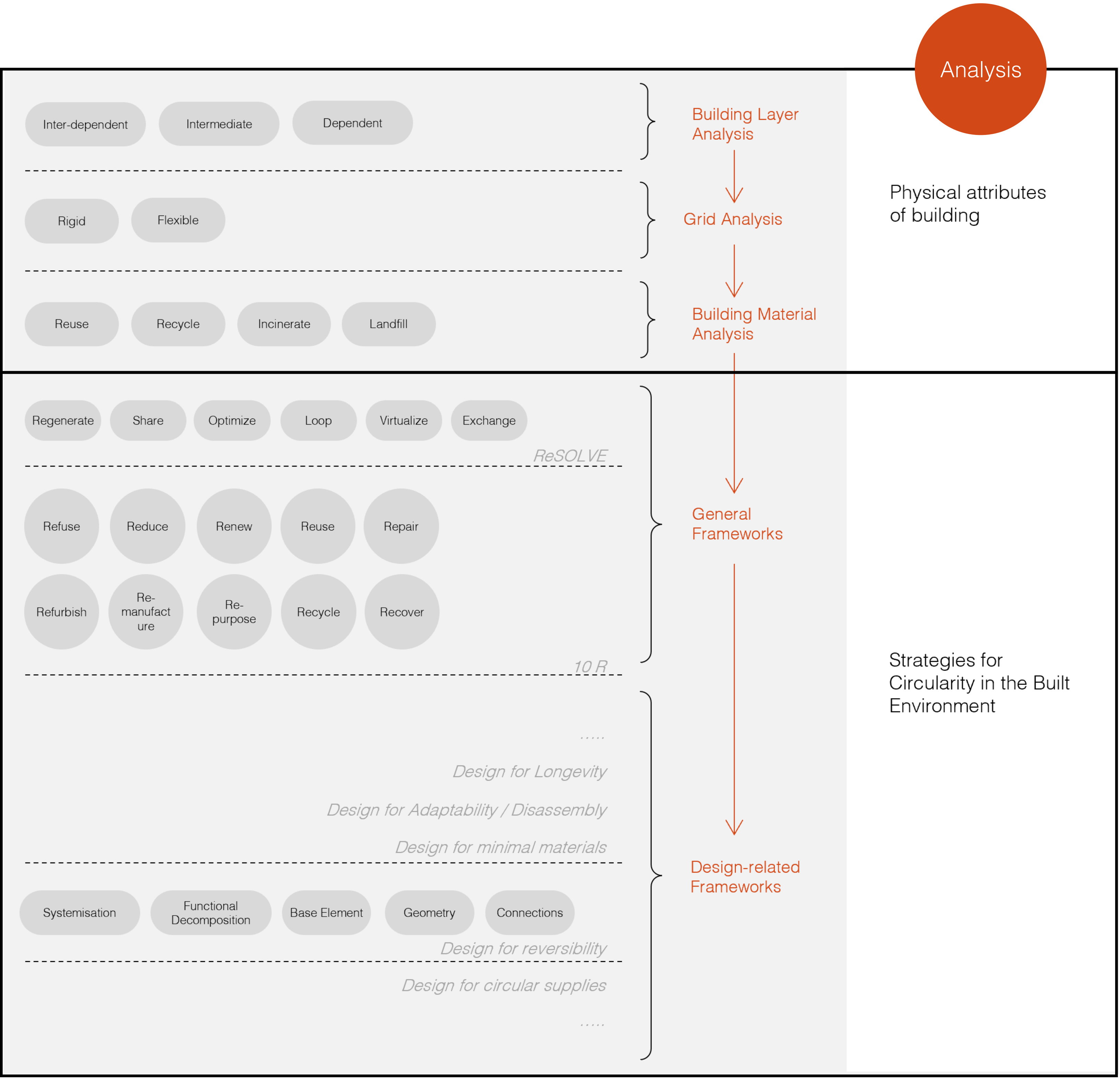


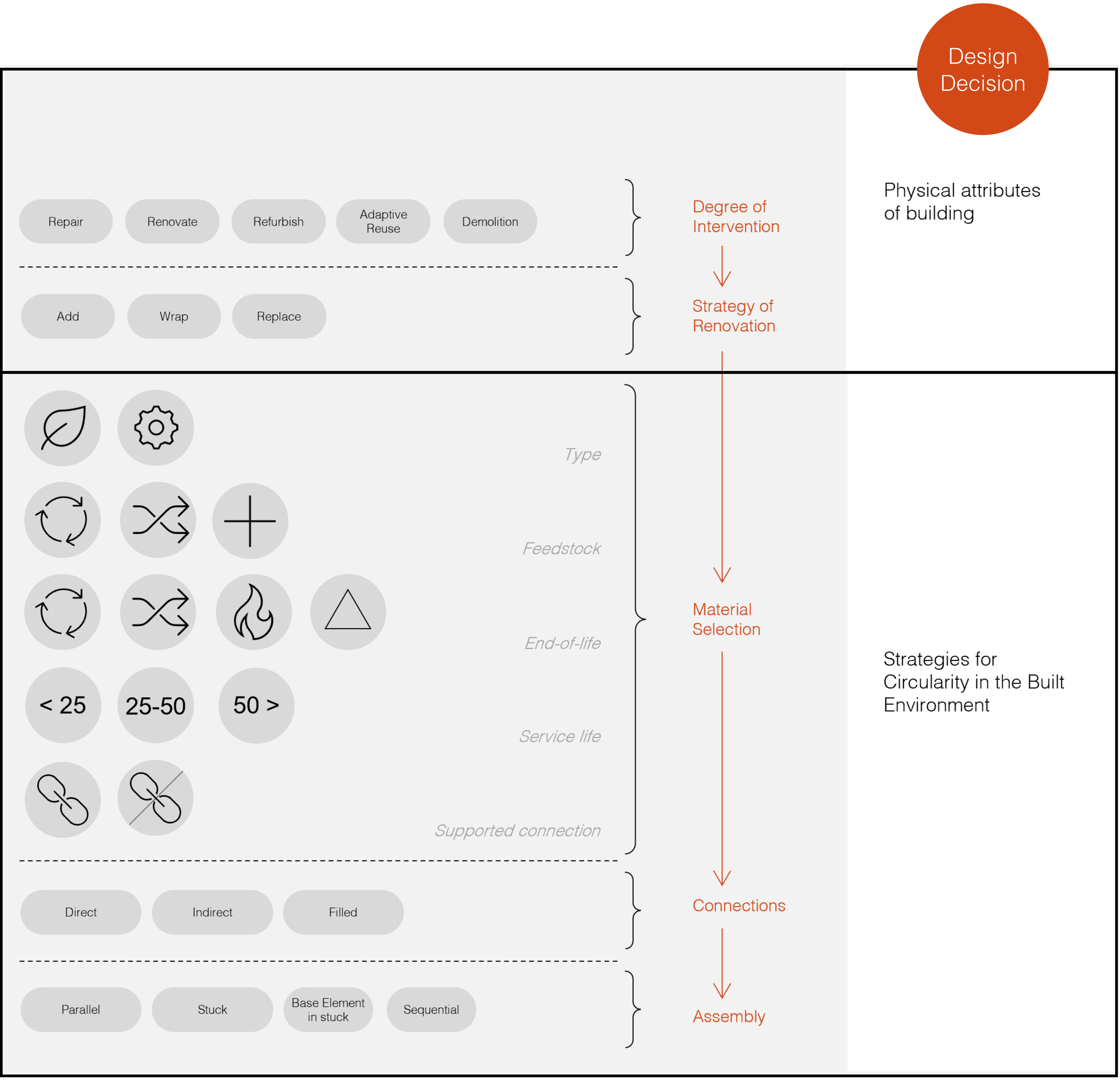
Figure 48 - Isometric view of 'Reduce' option

Design Framework

An overview of the previously completed steps can be seen in the design framework. The framework can be split into two parts (a) analysis of the building itself, and (b) knowledge of circularity and circular design strategies.



The next part relates to all the design decisions. This can also by split into two parts, (a) design decisions directly influenced by the physical attributes of the building – such as the decision to repair, renovate or demolish, and (b) decisions related to the new design / planned intervention.



Quantification of Materials

The next step in the process was calculating the quantities of materials that were used in each option. These were of two types, (a) calculation of the generated construction demolition waste and (b) calculation of new materials used in the options. The quantities were calculated for the main building façade only and not all the wings / extensions of the building.

In the calculation for the generated construction waste, the total waste is calculated based on the volume. It is seen that the part panel generates % less waste by volume.

In the calculation of the quantities of new materials, the approximations made for the design are elaborated in the figure below. These values – in running length, square meter area and total volume are further used in the LCA tool.

Full Panel (Applicable for Option 1, 2, 3)							
Type	Material	Amount	Length [mm]	Height [mm]	Depth [mm]	Volume [cum]	Total Volume [cum]
Exterior Finish	Concrete Cladding	296	1800*	3600*	70	52.69	
Interior Finish	Masonry Wall	296	1800*	3600*	210	226.88	
Window	Window	296	1350	2100	61	-	
Exterior Finish	Stone Cladding	296	1350	820	50	16.38	295.96

Part Panel (Applicable for Option 4)							
Type	Material	Amount	Length [mm]	Height [mm]	Depth [mm]	Volume [cum]	Total Volume [cum]
Exterior Finish	Concrete Cladding	-	-	-	-	0	
Interior Finish	Masonry Wall	296	1350	820	210	68.81	
Window	Window	296	-	-	-	-	
Exterior Finish	Stone Cladding	296	1350	820	50	16.38	137.89

Table 9 - Calculation of quantities of construction and demolition waste generated by volume

Full Panel (Applicable for Option 1, 2, 3)								
Type	Material	Amount	Area [sqm]	Length [m]	Volume (cum)	Total Area [sqm]	Running Length [m]	Volume [cum]
Exterior Finish		148	7.29			1078.9		
Insulation		148	7.29			1078.9		
Interior Finish		148	7.29			1078.9		
Window	DGU timber, AL	148	5.67			839.2		
Structural Frame	Wooden	148	0.015	33.80	0.51			75.04
	AL, SS	148	0.0105	30.30	0.32		4484.40	47.09

Part Panel (Applicable for Option 4)								
Type	Material	Amount	Area [sqm]	Length [m]	Volume (cum)	Total Area [sqm]	Running Length [m]	Volume [cum]
Exterior Finish		296	1.01			299.0	0.00	0.00
Insulation		296	1.01	0.14	0.14	299.0	41.44	41.85
Interior Finish		296	1.01			299.0	0.00	0.00
Window	DGU timber, AL	296	2.835			839.2	0.00	0.00
Structural Frame	Timber	296	0.015	2.10	0.03		621.60	9.32

Table 10 – Calculation of quantities of new materials

Figure 49 – Calculation of material quantities for full panel and part panel

Selection of Assessment tool

The assessment needs to encompass two kinds of factors, (a) circularity related and (b) related to the renovation. The research is primarily about the circularity of the materials but since circularity almost never the primary reason for the renovation, factors such as energy, comfort also play an important role. Within these factors as well, there are some which are quantifiable and some which cannot be quantified. The table below shows the primary criterial selected for the assessment.

Primary Criteria (Circularity)	Fixed Variables
Life Cycle Analysis Approach (Tool – OneClick Life Cycle Approach)	Thermal Performance
Circularity (Tool – OneClick Building Circularity Index)	Energy Performance
Materials Waste Generation (calculations of qty)	Daylight and Views
	Thermal comfort

Table 11 – Variables and fixed criteria in design

The tools selected were Life Cycle Assessment tool and Building Circularity Index. These were utilized through the platform OneClickLCA. The process is explained in detail in the next chapter.

Chapter Summary

In the design framework, the materials were identified as an important starting point as it is directly connected to the appearance of the building and therefore a key aspect for the designer as well as the end user. Parallelly, the preliminary options were first developed to create a standard panel size. Many options were sketched out of which the ones with least variation in sizes were selected. Finally, a material study in detail was conducted and material options were made, based on the layers of the façade. Combining the different materials from the layers, the four design options were created. The 1st design option 'Reclaim' consists of reused and reclaimed materials and products from those same or external sites. The 2nd design option 'Renew' consists of nature-based materials and products that can be returned to the environment. The 3rd design option 'Recycle' consists of moderate and high quality recycled (and recyclable) materials. The 4th design option or 'Reduce' used little material as it targeted a smaller area in the renovation.

06

Assessment

In this chapter, the methods to assess the design for its circularity are discussed. The main tools being used to evaluate the design are the Building Circularity tool and the Life Cycle Assessment (LCA) tool. The software used to conduct this evaluation is OneClickLCA. The tools are first described in detail, then the results of the evaluation are presented. The chapter concludes with the main outcomes of evaluation and the inferred design recommendations.

Life Cycle Assessment

Life cycle assessment is a technique to analyze a product/building's entire life cycle (i.e., raw material extraction, processing, manufacture, distribution, use, disposal) with respect to the environmental impacts and sustainability (Muralikrishna & Manickam, 2017). The life cycle assessment tool encourages early design optimization. With a large database of product EPD's (Environmental Product Declaration), the tool uses indicators or 'impact categories' to measure the performance of the product/building. Some of the commonly used indicators as given below -

- Global warming potential (GWP), [kgCO_2 eq]
  Indicator of potential global warming due to emissions of greenhouse gases to air. This is divided into 3 subcategories based on the emission source: fossil resources, bio-based resources, and land use change.
- Acidification potential (AP), [kgSO_2 eq]
  Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides.
- Eutrophication potential (EP), [kgPO_4 eq]
  Indicator of the enrichment of the water ecosystem with nutritional elements, due to the emission of nitrogen or phosphor containing compounds
- Ozone depletion potential ODP), [kgCFC_{11} eq]
  Indicator of emissions to air that cause the destruction of the stratospheric ozone layer.

Some of the other indicators used are the Formation of ozone in lower stratosphere (POCP), total use of primary energy and Biogenic carbon storage (Bio CO_2). For this project, the GWP and BioCO_2 are the main indicators chosen as it is useful for evaluation in the early design stages.

The calculations for this project are performed with OneClickLCA calculation tool. The software is fully compliant with EN 15978 standard. OneClickLCA has been third party verified by ITB for compliancy with the following LCA standards: EN 15978, ISO 21931–1 and ISO 21929, and data requirements of ISO 14040 and EN 15804 (OneClickLCA, 2021a).

Stages of Life Cycle

OneClickLCA supports calculations of all life cycle stages from Cradle to Grave as defined in EN 15978, including construction products and processes in A1-A5, building use, maintenance, energy and water consumption in B1-B7, end-of-life impacts in C1-C4 and external impacts in module D (OneClick LCA, 2021).

In the assessment following life cycle stages according to EN 15804:2012 were included:

Product stage

- A1: Raw material extraction and processing, processing of secondary material input (recycling, etc)
- A2: Transport to the manufacturer
- A3: Manufacturing

This module accounts for all carbon emissions generated throughout the production of materials until they are ready to be transferred from the factory. They are typically stated by the manufacturer since it might be challenging for a third party to calculate the actual carbon emissions without sufficient internal data.

Transportation from manufacturer to site

- A4: Transport to the building site

The emissions resulting from this module consider the distance between the manufacturer and the site, as well as the form of transportation and the load of the materials. The OneClickLCA program utilized in this investigation calculates these automatically.

