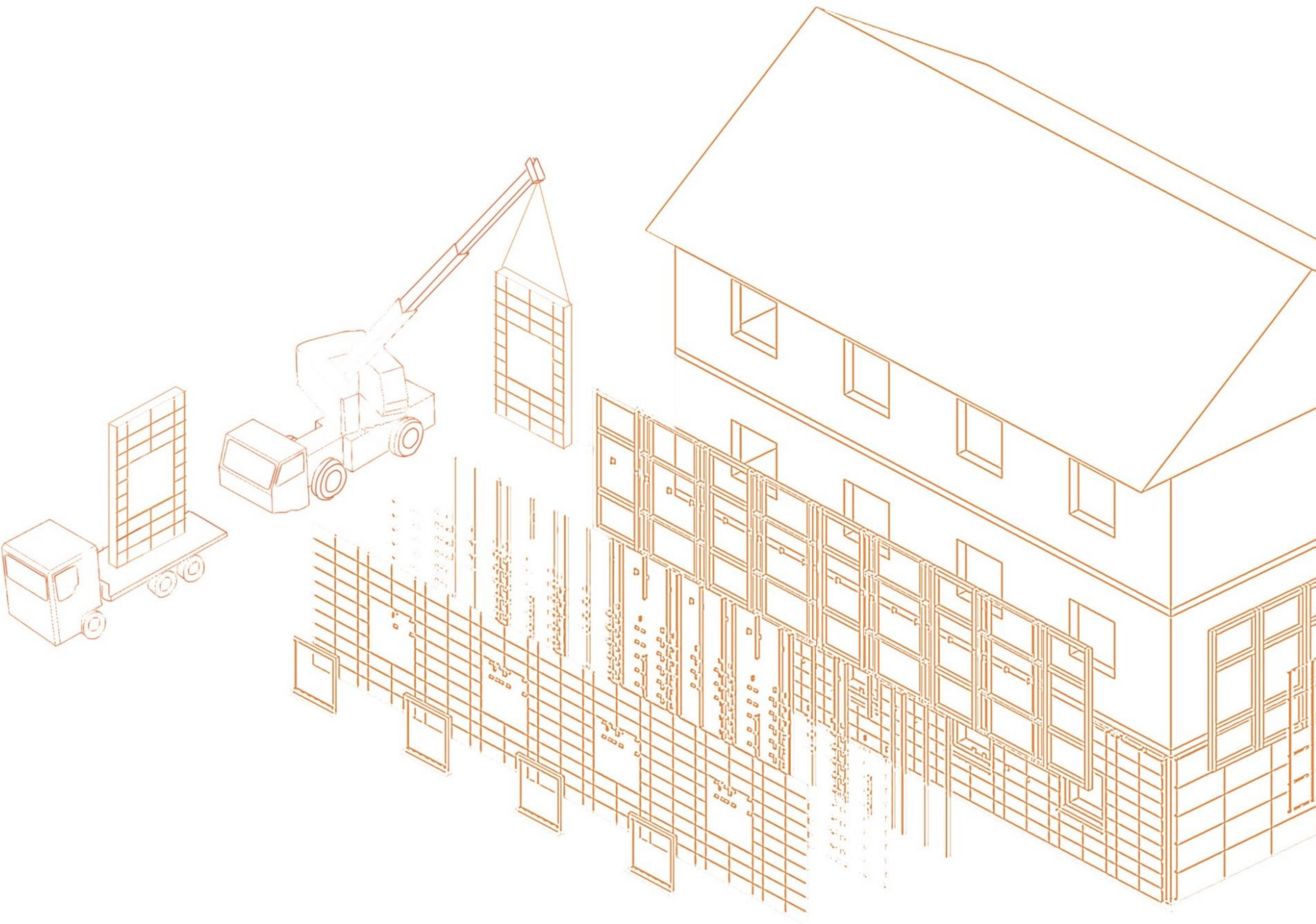
Circular Façade Design for Various End-of-Life scenarios

Gargi Gokhale
5745292



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Mentors: First mentor – Dr. Ing Thaleia Konstantinou
Second mentor – Ir. Dr. Sultan Çetin
Third mentor – Dr.ir. Magdalena Zabek

External Examiner: Dr. René van der Velde

Student Name: Gargi Gokhale

Student Number: 5745292

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Abstract

The linear economy of Take-Make-Dispose creates environmental pollution, increases the cost of raw materials, increases waste and creates CO_2 emissions. The new Circular Economy Action Plan aims to design products that prevent waste and retain resources in the EU economy. The building and construction industry contributes to 35% of the total waste produced globally. Facades are complex multilayered system with lifespan shorter than the structure. A façade system reaches its end of technical life often compared to the structure. Effective End-of-Life management of a façade can enable material recovery, recycling and reuse. The environmental impacts play an important role in the End-of-Life decision making of a system followed by the material costs. Design aids like MFA and LCA act as the evaluative design aids to access circularity based on the environmental impacts. But these evaluative design aids are time-consuming. Thus, the generative design aids that are based on the evaluative design aids can guide the façade designers in designing a façade system which is circular at the End-of-Life. The project derives guidelines for a circular End-of-Life design of a façade system. The project employs a mixed methodology consisting of literature research and research through design process. Several design variants with different End-of-Life scenarios were designed and evaluated for environmental impacts and market-based material and installation costs. Results indicated that reuse scenarios had the least environmental impacts, but the reuse scenario was governed by the lifespan of the materials in the system. The market-based material and installation costs of the materials were found to be high for long-lifespan materials compared to the short lifespan materials. For the bio-based variants, it was found that despite having lower global warming potential impacts at the manufacturing stage, in most of the cases, the materials are downgraded at the End-of-Life. The environmental impacts and costs were compared to form the design guidelines for façade designers to take decisions at the preliminary design stage. Further, the guidelines are translated information considerations based on the tipping points identified after analysing the results. The guidelines and the information considerations are further validated by designing a façade system based on the variants.

Key words: Circular Façade Design, End-of-Life scenarios, Façade system.

Abbreviations

CE – Circular Economy

EoL – End-of-Life

MCI – Material Circularity Index

LCA – Life Cycle Assessment

BCI – Building Circularity Index

MFA – Material Flow Analysis

GWP – Global Warming Potential

Bio-CO2 storage – Biogenic Carbon Storage

ODP – Ozone Depletion Potential

AP – Acidification Potential

EP – Eutrophication Potential

POCP – Formation of Ozone of lower atmosphere

ADPE – Abiotic Depletion Potential for non-fossil resources

ADPF - Abiotic Depletion Potential for fossil resources

LC1 – Life Cycle 1

LC2 – Life Cycle 2

LC3 – Life Cycle 3

Definitions

Material – The basic substances used to create a standardised material. They have a specific chemical and physical properties that determine their suitability for various applications. For example, steel, glass, aluminium, wood etc.

Standardised Material – The materials that conform to specific standards or specification set by the construction industry. They are according to the quality and performance requirements set by the construction industry. For example, structural steel I section, aluminium profile section etc.

Component – Part or an element of a larger system. It consists of one or more standardised materials. Each component performs a specific function within the system. For example, façade structure, insulation etc.

System – An assembly of interconnected components that work together to perform a complete function or set of functions. Systems are complex and involve multiple interacting parts. For example, façade system.

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1. Introduction

The introduction section focuses on the transition from a linear economy to an economy which aims to reduce the environmental pollution and waste and focuses on maximising reuse and recycling of materials in the building and construction industry. This forms the background of the research. The research aims to connect the design stage to the EoL stage for designing circular facades. Further, the section introduces the problem statement of the research, the objectives, research question and the methodology along with the relevance of the research.

1 Introduction

1.1 Background Research

The linear economy of Take-Make-Dispose creates environmental pollution, increases the cost of raw materials, increases waste and creates CO_2 emissions (Ellen MacArthur Foundation, 2013). To tackle this issue, there is a transition from a linear economy model to a circular economy model which is regenerative and restorative by design, uses materials at their highest value and encourages to use the product again in the cycle. This economic model, helps in narrowing, slowing, closing and regenerating the resource loops (Bocken et al., 2016). The new Circular Economy Action Plan targets how products are designed and aims to ensure that the waste is prevented and the resources used are kept in the EU economy for as long as possible (CEAP, 2020).