<u>Construction and installation emissions</u>

- A5: Installation into the building

Construction activities such as foundation construction and other on-site activities account for most of the emissions calculated in this module. Other emissions from on-site material waste are covered in this module as well. In some cases, product declarations contain this information; in others, assumptions must be made.

<u>Use Stage – Maintenance, Repair and Refurbishment</u>

- B1: Use or application of the installed product
- B2: Maintenance
- B3: Repair
- B4: Replacement
- B5: Refurbishment

This module contains emissions from building material maintenance, repair, and replacement during the building's lifetime. Based on the service life specified in the EPD of products, the analysis frequently considers replacement as the sole choice. Other maintenance-related emissions are rarely listed in product declarations or software, thus they aren't considered and assumed to be similar for different materials.

<u>Use Stage – Operational</u>

- B6: Operational energy use (eg., operation of the heating system and other building-related installed services); ("Life Cycle Stages - OneClickLCA Help Centre")
- B7: Operational water use

The carbon emissions from energy and water usage over the building's lifetime are included in these components. In this module, buildings with efficient designs emit significantly less carbon. These modules are not included in this report since they are irrelevant to embodied carbon emissions from construction materials. For the purpose of evaluation, constant values have been considered.

<u>End of life stage</u>

- C1: De-construction, demolition
- C2: Transport to waste processing
- C3: Waste processing for reuse, recovery and/or recycling
- C4: Disposal

These modules account for emissions from deconstruction or demolition, waste processing, and material disposal at the end of their useful lives. Module C3: Waste processing is directly related to the module D: benefits occurring from the type of disposal. This module depends on the scenario considered by the LCA practitioner or designer. This module must be considered in the assessment because the end-of-life scenario chosen may have an impact on the design details.

<u>Benefits beyond the system boundary</u>

- D: Reuse, recovery and/or recycling potentials, expressed as net impacts and benefits

The end-of-life scenario used in module C3 (recycle/reuse/incineration/landfill) affects the benefits allocated to the material in this module. Currently, this module is only required to be declared separately and not included in the total calculation as it would be impossible to check the future design decisions. This is however reflected in the Building Circularity indicator, as explained further in the report.

Product Stage			Construction Process Stage		Use Stage							End-of-Life Stage				Benefits and Loads beyond the System Boundary		
Raw material supply	Transport	Manufacturing	Transport to building site	Installation into building	Use/application	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal	Reuse	Recovery	Recycling
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D	D	D
x			x	x	x					x	x	x				x		

Cradle to Grave

Cradle to Cradle

Table 12 - Stages in Life Cycle Assessment, (author)

Service Life

Technical service life - In the technical service life, it is assumed that the same type of materials has the same service life setting. The technical service life represents how long materials last in good conditions and this service life setting is the recommended default.

Commercial service life - The commercial service life setting should be selected when doing retail or hotel projects, in which the service life of the interior (and other materials) is shorter. Eg flooring and finishes will be replaced more often with this service life setting.

Product-specific service life - With this service life setting the service life values vary per manufacturer and the settings from the EPD will be used. Choose this service life setting for DGNB, E+C- and MPG calculations.

RICS default service life - With this service life setting the service life values will take the recommended values from the RICS guidance.

https://oneclicklca.zendesk.com/hc/en-us/articles/360015065139

Building Circularity Index

The Building Circularity tool by OneClickLCA allows the tracking, quantification, and optimization of circularity of materials sourced and consumed throughout the life cycle of a building, as well as the circularity at the end of its life cycle. It facilitates the choosing of material sources, selecting types of connections, and finally measuring the circularity of the design. The tool provides a comprehensive image by first, allowing a detailed breakdown by material type. Second, by allowing the selection of material installation practices such as using DfD or DfA. Third, it also allows the selection of an end-of-life processing chain. The weighing factors for each material source and end-of-life scenario, as well as the calculation period can by modified. With the help of the OneClickLCA guide (OneClickLCA, 2021b), these are explained briefly below.

Material Input

Recycled, Renewable or Reused contents

This feature allows one to select the percentage of recycled, renewable, or reused materials in the resource by mass. This does not directly influence the LCA results but is used to document material circularity. Some products have the recycled, renewable, or reused percentage defined with a default value, which can be based either on the product or the type of product. The wastage defines the construction site wastage for the selected materials and is based on default or typical values. This amount can vary based on the construction process, building and design.

Recycled	Renewable	Reused	Wastage	DfD	DfA	EOL Process
None	None	100 %	None	☑	☐	Brick/stone crushed to
69 %	69 %	None	8 %	☑	☐	Landfilling (for inert
87 %	87 %	None	16.7 %	☑	☐	Wood incineration
None	43.322 %	None	None	☑	☐	Glass-containing product
None	100 %	None	16.7 %	☑	☐	Wood incineration

Figure 50 – Material content; OneClickLCA

Design for Disassembly and Design for Adaptability

This feature allows one to select if the material/product assembly is designed for disassembly, for eg, using dismountable fasteners instead of glue or if it allows otherwise non-destructive removal of the material. It also allows one to select if the material/product assembly is designed for adaptability, for eg, if the product used is adaptable to future adaptations of the building.

Recycled	Renewable	Reused	Wastage	DfD	DfA	EOL Process
None	None	100 %	None	☑	☐	Brick/stone crushed to
69 %	69 %	None	8 %	☑	☐	Landfilling (for inert
87 %	87 %	None	16.7 %	☑	☐	Wood incineration
None	43.322 %	None	None	☑	☐	Glass-containing product
None	100 %	None	16.7 %	☑	☐	Wood incineration

Figure 51 – DfD, DfA; OneClickLCA

End of Life Processes

This feature allows the selection of a specific EOL process for a material. By default, they are assigned a specific process depending on their type. These scenarios also vary from material to material.

Recycled	Renewable	Reused	Wastage	DfD	DfA	EOL Process
None	None	100 %	None	☑	☐	Brick/stone crushed to
69 %	69 %	None	8 %	☑	☐	Landfilling (for inert
87 %	87 %	None	16.7 %	☑	☐	Wood incineration
None	43.322 %	None	None	☑	☐	Glass-containing product
None	100 %	None	16.7 %	☑	☐	Wood incineration

Figure 52 – End of life; OneClickLCA

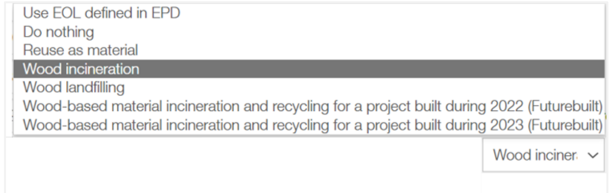


Figure 53 - End of life scenarios, OneClickLCA

Circularity Score Weighing Factors

This feature allows the adjustment to weighting factors for the materials recovered and materials returned. The values set are default but can be modified to suit the requirements.

Materials Recovered

Materials Recovered represents the use of circular materials in the project. It is the sum of the mass shares of virgin, recycled, reused and renewable materials, each multiplied with the corresponding weighing factor defined in this query. For this project, the following weighing factors have been used.

Virgin	0
Renewable	1
Recycled	1
Reused	1

Table 13 - Weighing factors for materials recovered

Materials Returned

Materials Returned represents the end-of-life circular handling of materials that were used in the project. It is the sum of the mass shares of waste undergoing all different waste handling methods, each multiplied with the corresponding weighing factor defined in this query. For this project, the following weighing factors have been used.

Reuse as material	1
Recycling	1
Downcycling	.5
Use as Energy	.5
Disposal	0

Table 14 - Weighing factors for materials returned

Calculation Period

The calculations are reflected based on the service life of the building and can be changed. The period selected for this project is 60 years, and is kept constant for all the design options and variations.

Inputs

General Inputs

The following values were input in the software and were kept constant for all design options and variations.

- Area – 2880 sqm
- Gross internal floor area - 11520 sqm
- What is the consumption of energy? – 200 [kWh/sqm]
- Total energy consumption - 23,04,000 [kWh]
- What should be the calculation period? - 60 years
- What is the service life of my building? - 60 years

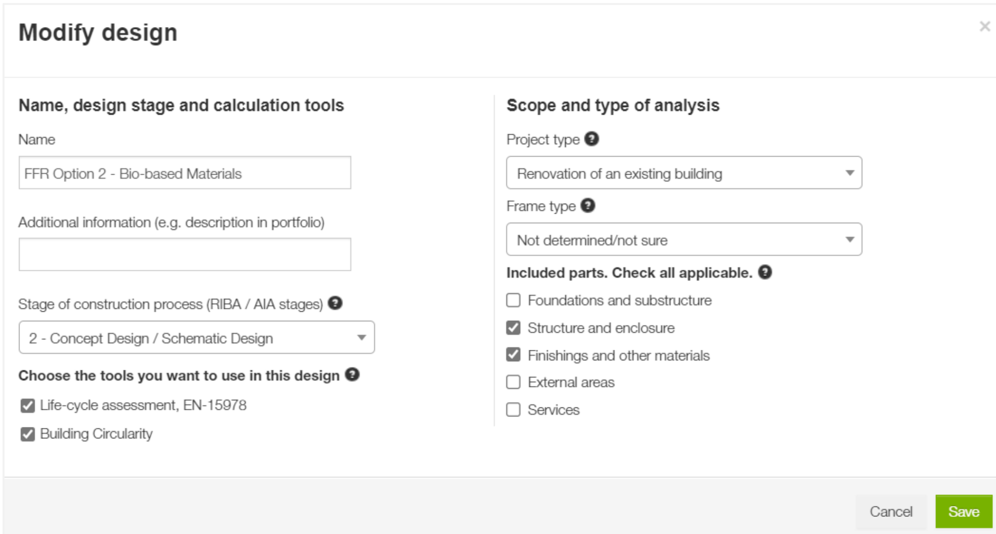


Figure – LCA settlings

Material Inputs

The materials are selected from the OneClickLCA database. If the exact materials were not found as per design – materials with the same characteristics were chosen. The table below gives an overview of the materials selected for each of the design options.

Option	Resource	Quantity	Unit	Thickness	Comment	Service life
Option 1 - Reclaim	Double glazing windows with wooden	839	m2		Window	40
	Planed and strength-graded timber,	75	m3		Structural Element	As building
	Loose fill cellulose insulation, fo	1078	m2	x 200 mm	Insulation 1	As building
	Oriented Strand Board (OSB), 6 -	1078	m2	x 12 mm	Insulation 2	As building
	Bricks from construction waste, 210	215600	kg		Exterior Finishing	As building
	Wooden cladding and decking, pine o	1078	m3		Interior Finishing	As building
Option 2 - Renew	Straw insulation panels for exte	1078	m2		Insulation, main wall	As building
	Double glazing windows with wooden	839	m2		Window	60
	Wooden decking, cladding and pla	1078	m2	x 28 mm	Exterior Cladding	As building
Option 3 - Recycle	Acoustic cladding from textile and	1078	m2		Interior Finish	As building
	Galvanised steel profiles (studs) f	4484	m		Structure	As building
	Recycled textile and fabric insulat	1078	m2	x 150 mm	Insulation 1	As building
	Wood fibre insulation boards, bioge	1078	m2	x 40 mm	Insulation 2	As building
	Aluminum frame window, size: 1.23 x	839	m2		Window	As building
	Ceramic façade cladding, 24 - 30 mm	1078	m2	x 24 mm	Exterior Finish Kerloc	50
Option 0 - Reduce, Reuse	Natural stone massive slabs (EURORO	299	m2	x 90 mm	Exterior Finish	60
	Wood fibre insulation boards, R= 3.	42	m3		Insulation	60
	Medium density fiberboard (MDF), so	299	m2		Interior Finish	60
	Double glazing windows with wooden	839	m2		Windows	40
	Cross Laminated Timber (CLT), Thick	9	m3		Structure	60

miro

Figure 54 - Material Inputs for the 4 Design Options

Results

The four options have been first compared within each other for the LCA and embodied carbon analysis.

- ‘Reduce’ and ‘Renew’ have the lowest embodied carbon impact.
- Circularity increases if the calculation period increases.
- The end-of-life scenario has the greatest impact on the circularity of the material.
- For a calculation period the same as the life of the building, materials with greater service life do not have a significant impact.
- Using reused materials greatly reduced the impact in both Life Cycle Assessment and Building Circularity tools.
- Most products and materials are available within Netherlands and hence really saving on transportation costs and impact.
- Increasing the percentage of reused or recycled content in the materials greatly increases the circularity.

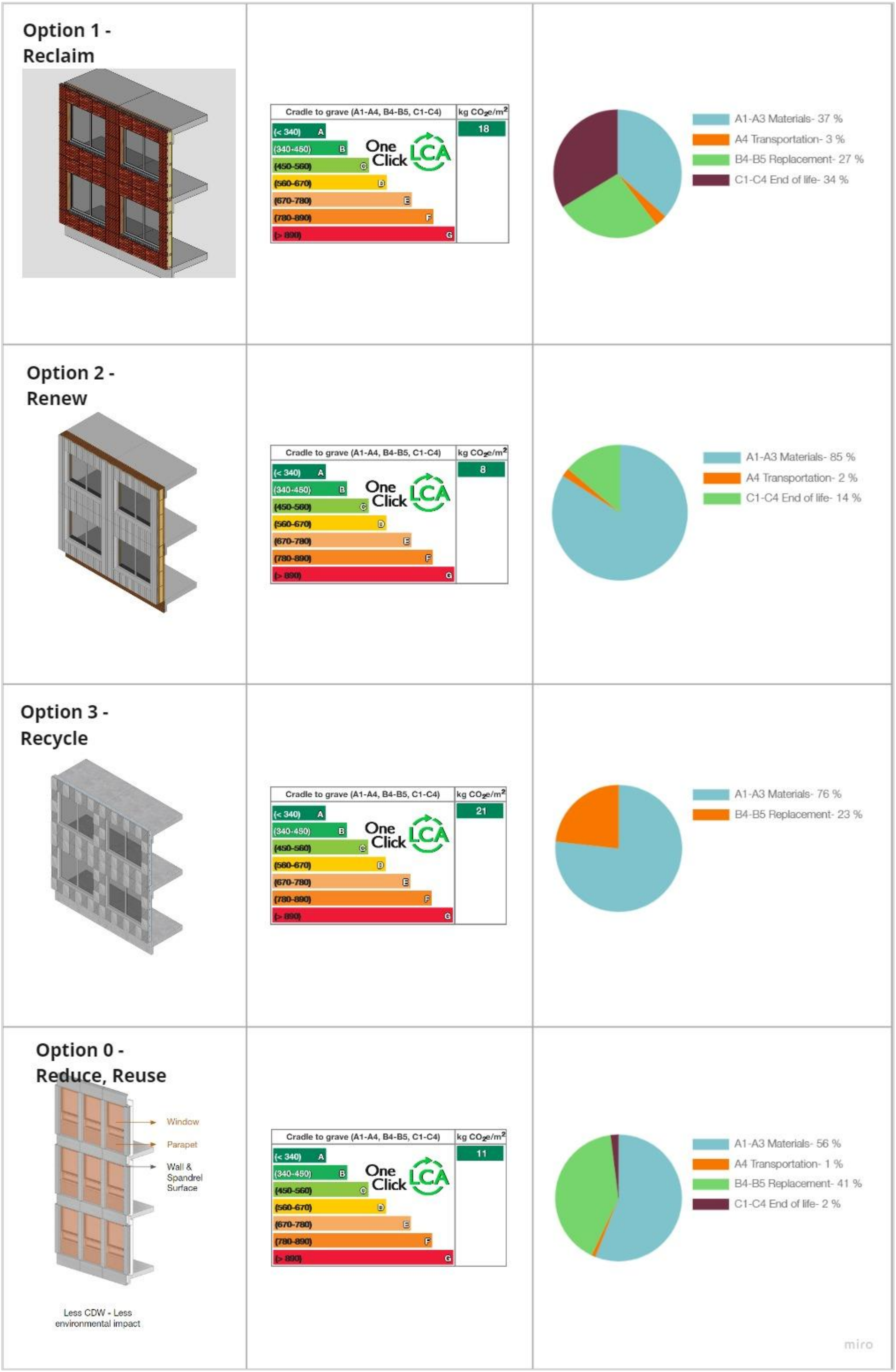
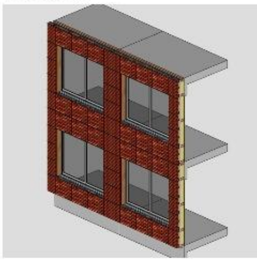
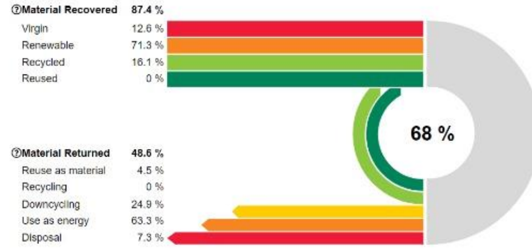