The building and construction industry accounts for 35% of the total waste produced globally (European Commission, 2022). The circular economy butterfly diagram (Ellen MacArthur Foundation, 2017) digs into the circularity loops that are created for a material's biological and the technical cycle. In the biological cycle, the materials are fed back into the loop since they are returned back to the nature. Contrarily, in the technical cycle, the materials cannot be directly returned back to the nature. The technical cycle intends to extend the life of the product and materials by keeping them in circulation by reusing, refurbishing and recycling the materials back into the system.

Facades are multilayer systems with many different connection types and elements that fulfil specific functions, designed and maintained by a global supply chain (Hartwell et al., 2021). Due to the evolving façade design, systems that are difficult to disassemble and re-process at their end of service life are being designed. A façade system contributes to a total of 20% cost of construction and an embodied carbon of about 10-20% (BES Consultants, 2022). It has an effect on the operational energy of the building. The lifespan of a façade is less compared to the structure (Brand, 1994). This indicates that a façade reaches its end of service life earlier compared to the structure and needs to be replaced or maintained. The different scenarios at the end of service life of a façade should be considered at the design phase itself (Rose et al., 2018; Hartwell et al., 2020). This will support in achieving strategies for facades which minimize waste.

1.2 Problem Statement

The EoL phase of a system is crucial in a circular economy due to a number of reasons. Extending the life of a system through circular practices leads to energy savings and less negative environmental impacts (European Commission, 2020). Constructive management of the EoL of systems enables recovery, recycling or reuse of materials and components thus enabling the circular flow of the resources (Frosch and Gallopoulos, 1998). Effective handling at the End-of-Life of a system helps in reducing the waste sent for landfilling or incineration minimising the environmental pollution (Ellen MacArthur Foundation, 2013). Additionally, the EoL stage presents economic opportunities for the reverse logistic services, recycling facilities and remanufacturing facilities (Kirchherr et al., 2017). Considering the EoL phase during the design stage instigates the creation of systems that support circularity (Zonk & Geyer, 2017).

Numerous design aids are available to guide designers in making decisions that incorporate principles of circularity. They can be broadly classified as generative design and evaluative design aids (Bocken et al., 2014). The generative design aids include thumb rules, checklists, guidelines and archetypes. The evaluative design aids help to evaluate the circularity of a generated design. Van Stijn and Gruis (2020) reviewed the generative design aids. They concluded that these generative design aids assist in developing a circular design, but they do not specify which of the options is more circular.

Several assessment methods and indicators aid in evaluating the design for circularity. These include the Material Circularity Indicator (Ellen MacArthur, 2015), C-CalC by Cenergie (2019), Label Circularity Indicator by the Flemish Construction Confederation (2017), Building Circularity Index developed by Alba concept (2015). LCA by UNEP AND SETAC (2002) equips the designers to measure the environmental impacts throughout the life cycle of the product, process or service. The MFA calculates the flow of materials in a system.

According to van den Berg et al. (2023), decisions regarding the strategies for reuse, recycle and recover at the EoL of a construction project are primarily influenced by the environmental gains (60%), followed by economic costs (27%), technical aspects (9%), and social gains (4%). Hence, environmental gains play a major role in the decision-making process. Evaluative design aids that assess the environmental gains include MFA and LCA. The MFA measures the quantity of materials and energy in a system (Brunner and Rechberger, 2003). LCA evaluates multiple environmental categories and considers the environmental impacts associated with different life cycle stages of a product or a service (Hitch Hiker's Guide to LCA. Studentlitteratur (2004). LCA and MFA are considered as time-consuming approaches (Cambier et al., 2020; De Wolf et al., 2017). Thus, design guidelines based on the environmental impact decisions will help the designers to implement circularity concerned with EoL scenarios into practice.

There are a few design guidelines derived from evaluation of the environmental impacts and that take into consideration MFA and/or LCA as the evaluative methods. van Stijn & Gruis (2020) proposed guidelines derived from evaluative methods for façade systems that consider the environmental impacts of various design variants but they are not particularly focused on the EoL impacts and the EoL scenarios. They evaluate the various circular design variants for different building components including façade systems. They do not take into consideration the technical lifespans grouping approach for the components in the variants during the development of the circular design options. The guidelines do not account for the different standardised materials that can be used for a façade system, which have varying technical lifespans and different circular EoL scenarios. For example, long lifespan materials are considered as circular since they can be reused, some materials can be recycled at the EoL and have a short lifespan, these materials can still be considered circular because they can be returned back into the system, bio-based materials are also considered circular. Thus, the question arises which of these circular variants create less environmental impacts at the manufacturing stage and the EoL stage?

There are a very few design guidelines for the façade designers that take into account the various End-of-Life scenarios of a façade system and the information that needs to be considered to follow the guidelines.

1.3 Objectives

The main objective of this report is to equip the façade designers with circular design guidelines that account for various End-of-life scenarios and the necessary information that determine the circularity which are derived from the guidelines. To achieve this, the report will address the following sub-objectives in order to achieve circularity in façade systems:

1. Identify different circularity assessment methods in the built environment which investigate environmental impacts.
2. Conduct a generative design approach to establish circular design guidelines.
3. Develop comprehensive design guidelines for integrating circular EoL considerations during the design phase.
4. Determine the necessary information to consider for a circular EoL for following the guidelines,

Thus, the objective of this report is to guide the façade designers in making informed decisions about circular façade design by considering various EoL scenarios in a façade system.

1.4 Research Questions

Main question –

What design guidelines can help the façade designers integrate the considerations for a circular End-of-Life (EoL) of a façade system during the design phase and what is the information that needs to considered while following these design guidelines?

Sub questions –

1. What are the different assessment methods for circularity?
2. What are the design guidelines to integrate a circular EoL during the design stage?
3. What information impacts the circularity of the EoL stage based on the design guidelines?

1.5 Approach & Methodology

The research project follows a mixed methodology which consists of literature review and research through design. The research will be conducted in the following phases – (1) Literature study, (2) Case study and case development, (3) Preliminary Design, (4) Design Evaluation, (5) Design Proposal as Validation of the Guidelines and (6) Discussion. An initial literature study was conducted to gain insights about circularity in the built environment, façade circularity, façade stakeholders and different circularity assessment methods. After the literature study, a problem statement was defined. Further, AEGiR façade renovation project was chosen as a case study and the core concepts of the project were adapted to develop a case in the context of the Netherlands. Subsequently, the methodology consists of Research through Design approach, wherein various design variants were designed and evaluated based on different key performance indicators. The variants were evaluated for multiple lifecycles and the results were analysed to derive the design guidelines along with the information.