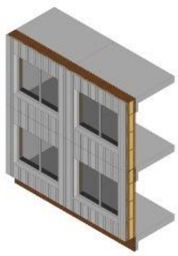
Figure 55 - Embodied Carbon Comparison

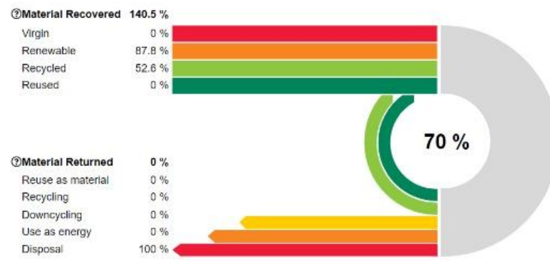
Option 1 - Reclaim



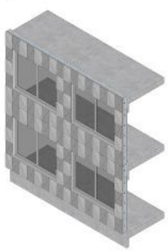


Option 2 - Renew

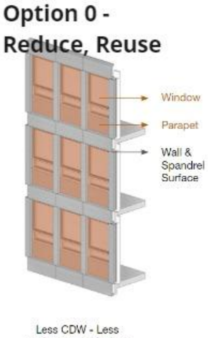




Option 3 - Recycle



Option 0 - Reduce, Reuse



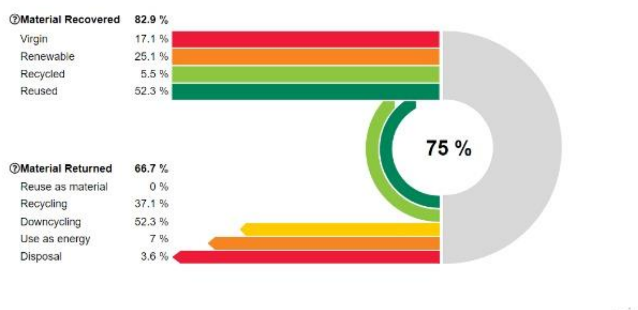


Figure 56 - Building Circularity Comparison

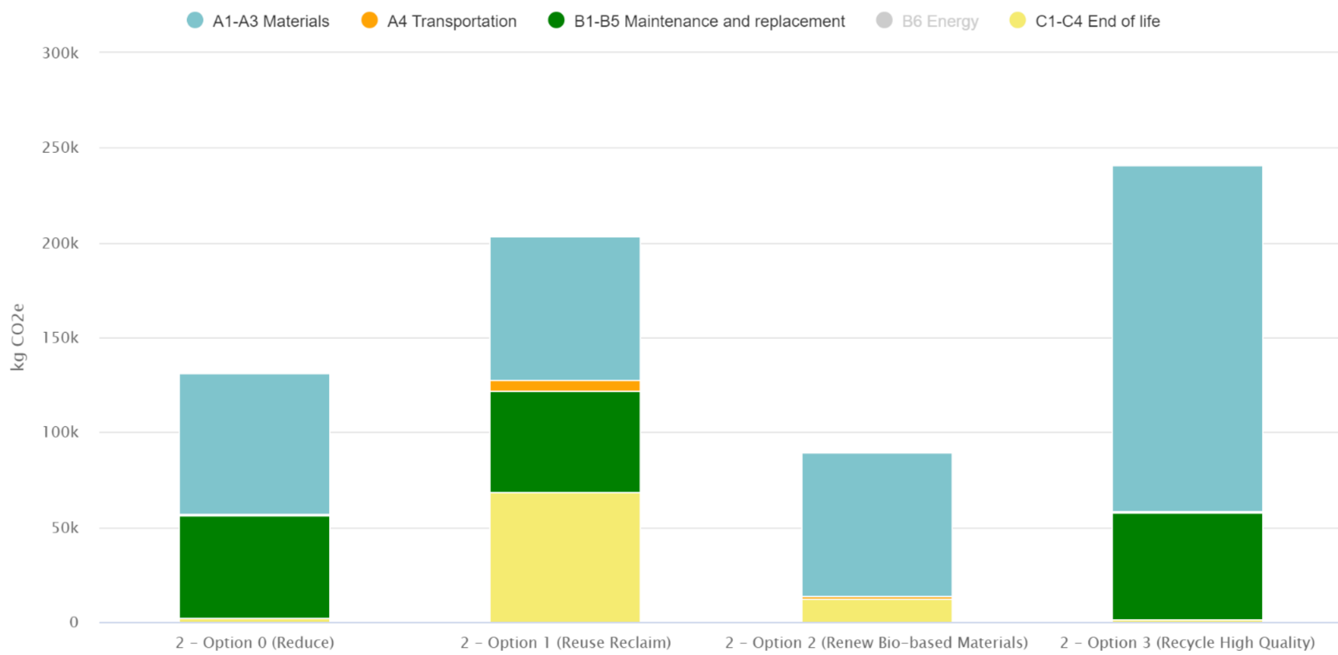


Figure 57 – Embodied carbon overview

Observations

Testing these material selection strategies for façade renovation projects led to the following results.

General/ Embodied Carbon -
It is observed that the change in embodied carbon is only impacted due to the change in material quantities. It is also impacted by rescuing materials because when materials are reused from the current site, the transport distances are reduced, thereby reducing the embodied energy.

General/ Building circularity -
Building circularity is also most impacted when the materials are of the reused category. Then it is impacted by the biobased materials category. It is least impacted when materials are recycled. Using virgin materials reduces the overall building circularity. This indicates that it would be preferable to use a larger percentage of reused of bio-based materials in the design by volume.

The highest impact in the building circularity is caused due to the change in end-of-life scenario. The options have performed better when reuse and recycled have been chosen. However, it must be noted that reuse is prioritized over recycling, recycled is prioritized over down-cycling, and down-cycling is prioritized over incineration.

Selection of Options
This preference is also seen overall, as the reduce and renew options have performed better. Their scores are 75% and 70% respectively. Both the options also allow the repetition of the same panel sizes, which is an advantage for circular construction.

There are however also some limitations of each of these options. In the reduce option, since a large part of the façade is maintained, the new design is required to somewhat match the thickness of the existing façade. Thus, the materials used are high performing (have a less volume for a given thermal performance) and are possibly less circular (than renewable). Whereas in the renew option, while the materials used are bio-based, there is a large amount of construction demolition waste being generated due to the replacement of the entire façade.

To achieve a façade design option which uses bio-based, low impact materials and reduces the amount of construction and demolition waste, the final selected option will be a combination of the Reduce and Renew option.

Chapter Summary

On conducting the LCA and Building Circularity analysis, it was found that out of the four design options, Option 2 – Renew, and Option 4 – Reduce, both have comparatively better results. Option 2 has performed best as it has the lowest carbon impact. Option 0 has a comparatively higher carbon impact but has low generation of construction demolition waste. It is indicative of the fact that the final design option for this case of the Applied Physics building will be a combination of the two options.

07

Design Proposal

This chapter showcases the final option which was selected and then developed to achieve design drawings.

Panel Design

The final design proposal has the following advantages when considering a circular façade design –

- Reduced size variations in façade panels, windows, and other elements, by maintaining a constant panel size (only increasing in modular dimensions).
- Considers the existing building as a material bank and reuses parts of the existing façade through urban mining.
- Uses materials that have a high content of renewable material feedstock.
- Uses materials that allow connections that can be disassembled, thereby allowing the façade panels to be designed for disassembly
- The end-of-life scenario for most of the materials is reuse (stone panels, CLT, timber battens), recycle (straw insulation).
- The dimensions are standard (floor height, window widths, parapet height), thereby reducing wastage during construction of the panels.
- Designed to be a prefabricated and assembled on the site.

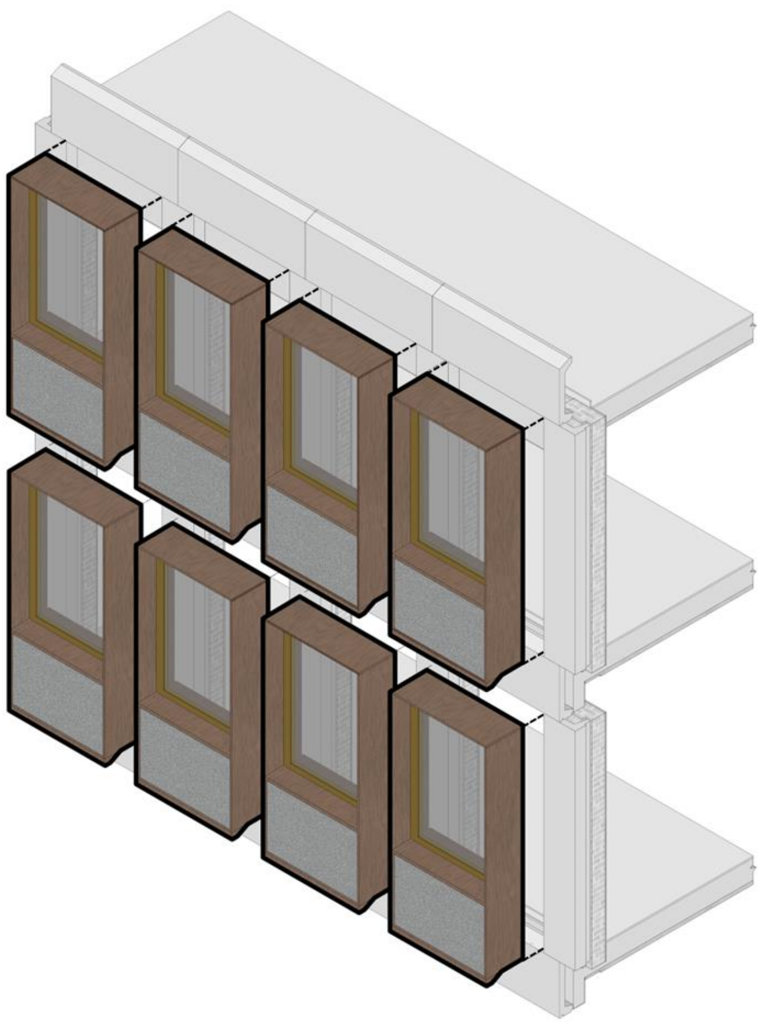


Figure 58 - Isometric view of the final panel, (author)

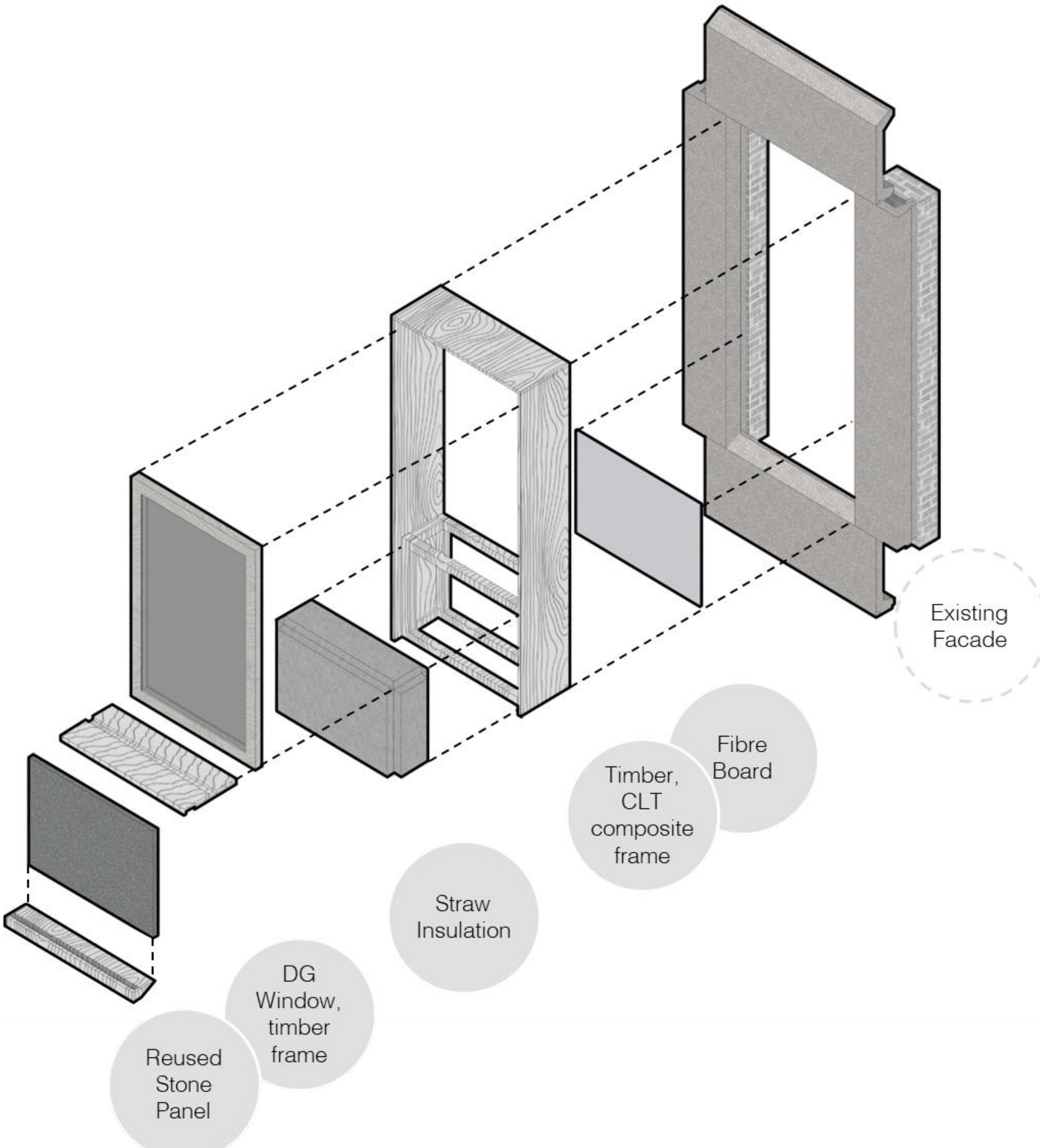


Figure 59 - Layer distribution of the panel in an exploded view, (author)

Technical Details

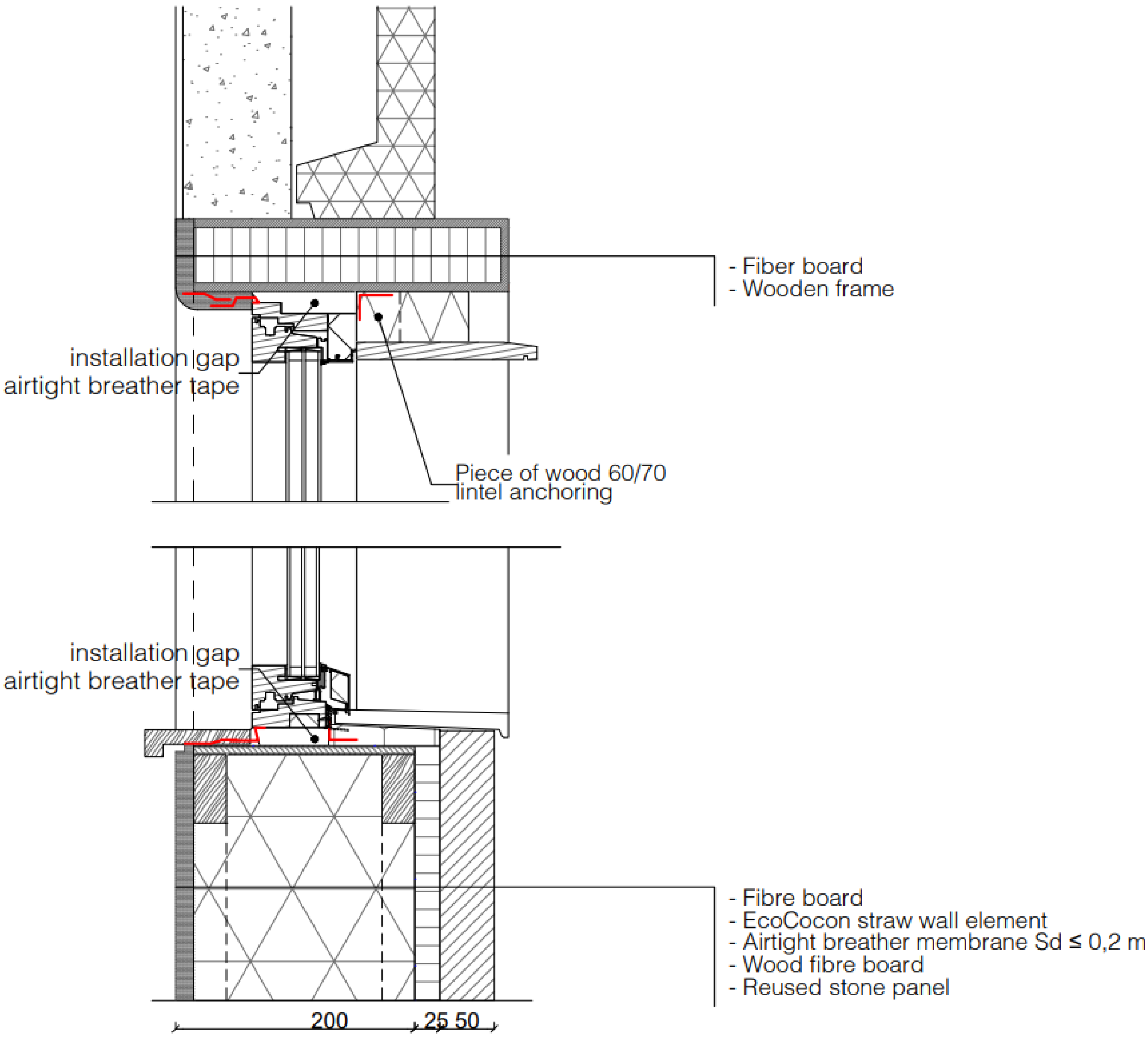
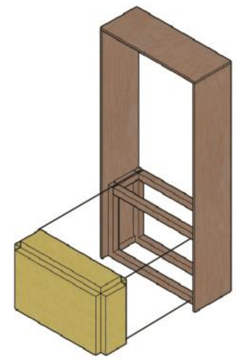


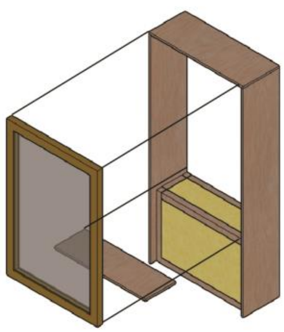
Figure 60 - Vertical section of the panel (representation purposes only), (author)

Figure 61 - Assembly order of the panel, (author), next page

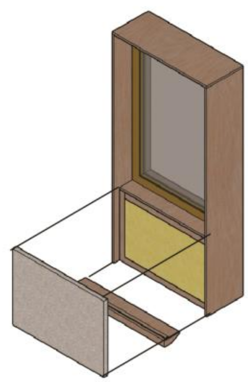
1 Making basic structural frame



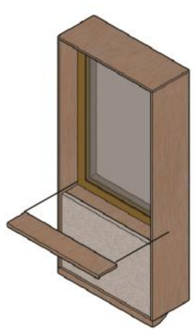
2 Adding insulation



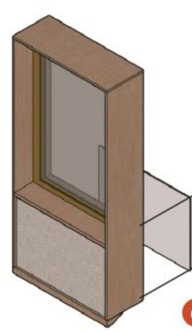
3 Window and sill element



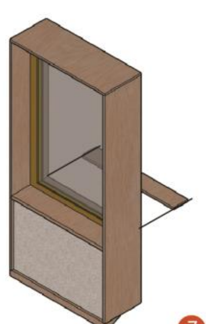
4 Exterior finishing element



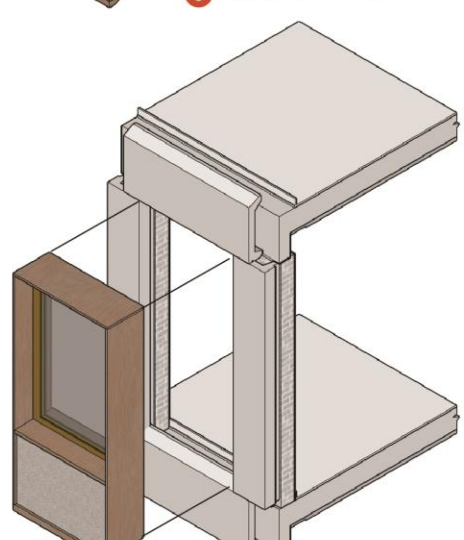
5 Exterior finishing element



6 Interior finishing element



7 Interior finishing element



8 Attaching facade panel to wall

Figure 62 - Rendered view of facade, (author)

08

The Broader Picture

This chapter answers the last sub question. It discusses the influence of a more circular design process on the other stages of the realization process. It also discusses how the third strategy of ‘circular business models’ is connected to the design and the first two strategies. Finally, some changes are observed in the design and planning process when designing for a circular façade.

The Project Realization Process

The focus of the thesis has been on the early design stage of a building renovation project, however the entire project realisation process is much larger. Implementing circularity should be a holistic approach as well, and follow a systems approach. This means encompassing not just the design stage, but also production, manufacture and the business models. The steps that need to be understated to ensure circularity in the façades are elaborated here.

Stages of a Project

The thesis project is based in stage two of the entire process of construction. This is the conceptual design phase. These stages are illustrated in the figure by (RIBA, 2020). The building design process is influenced by many actors as well as strategies. For the ease of defining these tasks and following them efficiently, the RIBA framework defines some guidelines categorized within stages. These stages are now used to comment on the influence of the final design product on other stages and vice versa.

Figure 63 – Life cycle stages of a building

Business models associated with Circular Design

From the literature studied earlier, three groups of applications are identified. These were resource and waste management strategies, reversible design strategies and business models. So far, the design has only dealt with the first two categories since they are directly a part of the core design process. The business models are however important to introduce a circular system – not just a circular design.

The following framework by (Moreno et al., 2016) provides designers with a holistic view on how to approach circular design. It integrates relevant and important business models and circular design strategies. These business model strategies can fall under one of the 5 archetypes. (a) Circular supplies: A business model based on industrial symbiosis in which the residual outputs from one process can be used as feedstock for another process, (b) Resource value: A business model based on recovering the resource value of materials and resources to be used in new forms of value, (c) Product life extension: Those business models that are based on extending the working life of a product, (d) Extending product value: Those business models based on offering product access and retaining ownership to internalize benefits of circular resource productivity, (e) Sharing platforms: Those business models that enable increased utilization rates of products by making possible shared use/access/ownership.

The final design proposal supports the archetypes of Circular supplies and Product value extension.

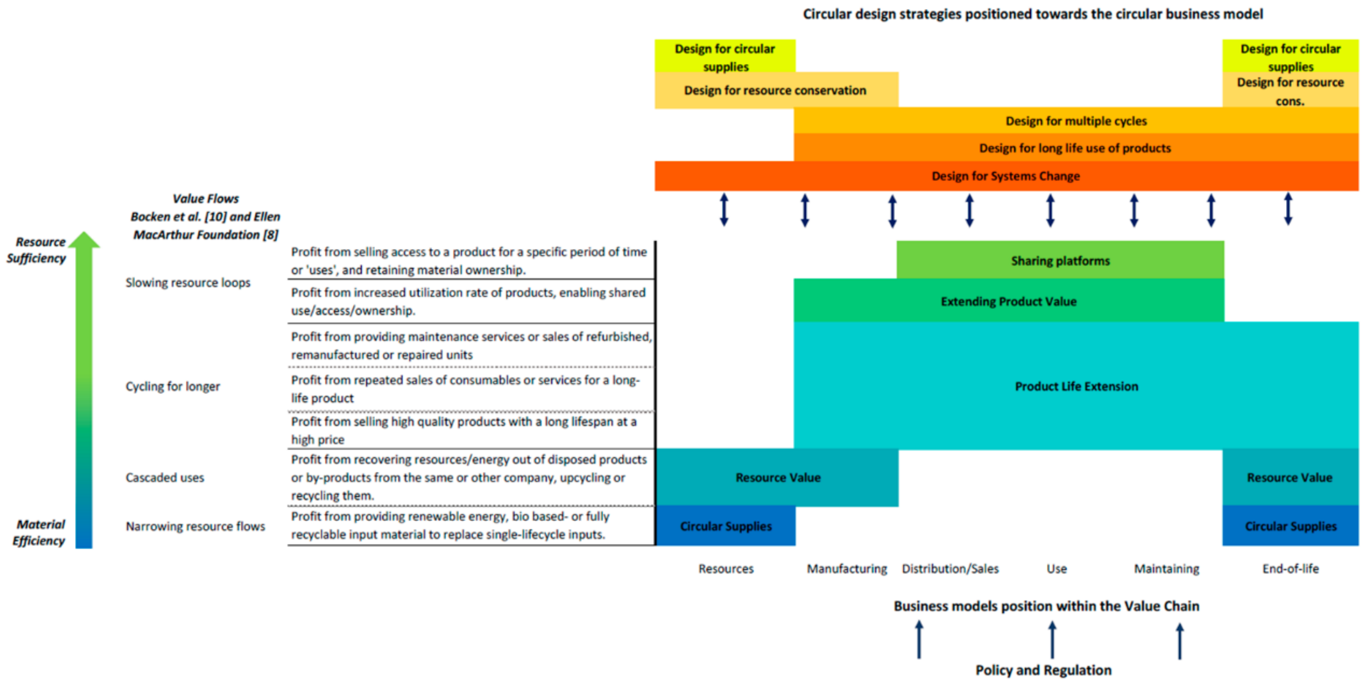


Figure 64 – Relation of circular business models with the design strategies, (Moreno et al., 2016)

Steps for Circular Facade Systems

Strategic Planning

- There is a requirement of necessary demolition audits, so that the designer is well informed before taking design decisions.
- The business models need to be incorporated earlier on in the strategic design phase, and the compatibility with the design should be cross checked beforehand
- There needs to be more research on new materials, so as to facilitate market development and promote acceptance.
- These new circular materials require more testing and evaluation, so that the technical information can be used to develop material databases. This will promote a greater use of these materials in new projects.
- More creative ways of reusing materials should be developed and documented.

Construction & Manufacturing

- The construction of the façade panels should focus on prefabrication.
- There should be a greater use of BIM, and digital twins to document and store information specifically related to the faced – such as the panel information, material information.

Use and EOL

- Generate a building renovation passport and materials passport required during handover
- Developing skills and tools for teams to be able to breakdown and disassemble the facade at end of useful life.

- Design for the end of life it's currently based on imagination, future of material use needs more direction. Therefore, during the technical design phase, a plan for disassembly should also be made and end-of-life of materials specified.

These points are also summarized in the figure below.

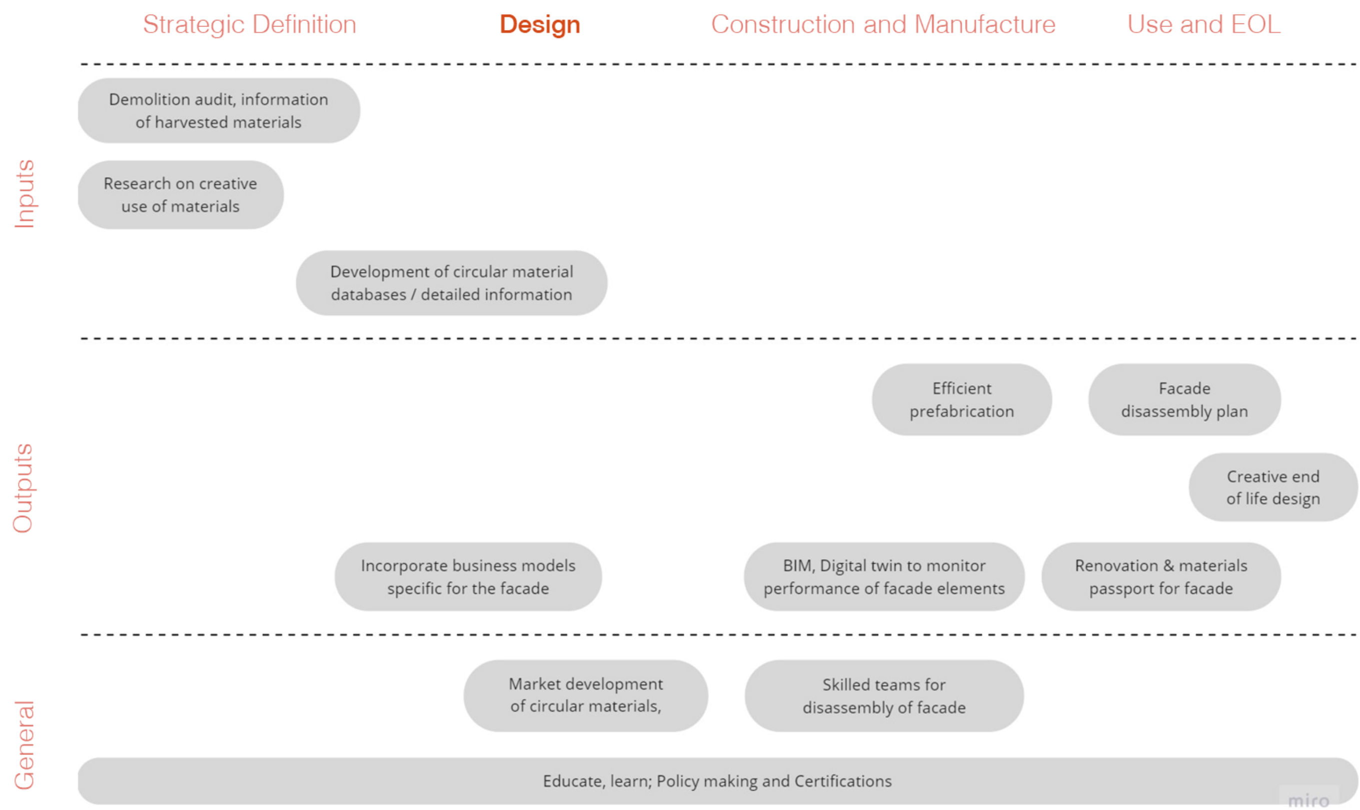


Figure 65 – Steps that influence circularity, (author)

Chapter Summary

This chapter answers the last sub question of the thesis project. It elaborates on the stages of the design process and the business models – all that ensure not just a circular design but also a circular system for a façade. It concludes with steps that can be undertaken to ensure circularity in the whole process of façade design.