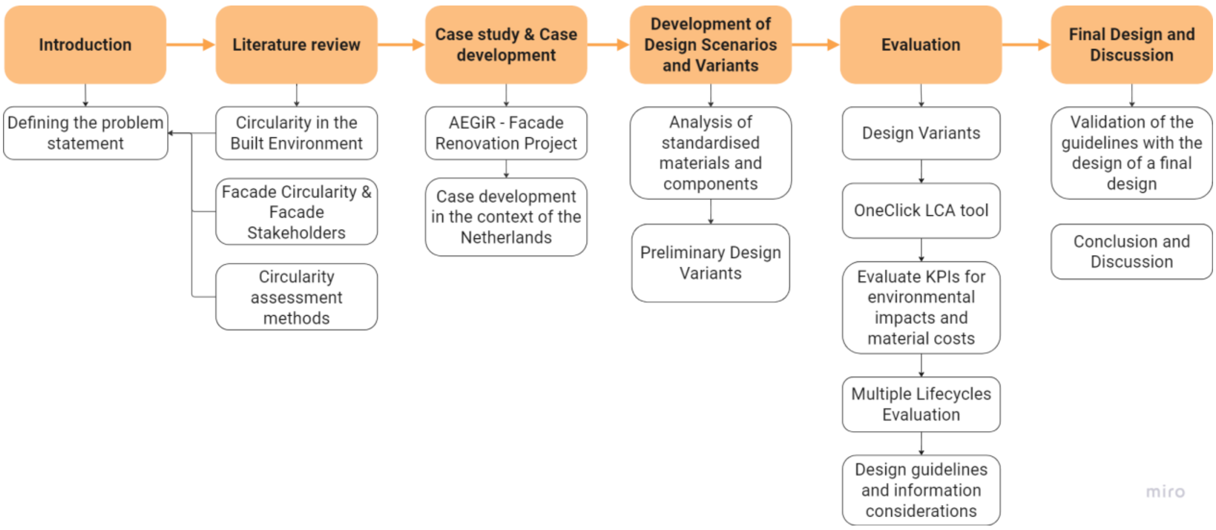


Figure 1 Flowchart representing the methodology followed by author

1.6 Planning & Organisation

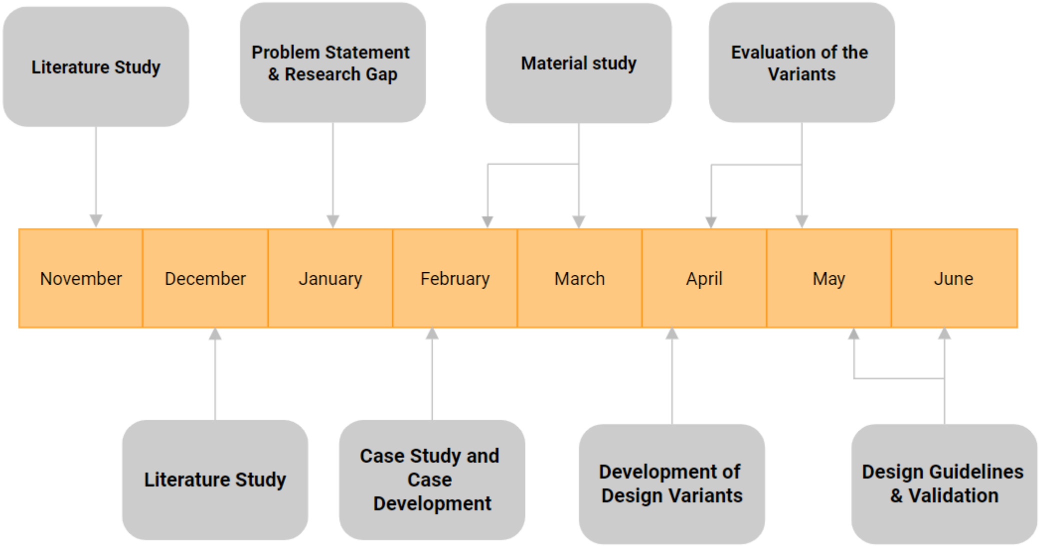


Figure 2 Timeline of the Project by author

The timeline starts with an initial literature study to derive the research gap and a research question. It was again followed by a comprehensive literature review to distinctly elicit the problem statement, research gap and the research questions. Further, a case was developed in the context of the Netherlands and AEGiR façade renovation project was studied for comprehending the components in a façade system that adapt a wrap-it approach for façade renovation and help reduce the operational energy demands. The AEGiR project case study was followed by material study and simultaneous development of design variants. The design variants were evaluated and design guidelines were formulated based on the results.

1.7 Relevance

The research evolves around the concepts of circular built environment and façade systems. It includes the assessment of the environmental impacts at the EoL of the façade system. The study intends to increase the circularity in the façade industry by considering the different EoL scenarios during the design stage. The study is relevant since it bridges the gap between the Design stage and the EoL stage of a façade system. It assists the designers to design the façade taking into account the guidelines. Thus, the research involves the design stage and the EoL stage of the façade system.

The research contributes to the knowledge of circularity at the EoL stage of a façade system. It not only considers the various EoL environmental impacts but also the environmental impacts caused during the material manufacturing and use. The resulting design guidelines which are developed based on evaluative approach help to enhance the existing guidelines for circularity and propose specific guidelines for façade circularity. Thus, the research has a scientific contribution to the field of façade circularity. The research also plays an important role for the practice since it provides the façade designers with guidance to take informed-decisions. It helps to reduce the environmental impacts of the façade systems which can further help with achieving certification for sustainable building practices.