09

Conclusion

This final chapter provides an answer to the main research question, based on the answers to sub-questions. This is followed by the recommendations for further research and the reflection.

Answer to Research Questions

Renovation goals for Office buildings in the Netherlands

SQ. 1 - What is the state of the art of non-residential building renovations especially for the building facade, in cold countries like the Netherlands?

In the Netherlands, there is a large percentage of vacant building stock which needs to be renovated soon to match the current requirements of the end user. While the primary motivation cited for various retrofits was aesthetics or image upgrade, an improved thermal envelope and remediation is observed to be undertaken in most projects. Some of the interventions include adding insulation on external walls and installing double or triple glazed windows. These involved sometimes a partial replacement or complete demolition of the façade. It was found that facade design is increasingly becoming more complex since the facades (especially of office buildings) must not only meet aesthetic and functional upgradation, but also meet the current building standards of energy performance thermal acoustic performance daylight and view factors and indoor comfort. The building standards were then referred to understand the required energy performance for public buildings, and the required thermal performance of facades in major renovation projects. It was also found that to efficiently *design* a complex facade system, it can be broken down into further components such as exterior cladding primary facade frame infill elements interior finish etc, whereas to efficiently *construct* a complex facade system, prefabrication has proven to be high performing less time consuming economically efficient and better quality than non-industrialized approaches.

Circular Design Strategies applicable for Circular Façade Design

SQ. 2 - What are the design strategies applicable for circular facade design?

Literature indicates three main strategies, these are resource and waste management, design for reversible buildings, and business models in the construction value chain. Resource and waste management, as the name suggests deals with avoiding resource consumption, reducing materials landfilling, and reusing of building elements. The design for reversibility deals with using disassembly techniques, modular and standard dimensions, impermanent connections, use of materials passports. The business models deal with new service-oriented models such as product service systems, pay per use etc. These strategies are applicable for circular facade design as well as a circular built environment. It is observed from a study of circular building examples, that in practice the use of these strategies is more scattered. Use of circular materials, design for disassembly, Use of product as service, and pay per use have a more widespread use so far.

Design Process to Implement Circularity

SQ. 3 - What is the design process to implement circularity during façade renovation projects?

The design process to implement circularity can be divided into two parts. The first part of the design process is the analysis. Understanding the architecture of the building in question, along with a familiarization with circular design strategies are important initial steps. The second part of the design process is decision making. The first set of decisions are related to the strategy of renovation and the degree of intervention. This is informed through the analysis of the existing building. The second set of decisions are related to the material selection the connections and the assemblies of the actual façade design. This is informed through the analysis of circular design strategies and frameworks. The initial conceptual design options are then evaluated on their circularity potential (for the current thesis project, a lifecycle assessment and building circularity index are identified as appropriate tools for evaluation). The conceptual design which is more suitable is than selected and modified in order to achieve a higher circular potential.

Steps that influence circularity in other stages of the process

SQ.4 - What steps undertaken in the pre-design and post-design stages of the building renovation process influence the circularity of the façade?

A circular design, and planning process is different from a regular process, if one is designing a circular façade 'system'. There is a higher interrelation between the other stages of project realization. The design should be prefabricated when manufactured. the process also demands the generation of a building renovation and materials passport. It is also important to use new technologies such as BIM and digital twins to document and store information. Additionally, there should be development and use of additional tools to improve coordination between the actors. there is also a need to develop the skills and tools to disassemble the facade at the end of its useful life. It is important to create a disassembly plan and create facilities for storage of extracted materials. On the other hand, the design should be informed buy more research and examples of creative ways of reusing materials. There should also be inclusion of new circular materials in product and material databases so that technical information is available readily. There is also a need for development and acceptance of new circular materials (reused or biobased).

Implementation of circularity in facades during the planning and design processes of building renovation projects

RQ. - "How can we implement circularity in façades during the planning and design processes of building renovation projects in the Netherlands."

Planning for a circular façade in renovation projects requires a deeper analysis of the building conditions and the requirements for end users. This process is This is an integral information loop between the manufacturer, researcher and the designer. The planning process also requires a framework that can be easily translated into the design. To facilitate the *design* of circular facades, first, one should not look at the façade component as a whole, but instead break it down into various layers serving their own function. This allows the approach to be systematic during the material selection and connection design process. Second, the façade design should target the minimum resource use and waste generation in order to reduce the overall embodied energy. Third, for the new intervention, materials with a higher volume of reused content should be prioritized first and a higher volume of bio-based content should be prioritized second. Fourth, the materials that are selected should support connections for disassembly and avoid adhesive and chemical connections. Ensuring that these steps are followed early on in the design process will result in a more circular façade.

Discussion

Discussion

The ideal design framework or process does not exist. It varies from building to building, especially in the case of renovations. Renovation projects require a deeper study of the existing building. This cannot be approached with one method fits all. It is therefore important to reflect on the decisions taken throughout the process.

Circularity is a broad yet integrated approach – involving resource management but also business models - and this is reflected in the various frameworks and strategies present in current literature. This proved to be a challenge while selecting a design strategy – which is focused only on the ideal design approach. The case studies and pilot projects presented also incorporated scattered aspects of circular designing.

Since the thesis targeted the early design stage of a façade renovation project, it was important for the technical design to resonate with the architectural design. The 10R could easily translate into material based architectural concepts while also incorporating broad principles of resource management like slowing, narrowing or closing loops. The concepts most noticeable implication on design is primarily related to materials.

To systematically design the façade based on the different material resource, the façade element was further broken down into layers based on the functions. This allowed the selection of materials that satisfied the properties of each layer. The materials of the same layer could also be then compared amongst each other, and their compatibility could be checked with materials of adjacent layers.

This layer wise distribution methodology can also be extended to other elements of a building system or other façade typologies.

The compatibility of materials in the adjacent layers is dependent on their lifespan, end of life scenario, and also their physical properties such as water resistance, combined thicknesses, etc. this further facilitates the design for disassembly and assembly order in the next stage of detailed design.

The information flow that was most significant to the design process was the embodied energy (from a life cycle approach) and the material feedstock composition.

The designer needs to prioritize material selection greatly. This impacts the circularity of the building in a large capacity, especially the % composition of feedstock and specific end of life. This is then followed by the connection.

It was also found through the lifecycle assessment that biobased materials performed better as they had a low overall embodied carbon value. It was important however to confirm if the raw materials for this option were sourced from the Netherlands (or nearby areas) – e.g., It is seen that raw materials for bamboo-based products are being sourced from China, and this impacts the energy in transportation greatly. In the application itself, biobased materials needed a larger thickness to achieve the same thermal performance. This can be overcome by using these materials in combinations.

The compatibility of some materials is debatable - in the cases when the construction thickness would be exceptionally high. or not meet the required thermal resistance. This was particularly seen in the case of biomaterials – where, and additional insulation layer was added as a buffer between the primary insulation and the exterior cladding.

Another material type that performed well was the reclaimed and reused materials. these materials do not require any processing before being used a second time. However, they are very limited in terms of dimensional flexibility, they might not be available in suitable quantities. Visually, they tend to have a worn appearance – which might not suitable for every project. In this case it is preferable to conceal them using exterior layers.

There are also barriers in searching evaluating and fixing reused materials. Reused materials, as observed during the design process, are mostly available for the exterior or the interior finish layer. There were no reused materials available for the layer.

During the process of material selection, it was found that the layers of exterior finish, insulation and interior finish had the most available circular options in the market. The use of these materials was to an also explored in many projects and case studies. The circular materials available for the exterior finish layer were however sometimes lacking EPD's and formally documented physical properties despite having scaled production.

The interior finish layer provides more opportunities to innovatively use in reused materials as it is not exposed to the elements and is subject to lesser deterioration. These however still need to meet acoustic requirements depending on the function of the space.

Limitations

The project overlooks the possibilities of cases where materials extracted from facades can be reused in other building layers such as the structure or flooring.

Information for reclaimed materials comes from (a) online databases of urban mining companies and (b) localized industry knowledge. However, for the case of this project the latter was overlooked.

There are more tools such as the material circularity indicator, etc. to measure and evaluate the circularity of a product.

The research focused only on the Global Warming Potential (GWP) indicator of the building materials, i.e. CO2 equivalents of greenhouse gases. It does not consider other impact indicators such as acidification, eutrophication potential etc.

There is also no cost analysis performed for the façade options, which plays an important role in determining a vision and guide design decisions.

Recommendations for Further Research

- Develop more design-based strategies for the circular built environment
- Execute pilot projects to document the more practical aspects related to the process. Compare and evaluate such circular projects for more insights.
- Research and documentation of the creative reuse of materials at their end of life through a study of existing examples and experimentation.
- Mapping design decisions of circular building design challenges through workshops to form better roadmaps / frameworks.

Additional Remarks

- Research is required on how reused materials being used in innovatively, in architectural projects. The end-of-life scenario is left up to the imagination of the present architect, but there needs to be more concrete scenarios that can thereafter inform the initial design of the products.
- Most countries will have their own solutions, which are local and therefore already more sustainable. It is important for circularity to explore locally manufactured and sourced products.
- Renovation is more complex than a new building design because it considers the EOL of the extracted materials from building at the start of the design process. For new buildings, it is only considered at the end.
- The 'construction' stage also includes demolition, which is usually the last stage for new buildings. This means that a lot of activities that were to happen in the last stage are now happening in between the entire process.
- There are many 'circular materials' such as bio-based and reclaimed materials, which are available in the market. However, there is no standard information available for them / they are not yet a part of databases in tools like Ubakus and OneClickLCA. This poses a challenge for the designers. Moreover, the product EPD's do not yet share different ways that the product can be reused.
- Circular alternatives for materials for different layers – individually - are available in the market but might not be preferred in traditional construction due to larger thicknesses or they might be more expensive.

Conclusion

The building and construction sector is a highly resource and energy consuming sector, and in the past few years there has been a need and motivation for a paradigm shift. However, there are many challenges in a transition to a circular economy. There has been a growing interest towards designing a circular built environment - in research as well as practice. But this transition is not happening on all levels together – for e.g., circular design principles are being followed while designing buildings, but the products used in these buildings might not support circular business models. There is also a lack of a strategic approach for implementation of circular design principles in the built environment.

Building retrofit has been a growing area of research in the past decade. This is because a large building stock is currently outdated in terms of user comfort and energy performance and needs to be renovated to be able to accommodate the needs of the end users and meet safety and energy standards and regulations. It is observed that many the improvement measures in renovation projects are to do with an upgradation of the building envelope.

The thesis recognizes the building facade as a key element of impact - both in building renovation and circular design.

The thesis explores this subject using a research-through-design methodology and takes the help of existing literature, executed examples, interviews with professionals to come up with an answer for the research question and sub questions. The thesis is divided in five phases, which will be conducted sequentially. The first phase is the literature review which will involve a theoretical study of the existing scenario and future perspectives. The main topics of facade renovation and circular design are explored here. The second phase involves the study of a chosen case. The third phase is used to develop a design framework, and thereafter design options for the case study. The fourth phase evaluates the design option. Lastly the fifth phase shares the recommendations and the final design.

Reflection

Approach and Preliminary Results

The research explores how we can implement circularity in the façade in terms of façade design as well as the planning and designing process. The main objective of this research is to (a) Develop a framework for the design, (b) Map the planning and design process, in the early stages of the building renovation design. The research methodology picked for this project is research through design – as the outcomes of the design process would help in generating new knowledge.

The design was preceded with an investigation of existing examples that helped to gain insights into the process. It also helped arrive at the most influential parameters for building circularity which were then taken as design variables for generating design options and then evaluating. The core part of the thesis was to come up with a circular facade concept for a building renovation, while documenting the process - especially the design development and finally selection of strategies. The use of knowledge from existing literature, architectural design methods, and evaluation based on a lifecycle approach give a good direction on design decisions as well as further design possibilities. This approach worked to the extent that I was able to derive common conclusions even while working on the façade design of a single building.

Feedback and Interpretation of Feedback

The feedback given was a good balance of the practical know-how and the academic processes. It was very specific to the subject of circularity and façade design and focused on the smaller details (such as the sourcing of materials) to the larger picture (such as the building sustainability goals). The feedback thus helped to make logical design decisions for a specific building but also draw conclusions which could be applied to a larger building stock. This was suitable for the theme of the research since design involves practice and theory.

Challenges and Further Results

One of the main challenges, however, was to convert the intuitive design decisions into objective recommendations. It was easier to translate research knowledge into design decisions, but more difficult to interpret design outcomes and form guidelines. I also learnt that research and design is a cyclic process. New challenges that are found in the design practice, can be overcome by further and detailed research. And the design can be used to identify research gaps and/or test research principles.

The P4 presentation marks the end of the research through design phase. The final part of the graduation will involve interpreting the recommendations and working further on the design to arrive at an end product - as it would occur in reality.

Relationship between Research and Design

In the case of this graduation project, the research provides a background knowledge of circularity, sustainability, and energy efficiency. All this information is important to make the design functional and appropriate. The design provides a methodology to achieve the goals that are set through literature and provide insights on research gaps that can potentially be explored.

Relationship between Graduation topic, Studio topic, Masters track and Master's program

The topic of *'Circular Façade Systems'* is directly related to the studio topic of 'Circular Building Design', the master track of 'Building Technology' and the master program of 'Architecture, Urbanism and the Built Environment'.

The theme of the master's track *'Building Technology'* focuses on the design and engineering of smart buildings that are comfortable, environmentally intelligent, and sustainable. In this context, the graduation project aims to reduce the material and energy consumption in a resource intensive industry. There is a great need for technical innovations which can transform the built environment and reduce the impact on the natural environment.

The Circular Economy 2050 has had industry-wide impact in the built environment. New architecture that encompasses circular strategies is being realized rapidly. Some of these examples such as the CircL Pavilion (Amsterdam) and Green House (Utrecht) have also incorporated many aspects of circularity which are on a building level as well as an urban level. The graduation topic aims to incorporate this wide range – investigating the detailed technical design as well as the industry/market. Hence, it is also directly related to the master's program of *'Architecture, Urbanism and the Built Environment'*.

Architecture is relatively long lasting; however, it needs to be adapted to meet the changing standards of human comfort, safety regulations, climatic requirements, apart from catering to the different functional needs and occupancies. The building envelope has a high impact on most of these aspects and is explored in detail in the project 'Circular Façade Systems'. Hence the graduation project has a strong connection to the studio topic of *'Circular Building Design*'. It is also related to the studios of 'Façade and Product Design' and 'Climate Design'.

Scientific Relevance and Further Research

Facade design today is a very complex and technical field, and there is a lack of a strategic approach to designing a circular façade. The graduation project – by offering a means to measure and assess circularity in the design stages – is a step towards a more circular built environment. As the process and outcome become more tangible, we can expect an increase in the implementation of such principles, as well as establishment of needful standards / certifications.

Socially, the built environment directly impacts all human beings and touches all aspects of our lives – including health, mental wellbeing, and productivity. The project relies on using technology to make such positive impacts on the built environment.

Professionally, the results of the graduation project can be used by researchers, and designers. The project aims to understand all the aspects related to making of a circular façade – from the market study to the technical design, and hence can be used by further research, project teams in the industry to design and plan for more circular building facades. The project will focus on the renovation aspects but can be applied to for new buildings as well. The project also focusses on non-residential buildings – such as offices, public and commercial buildings, as there is a knowledge gap for them. It will investigate real life examples of circular projects which are executed and relate them to the theoretical literature, so that the construction of such facades and structures can be improved.

Scientifically, this research brings together renovation goals, energy goals, circularity in the built environment. So far, there is a lack of research which has combined all these aspects. The research attempts to find business models, applicable strategies in theoretical research and real-life projects to support this knowledge gap. Also, it does so while looking at literature and case studies of practical applications. Existing frameworks express principled and philosophies but fail to offer specifics on how built environment assets and services must be developed procured designed constructed operated maintained and repurposed. Scientifically, the graduation project will be a step to remedy that.

The example of this graduation project can be used to undertake design process for future renovation projects. It will be insightful to execute and document the real-life application of this process, in order to study the challenges faced. The graduation project can also encourage development of materials and products which can be reused innovatively and recycled.

Ethical Issues

The conceptual design met the measurable standards for indoor thermal comfort, daylight, and views etc., but not the intangible aspects that are otherwise very crucial to good architectural design. Materials, colors, textures can have a positive as well as negative impact on the users and therefore they might or might not be suitable to use in a public building such as an institution or office. Since the building envelope is important as a protective shell to occupants, as well as an expression of the character of a building to everyone else, these factors become very critical design elements. These were however overlooked for the purpose of the research.

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Appendix

Estimation of Quantities

Quantity of New Materials by Layer

Full Panel (Applicable for Option 1, 2, 3)								
Type	Material	Amount	Area [sqm]	Length [m]	Volume (cum)	Total Area [sqm]	Running Length [m]	Volume [cum]
Exterior Finish		148	7.29			1078.9		
Insulation		148	7.29			1078.9		
Interior Finish		148	7.29			1078.9		
Window	DGU timber, AL	148	5.67			839.2		
Structural Frame	Wooden	148	0.015	33.80	0.51			75.04
	AL, SS	148	0.0105	30.30	0.32		4484.40	47.09

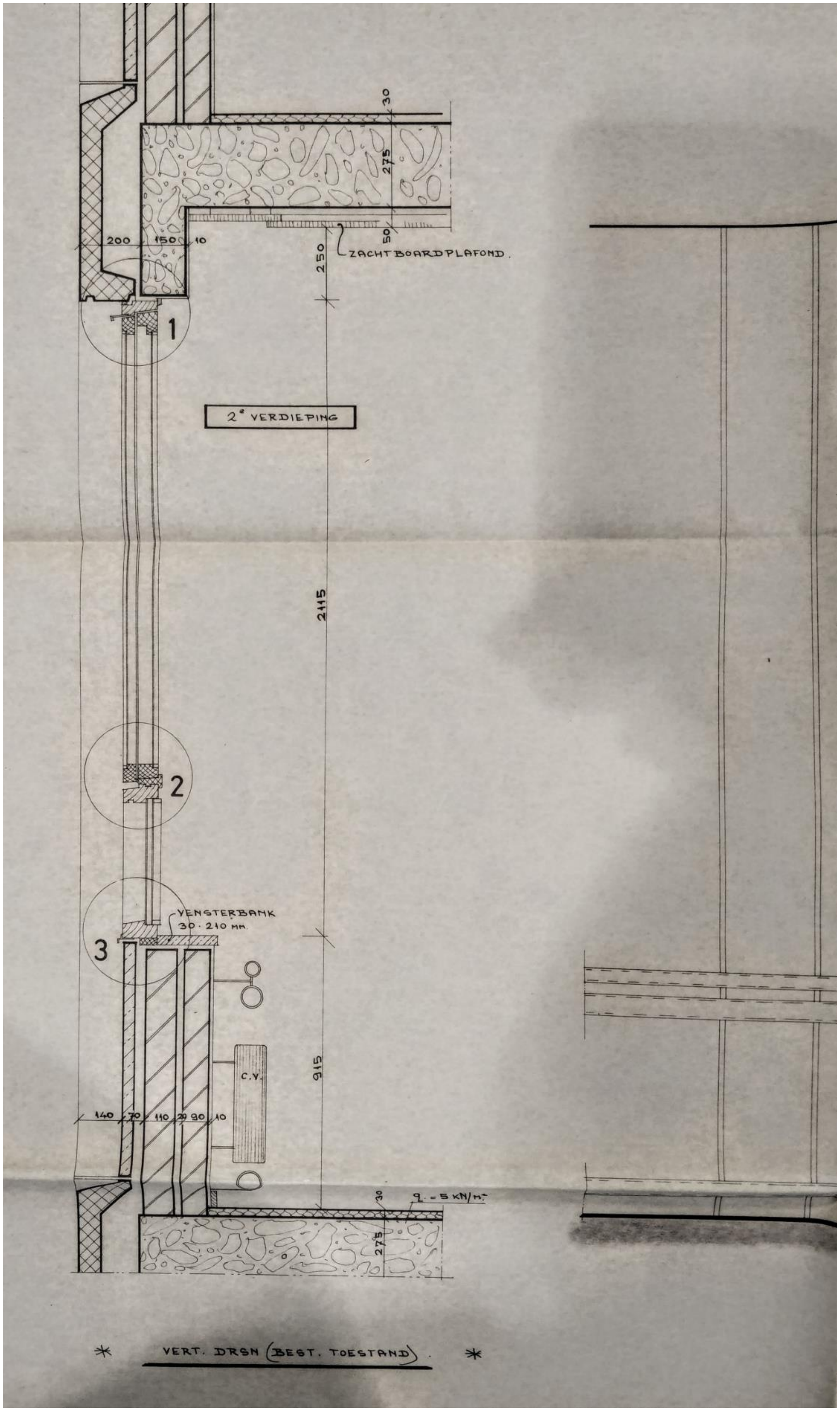
Part Panel (Applicable for Option 4)								
Type	Material	Amount	Area [sqm]	Length [m]	Volume (cum)	Total Area [sqm]	Running Length [m]	Volume [cum]
Exterior Finish		296	1.01			299.0	0.00	0.00
Insulation		296	1.01	0.14	0.14	299.0	41.44	41.85
Interior Finish		296	1.01			299.0	0.00	0.00
Window	DGU timber, AL	296	2.835			839.2	0.00	0.00
Structural Frame	Timber	296	0.015	2.10	0.03		621.60	9.32

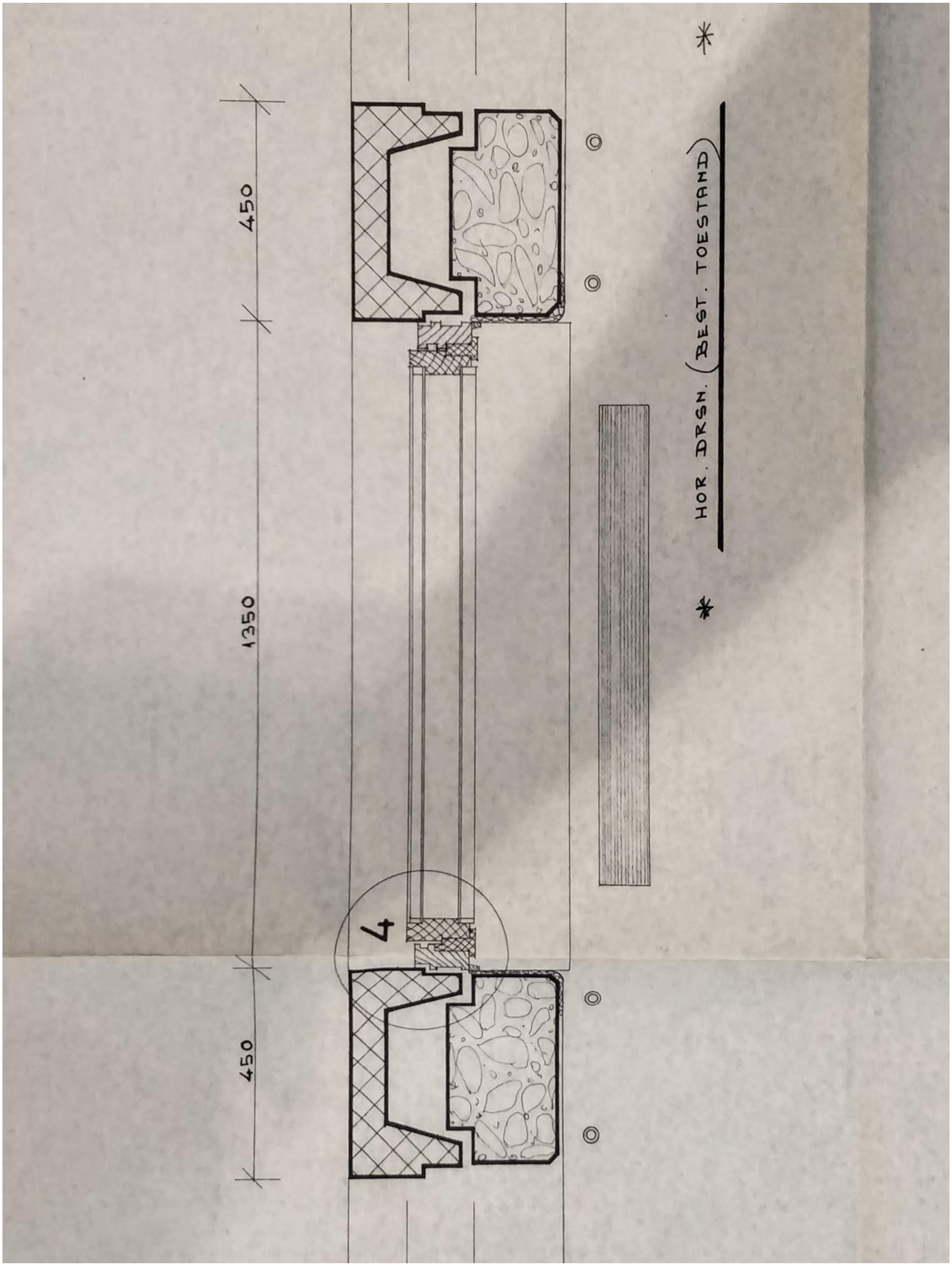
Quantity of Construction Waste by Component

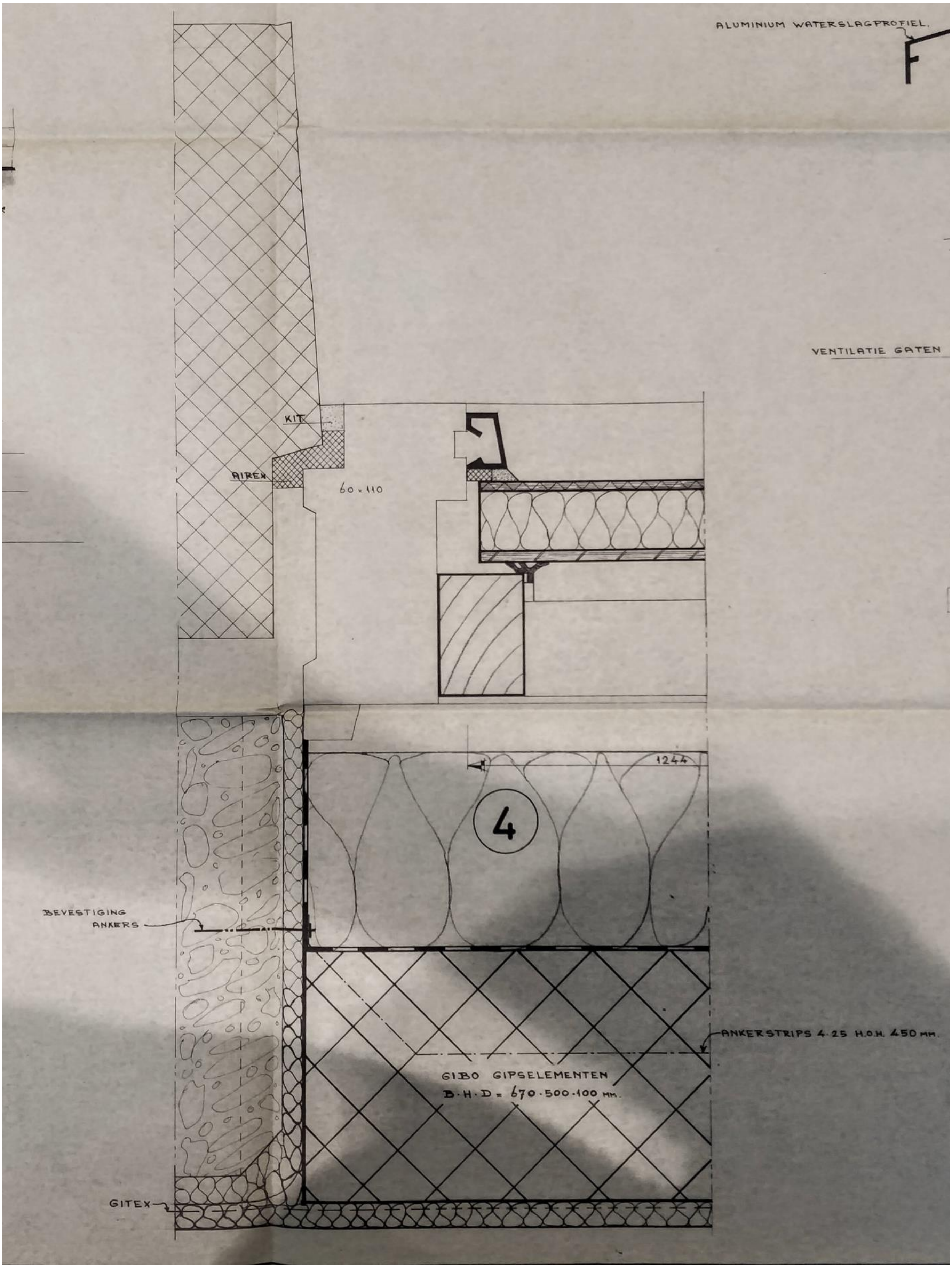
Full Panel (Applicable for Option 1, 2, 3)							
Type	Material	Amount	Length [mm]	Height [mm]	Depth [mm]	Volume [cum]	Total Volume [cum]
Exterior Finish	Concrete Cladding	296	1800*	3600*	70	52.69	
Interior Finish	Masonry Wall	296	1800*	3600*	210	226.88	
Window	Window	296	1350	2100	61	-	
Exterior Finish	Stone Cladding	296	1350	820	50	16.38	295.96