The research can be applicable to any façade designer in the context of Netherlands and is not specific to a certain company/ organisation. The research can benefit a wide range of façade designers. Since, the research does not focus on proprietary tools or methods, the findings are accessible and applicable to one and all regardless of their preferences of tools and methods. It helps to develop a shared understanding of circular design guidelines across the façade industry.

2 Literature review

The literature study focuses on the study of concept of circular economy including the circularity in the built environment and circularity in the façade systems. Further, different stakeholders in the façade industry are studied and their relationship with each other in terms of product and information exchange is studied. Different business models are analysed because they form an important part in closing the loop or to achieve circularity at the EoL. The literature study section explores the different circularity assessment methods.

2 Literature review

2.1. Circular Economy

2.1.1. Context

The Circular Economic model emerged to address the concerns related to the environment as an alternative for the Linear Economic model.

As defined by the European Parliament, (n.d.), CE is a system where materials never become waste, materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling and composting. The key principles of the model are designing out of waste and thinking in systems. There is a differentiation between the biological and the technical cycle as shown in the Figure 3. The biological cycle makes sure that the products are returned to the environment, while the technical cycle ensures that the products or materials re-enter the loop at different life cycle stages of a product.

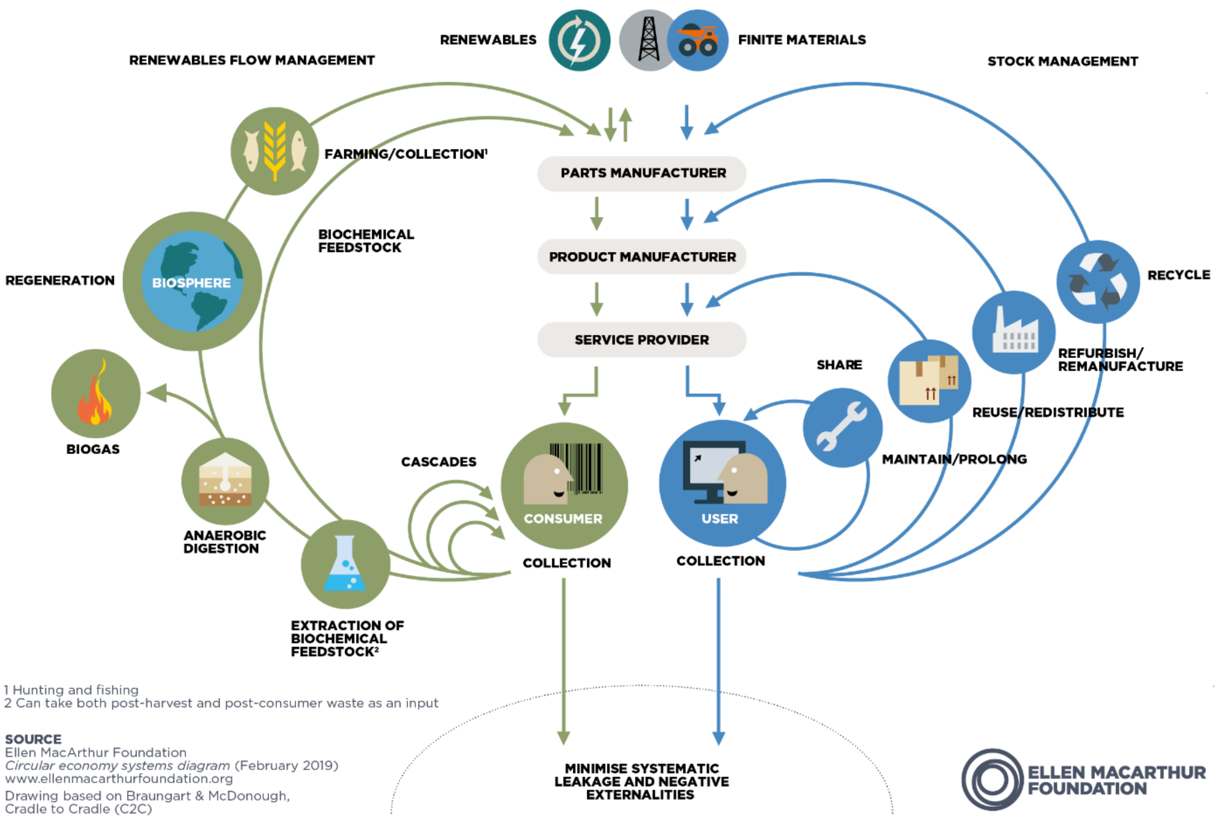


Figure 3 Butterfly Diagram by Ellen MacArthur Foundation

2.1.2. Systems' theories

The idea of closing the loop is not new and has been presented in the literature review by Van Dijk et al. (2014). These theories help to understand Circular Economy with respect to EoL stage and further enrich the research.

The theories have a similar principle as the Circular Economy –

Law of Ecology – The four laws of ecology formulated by Barry Commoner in 1970s describe the fundamental principles that govern the interactions between living organisms and their environment. This law enhances the concept of circular economy by highlighting that everything in

a system is connected to one another and in nature, there is no such thing as waste. The waste of one system acts as a nutrient provider of the other.
Law of Economy - This law operated through spiral loops with an aim of reducing the material flows as well as environmental degradation.