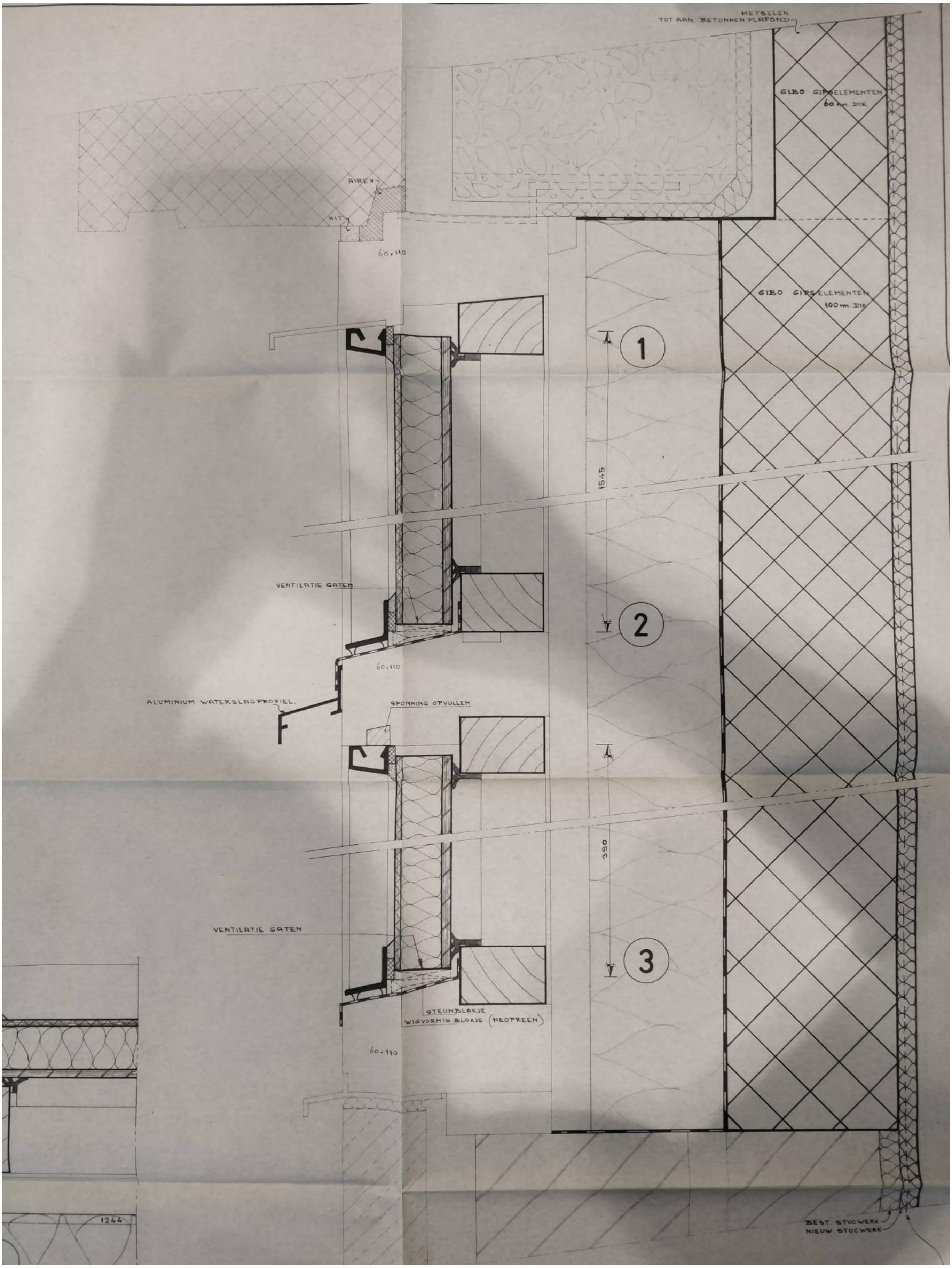
Part Panel (Applicable for Option 4)							
Type	Material	Amount	Length [mm]	Height [mm]	Depth [mm]	Volume [cum]	Total Volume [cum]
Exterior Finish	Concrete Cladding	-	-	-	-	0	
Interior Finish	Masonry Wall	296	1350	820	210	68.81	
Window	Window	296	-	-	-	-	
Exterior Finish	Stone Cladding	296	1350	820	50	16.38	137.89

Façade Drawings, Stadsarchief Delft


30
275
50
200
150
10
ZACHTBOARDPLAFOND.
250
1
2e VERDIEPING
2115
2
VENSTERBANK
30 · 210 MM.
3
915
C.V.
140
70
110
20
90
10
30
q = 5 KN/m²
275
VERT. DRSN (BEST. TOESTAND).


450
1350
450
4
HOR. DRSN. (BEST. TOESTAND)


ALUMINIUM WATERSLAGPROFIEL.
VENTILATIE GATEN
KIT
AIREX
60 x 110
1244
4
BEVESTIGING
ANKERS
ANKERSTRIPS 4.25 H.O.H. 450 MM.
GIBO GIPSELEMENTEN
B.H.D = 670.500.100 MM.
GITEX


METSELEN
TOT AAN BETONNEN PLAFOND
GIBO GIPSELEMENTEN
60 mm. DIK
AIREX
KIT
60.110
GIBO GIPSELEMENTEN
100 mm. DIK
1
1545
VENTILATIE GATEN
2
60.110
ALUMINIUM WATERSLAGPROFIEL
SPONNING OPVULLEN
390
VENTILATIE GATEN
3
STEUNBLOKJE
WIGVORMIG BLOKJE (NEOPREEN)
60.110
1244
BEST. STUCWERK
NIEUW STUCWERK

Design Option 1 – Reclaim

Ubakus Results

Thermal protection

U = 0,21 W/(m²K)

Interior insulation: No requirement*

excellent insufficient

Moisture proofing

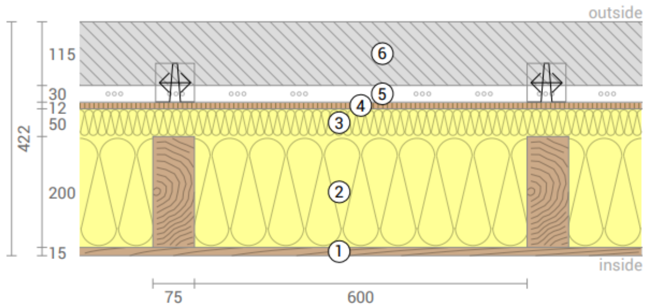
Drying reserve: 667 g/m²a
No condensate

excellent insufficient

Heat protection

Temperature amplitude damping: 75
phase shift: 23,3 h
Thermal capacity inside: 61 kJ/m²K

excellent insufficient



(1) Common beech (15 mm)
(2) Cork (200 mm)
(3) AGATON LEHM Schilfrohrmatte (50 mm)
(4) AGEPAN OSB 4 PUR (12 mm)
(5) Outside air (30 mm)
(6) solid brick 1400 kg/m3, DIN 105 (115 mm)

<-> Layers marked by arrows are perpendicular to the main axis.

U-Value calculation according to DIN EN ISO 6946

#	Material	Dicke [cm]	λ [W/mK]	R [m²K/W]
	Thermal contact resistance inside (Rsi)			0,130
1	Common beech	1,50	0,160	0,094
2	Cork	20,00	0,050	4,000
	Spruce (11%)	20,00	0,130	1,538
3	AGATON LEHM Schilfrohrmatte	5,00	0,055	0,909
4	AGEPAN OSB 4 PUR	1,20	0,130	0,092
5	Outside air	3,00		0,130
	trapezoidal sheet (Width: 7 cm)	7,00	10,000	0,007
6	solid brick 1400 kg/m3, DIN 105	11,50	0,580	0,198
	Thermal contact resistance outside (Rse)			0,040

Thermal contact resistances have been taken from DIN 6946 Table 7.
Rsi: heat flow direction horizontally
Rse: heat flow direction horizontally, outside: Direct contact to outside air

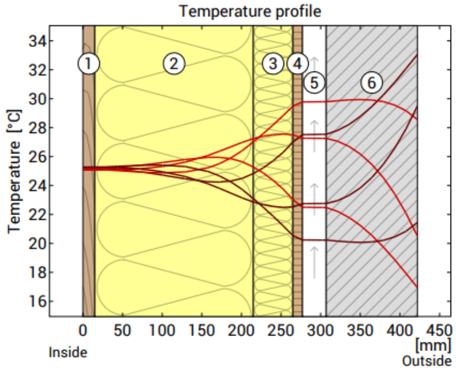
Thermal transfer resistances of resting air layers were calculated as follows:
Layer 5.1: Thickness 3 cm, Width ∞, DIN EN ISO 6946 Table 8, heat flow direction horizontally

DIN 6946 should not be used because the component contains room or outside air.

Heat transfer coefficient from finite-elements method **U = 0,208 W/(m²K)**
numerical uncertainty ~0,087%

Note: The U value was calculated according to DIN 10211. However, the calculation according to DIN 10211 has not yet been sufficiently tested and may contain errors. The alternative, DIN 6946, must not be used for this component.

Temperature profile



Temperature at 3pm, 11am and 7am
Temperature at 7pm, 11pm and 3am

(1) Common beech (15 mm)
(2) Cork (200 mm)
(3) AGATON LEHM Schilfrohrmatte (50 mm)
(4) AGEPAN OSB 4 PUR (12 mm)
(5) Outside air (30 mm)
(6) solid brick 1400 kg/m3, DIN 105 (115 mm)

Life Cycle Assessment Inputs

Code	Product	Layer	Quantity	Transport (1st Leg)	Service Life	Reused Material
DGW	Double glazing windows with wooden frame, 30.7 kg/m2, 1.4 W/m2K, biogenic CO2 not subtracted (for CML), FDES collective utilisable par toute entreprise qui produit en France des fenêtres et portes fenêtres, double vitrage acoustique ou standard, en bois tropicaux. (INSTITUT TECHNOLOGIQUE FCBA)	Windows	839 sqm	320	40	No
PST	Planed and strength-graded timber, pine or spruce, 460 kg/m3, planed timber: thickness 15-89 mm, moisture 8-15 ± 2%, strength-graded timber: thickness 34-89 mm, moisture 15-18 ± 2% (Stora Enso)	Structural Frame	75 cum	220	120	Yes
WCD	Wooden cladding and decking, pine or spruce, 445 kg/m3, 7-29 mm, 8-18%, moisture content (Stora Enso)	Interior Finish	1078 sqm	220	120	Yes
OSB	Oriented Strand Board (OSB), 6 - 40 x 590 - 1250 x 1840 - 6250 mm, 600 kg/m3, AGEPAN (Sonae Indústria)	Insulation	1078 sqm	340	120	No
LCI	Loose fill cellulose insulation, for wall application, L = 0.045 W/mK, R= 1.11 m2K/W, 50 mm, 3.25 kg/m2, 65 kg/m3	Insulation	1078 sqm	350	120	No
BCW	Bricks from construction waste, 210mm x 100mm x 50mm, 215mm x 102.5mm x 65mm, 228mm x 108mm x 55mm, 490/390/290mm x 90mm x 40mm, Caramel (StoneCycling)	Exterior Finish	215600 kg	60	120	Yes

Building Circularity Inputs & Results

Code	Recycle %	Renewable%	Reused %	Wastage %	DfD, DfA	EOL Process	Score
DGW	0	43.322	0	0	YES	Use EOL defined in EPD	68
PST	0	99	0	17.9	yes	Reuse as material	
LCI	69	69	0	8	yes	Landfilling	
OSB	0	98	0	16.7	yes	Wood incineration	
BCW	60	0	0	5	yes	Brick/stone crushed	
WCD	0	100	0	17.9	yes	Wood incineration	
DGW	0	43.322	0	0	yes	Use EOL defined in EPD	85
PST	0	99	0	17.9	yes	Reuse as material	
LCI	69	69	0	8	yes	Landfilling	
OSB	0	98	0	16.7	yes	Wood incineration	
BCW	60	0		5	yes	Brick/stone crushed	
WCD	0	100	0	17.9	yes	Wood incineration	
DGW	0	43.322	0	0	Yes	Use EOL defined in EPD	110
PST	0	99	0	17.9	yes	Reuse as material	
LCI	69	69		8	yes	Landfilling	
OSB	0	98		16.7	yes	Wood incineration	
BCW	60	0	0	5	yes	Brick/stone crushed	
WCD	0	100	0	17.9	yes	Wood incineration	
DGW	0	43.322	0	0	Yes	Use EOL defined in EPD	112
PST	0	99	0	17.9	yes	Reuse as material	
LCI	69	69	0	8	yes	Landfilling	
OSB	0	98	0	16.7	yes	Wood incineration	
BCW	60	0	100	5	yes	Brick/stone crushed	
WCD	0	100	100	17.9	yes	Wood incineration	

Design Option 2 – Renew

Ubakus Results

Thermal protection

U = 0,24 W/(m²K)

GEG 2020 Bestand*: U<0,24 W/(m²K)

excellent — insufficient

Moisture proofing

Drying reserve: 1432 g/m²a

No condensate

excellent — insufficient

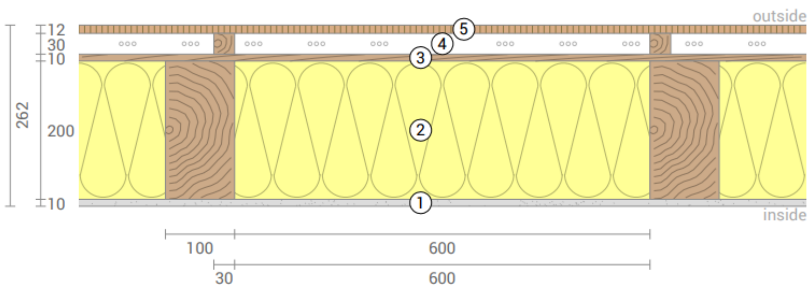
Heat protection

Temperature amplitude damping: 22

phase shift: 13,0 h

Thermal capacity inside: 48 kJ/m²K

excellent — insufficient



① Lehm-Oberputz (10 mm)
② PAVATEX PAVATHERM (200 mm)
③ Cross Laminated Timber (10 mm)
④ Rear ventilated level (30 mm)
⑤ Fundermax Max Compact Exterior (12 mm)

U-Value calculation according to DIN EN ISO 6946

#	Material	Dicke [cm]	λ [W/mK]	R [m²K/W]
	Thermal contact resistance inside (Rsi)			0,130
1	Lehm-Oberputz	1,00	0,910	0,011
2	PAVATEX PAVATHERM	20,00	0,040	5,000
	Cross Laminated Timber (14%)	20,00	0,130	1,538
3	Cross Laminated Timber	1,00	0,130	0,077
	Thermal contact resistance outside (Rse)			0,130

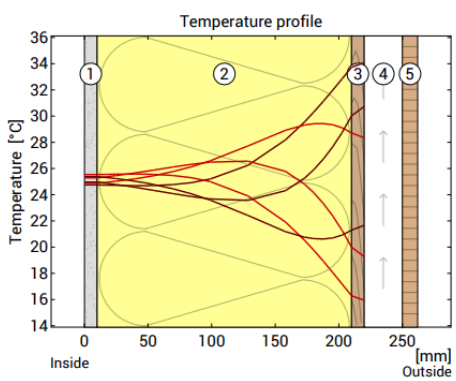
Thermal contact resistances have been taken from DIN 6946 Table 7.
Rsi: heat flow direction horizontally
Rse: heat flow direction horizontally, outside: Ventilation level

Upper limit of thermal resistance $R_{tot;upper}$ = 4,237 m²K/W.
Lower limit of thermal resistance $R_{tot;lower}$ = 4,132 m²K/W.
Check applicability: $R_{tot;upper}$ / $R_{tot;lower}$ = 1,026 (maximum allowed: 1,5)

The procedure may be used.

Thermal resistance $R_{tot} = (R_{tot;upper} + R_{tot;lower})/2$ = 4,184 m²K/W
Estimated maximum relative uncertainty according to section 6.7.2.5: 1,3%

Heat transfer coefficient U = $1/R_{tot}$ = **0,24 W/(m²K)**



Temperature at 3pm, 11am and 7am
Temperature at 7pm, 11pm and 3am

① Lehm-Oberputz (10 mm)
② PAVATEX PAVATHERM (200 mm)
③ Cross Laminated Timber (10 mm)
④ Rear ventilated level (30 mm)
⑤ Fundermax Max Compact Exterior (12 mm)

Life Cycle Assessment Inputs

Code	Product	Layer	Quantity	Transport (1st Leg)	Service Life	Reused Material
SIP	Straw insulation panels for exterior walls, L = 0.0493 W/mK, R=8.1 m2k/W, 400 mm, 66.19 kg/m2, Lambda=0.0493 W/(m.K) (EcoCocon)	1078 sqm	Interior Finish, Insulation	350	60	No
DGW	Double glazing windows with wooden frame, 30.7 kg/m2, 1.4 W/m2K, biogenic CO_2 not subtracted (for CML), FDES collective utilisable par toute entreprise qui produit en France des fenêtres et portes fenêtres, double vitrage acoustique ou standard, en bois tropicaux. (INSTITUT TECHNOLOGIQUE FCBA)	839 sqm	Windows	380	60	No
WCD	Wooden decking, cladding and planed timber for joinery applications, 755kg/m3, Moistr. 3-5%, Accoya Beech (Accsys Technologies PLC)	1078 sqm	Exterior Finish	220	60	No

Building Circularity Inputs & Results

Code	Recycle %	Renewable%	Reused %	Wastage %	DfD, DfA	EOL Process	Score
SIP	88.6	98.84	0	8	Yes	Landfilling	70
DGW	0	43.322	0	0	yes	Landfilling	
WCD	0	99	0	17.9	yes	Wood Landfilling	
SIP	88.6	98.84	0	8	Yes	Use EOL defined in EPD	75
DGW	0	43.322	0	0	yes	Use EOL defined in EPD	
WCD	0	99	0	17.9	No	Wood incineration	
SIP	88.6	98.84	0	8	Yes	Reuse as material	120
DGW	0	43.322	0	0	yes	Glass-containing product	
WCD	0	99	0	17.9	yes	Reuse as material	

Design Option 3 – Recycle

Ubakus Results

Thermal protection

U = 0,23 W/(m²K)

GEG 2020 Bestand*: U<0,24 W/(m²K)

excellent — insufficient

Moisture proofing

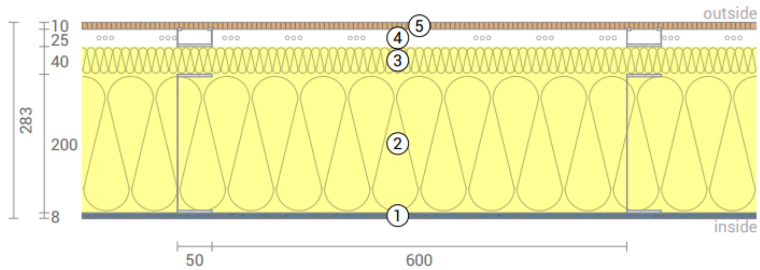
Drying reserve: 6793 g/m²a
No condensate

excellent — insufficient

Heat protection

Temperature amplitude damping: 6,7
phase shift: 9,3 h
Thermal capacity inside: 17 kJ/m²K

excellent — insufficient



① Textile Board (8 mm)
② Denim Insulation (200 mm)
③ AGEPAN TEP (40 mm)
④ Outside air (25 mm)
⑤ Kerloc Ceramic Facade Tiles (10 mm)

U-Value calculation according to DIN EN ISO 6946

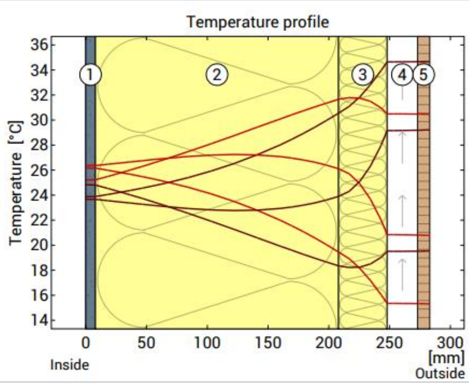
#	Material	Dicke [cm]	λ [W/mK]	R [m²K/W]
	Thermal contact resistance inside (Rsi)			0,130
1	Textile Board	0,80	0,200	0,040
2	Denim Insulation	20,00	0,039	5,128
	Steel (0,092%)	20,00	50,000	0,004
	Steel (Width: 5 cm)	0,06	50,000	0,000
	Steel (Width: 5 cm)	0,06	50,000	0,000
3	AGEPAN TEP	4,00	0,050	0,800
4	Outside air	2,50		0,130
	Steel (Width: 0,06 cm)	2,70	50,000	0,001
	Steel (Width: 0,06 cm)	2,70	50,000	0,001
	Steel (Width: 0,6 cm)	0,06	50,000	0,000
	Steel (Width: 0,6 cm)	0,06	50,000	0,000
	Steel (Width: 5 cm)	0,06	50,000	0,000
5	Kerloc Ceramic Facade Tiles	1,00	5,000	0,002
	Thermal contact resistance outside (Rse)			0,040

Thermal contact resistances have been taken from DIN 6946 Table 7.
Rsi: heat flow direction horizontally
Rse: heat flow direction horizontally, outside: Direct contact to outside air

Thermal transfer resistances of resting air layers were calculated as follows:
Layer 4.1: Thickness 2.5 cm, Width ∞, DIN EN ISO 6946 Table 8, heat flow direction horizontally

DIN 6946 should not be used because the component contains room or outside air.

Heat transfer coefficient from finite-elements method **U = 0,230 W/(m²K)**
numerical uncertainty ~0,30%



Temperature at 3pm, 11am and 7am
Temperature at 7pm, 11pm and 3am

① Textile Board (8 mm)
② Denim Insulation (200 mm)
③ AGEPAN TEP (40 mm)
④ Outside air (25 mm)
⑤ Kerloc Ceramic Facade Tiles (10 mm)

Life Cycle Assessment Inputs

Code	Product	Layer	Quantity	Transport (1st Leg)	Service Life	Reused Material
ACT	Acoustic cladding from textile and cotton wool, 1.19 kg/m2, Vibrasto 15 (TEXAA)	Interior finish	1078 sqm	60	60	No
GSP	Galvanised steel profiles (studs) for internal wall framing, 0.7 mm, 0.9 kg/m, 37 mmx73.5 mm	Structural Frame	4484 m	370	60	No
RTF	Recycled textile and fabric insulation, blown, R=3.25 m2K/W, L= 0.046 W/mK, 150 mm, 2 kg/m2, 13.3 kg/m3, Lambda=0.046 W/(m.K), COTON-FRP DOMOSANIX NITA-COTON-FRP NITA-COTTON ISOTEXTIL INNOCOTON COTON SOLIDAIRE (RMT Isolation SL)	Insulation 1	1078 sqm	60	60	No
WFI	Wood fibre insulation boards, biogenic CO2 not substracted, L = 0.044 W/mK, 173 kg/m3, EPD coverage: 0.037-0.05 W/mK, 20-240 mm, 80-250 kg/m3 (Gutex)	Insulation 2	1078 sqm	350	60	No
AFW	Aluminum frame window, size: 1.23 x 1.48m, 27.69 kg/m2, double glazing, SUPREME S77 (Alumil)	Window	839 sqm	380	60	No
CGC	Ceramic façade cladding, 24 - 30 mm, 31 - 42 kg/m2, 2000 - 2200 kg/m3 (Argeton)	Exterior finish	1078 sqm	320	50	No

Building Circularity Inputs & Results

Code	Recycle %	Renewable%	Reused %	Wastage %	DfD, DfA	EOL Process	Score
ACT	43	0.5	0	8	No	Landfilling	37
GSP	70	0	0	7.5	No	Steel recycling	
RTF	0	0	0	8	No	Landfilling	
WFI	69	69	0	8	No	Landfilling	
AFW	11	0	0	0	No	Glass-containing product	
CFC	0	0	0	10	No	Brick/stone crushed	
ACT	70	0.5	0	8	No	Landfilling	53
GSP	70	0	0	7.5	No	Steel recycling	
RTF	50	0	0	8	No	Landfilling	
WFI	69	69	0	8	No	Landfilling	
AFW	11	0	0	0	No	Glass-containing product	
CFC	50	0	0	10	No	Brick/stone crushed	
ACT	70	0.5	0	8	Yes	Reuse as material	75
GSP	70	0	0	7.5	yes	Steel recycling	
RTF	50	0	0	8	yes	Reuse as material	
WFI	69	69	0	8	yes	Reuse as material	
AFW	11	0	0	0	yes	Glass-containing product	
CFC	50	0	0	10	yes	Reuse as material	
ACT	70	0.5	10	8	Yes	Reuse as material	80
GSP	70	0	10	7.5	yes	Steel recycling	
RTF	50	0	10	8	yes	Reuse as material	
WFI	69	69	10	8	yes	Reuse as material	
AFW	11	0	10	0	yes	Glass-containing product	
CFC	50	0	10	10	yes	Reuse as material	

Design Option 4 – Reduce

Ubakus Results

Thermal protection

U = 0,23 W/(m²K)

Interior insulation: No requirement*

excellent insufficient

Moisture proofing

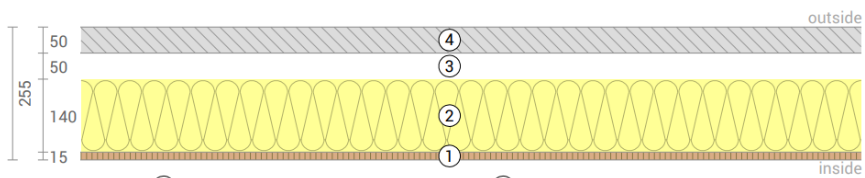
No condensate

excellent insufficient

Heat protection

Temperature amplitude damping: 8,1
phase shift: 8,8 h
Thermal capacity inside: 27 kJ/m²K

excellent insufficient



① Chip board / particle board (15 mm)
② STEICOflex 036 (140 mm)
③ Stationary air (50 mm)
④ Granit (50 mm)

U-Value calculation according to DIN EN ISO 6946

#	Material	Dicke [cm]	λ [W/mK]	R [m²K/W]
	Thermal contact resistance inside (Rsi)			0,130
1	Chip board / particle board	1,50	0,140	0,107
2	STEICOflex 036	14,00	0,036	3,889
3	Stationary air (unventilated)	5,00	0,278	0,180
4	Granit	5,00	2,800	0,018
	Thermal contact resistance outside (Rse)			0,040

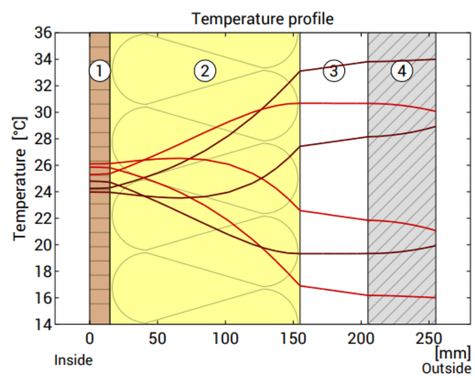
Thermal contact resistances have been taken from DIN 6946 Table 7.
Rsi: heat flow direction horizontally
Rse: heat flow direction horizontally, outside: Direct contact to outside air

Thermal transfer resistances of resting air layers were calculated as follows:
Layer 3: Thickness 5 cm, Width ∞, DIN EN ISO 6946 Table 8, heat flow direction horizontally

Thermal resistance R_{tot} = 4,364 m²K/W

Heat transfer coefficient $U = 1/R_{tot}$ = **0,23 W/(m²K)**

The following results are properties of the tested component alone and do not make any statement about the heat protection of the entire room:



Temperature at 3pm, 11am and 7am
Temperature at 7pm, 11pm and 3am

① Chip board / particle board (15 mm)
② STEICOflex 036 (140 mm)
③ Stationary air (50 mm)
④ Granit (50 mm)

Life Cycle Assessment Inputs

Code	Product	Layer	Quantity	Transport (1st Leg)	Service Life	Reused Material
NSS	Natural stone massive slabs (EUROROC)	Exterior Finish	299 sqm	200 km	60 years	Yes
WFI	Wood fibre insulation boards, R= 3.26 m2K/W, 140 mm, 15.4 kg/m2, 110 kg/m3, STEICOtherm dry (Steico)	Insulation	42 cum	350 km	60 years	No
MDF	Medium density fiberboard (MDF), sound absorbing, 16 mm, 13.9 kg/m2, 866 kg/m3, αw = 0.75 (class C)	Interior Finish	299 sqm	340 km	60 years	No
DGW	Double glazing windows with wooden frame, 30.7 kg/m2, 1.4 W/m2K, biogenic CO2 not subtracted (for CML), FDES collective utilisable par toute entreprise qui produit en France des fenêtres et portes fenêtres, double vitrage acoustique ou standard, en bois tropicaux. (INSTITUT TECHNOLOGIQUE FCBA)	Windows	839 sqm	380 km	40 years	No
CLT	Cross Laminated Timber (CLT), Thickness: up to 400 mm, 470 kg/m3, 12% moisture content (Derix GmbH & Co)	Structural Frame	9 cum	220 km	60 years	No

Building Circularity Inputs & Results

Code	Recycle %	Renewable%	Reused %	Wastage %	DfD, DfA	EOL Process	Score
NSS	0	0	100	0	Yes	Brick, Stone crushed	75
WFI	69	69	0	8	Yes	Landfilling	
MDF	87	87	0	16.7	Yes	Wood Incineration	
DGW	0	43.322	0	0	Yes	Party Recycled	
CLT	0	100	0	16.7	Yes	Wood Incineration	
NSS	0	0	100	0	Yes	Reuse as material	69
WFI	69	69	0	8	Yes	Reuse as material	
MDF	87	87	0	16.7	Yes	Use EOL defined in EPD	
DGW	0	43.322	0	0	Yes	Use EOL defined in EPD	
CLT	0	100	0	16.7	Yes	Use EOL defined in EPD	
NSS	0	0	100	0	Yes	Reuse as material	73
WFI	69	69	100	8	Yes	Reuse as material	
MDF	87	87	100	16.7	Yes	Use EOL defined in EPD	
DGW	0	43.322	0	0	Yes	Use EOL defined in EPD	
CLT	0	100	0	16.7	Yes	Use EOL defined in EPD	
NSS	0	0	100	0	Yes	Reuse as material	91
WFI	69	69	0	8	Yes	Reuse as material	
MDF	87	87	0	16.7	Yes	Reuse as material	
DGW	0	43.322	0	0	Yes	Reuse as material	
CLT	0	100	0	16.7	Yes	Reuse as material	