Regenerative design – This law tries to create systems that are self-sustaining and try to improve the natural environment around them.
Biomimicry –This law views nature from what we can learn from it instead of what we can consume or extract from it.
Industrial ecology –This law describes the world with respect to physical resource flows. It focuses on minimising waste and maximising resource efficiency.
The Blue Economy – It is an approach in which the byproducts of one product are repurposed to create new revenues and streams.
Cradle to cradle - This theory believes that whatever is the waste of one system is the food of another system. It is a design-driven approach which focuses on eliminating waste and pollution, regeneration and circulating products and materials at their highest values.

2.1.3. Conclusions

The transition from a linear to a circular economy is important to achieve sustainability and the butterfly diagram provides a broader idea of the circular economy. The report focuses on both the technical and the biological cycles. In managing the EoL of materials and components within a system, the technical cycle is more complex than the biological cycle. This complexity arises because the technical cycle aims to keep the materials and components in the loop which require careful handling and processing to ensure their usability. The different systems' theories help to develop an idea of different ways in which the systems' thinking can be applied to a project. They help to better understand the idea of waste minimisation which can be applied at different stages of the system development in the project.

2.2 Circularity in the Built Environment

2.2.1 Context

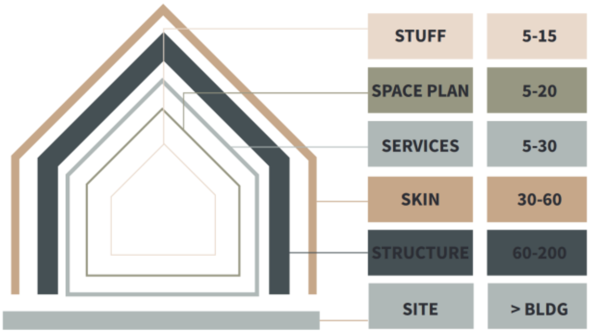


Figure 4 Building layers by Brand (1994)

The theory developed by Stewart Brand establishes a relation between time and a building. The Theory of Levels views a building as different layers depending on the characteristic of each layer. It further allocates a life span to each of these layers with a vision to make the building more adaptable and allowing it to age adequately (Brand, 1994). As shown in the figure, he identifies six layers of a building: the site (eternal), the structure (60-200 years), the skin (30-60 years), the services (5-30 years), the space plan (5-20 years) and the stuff (5-15 years).

2.2.2 Life cycle stages of a building

Life cycle stage	Product stage			Construction process stage		Use stage							End-of-Life stage			Beyond End-of-Life stage
Processes	Raw material supply	Transport	Manufacturing	Transport	Construction - Installation Process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy	Operational Water Use	Transport	Waste processing	Disposal	Reuse, Recovery and Recycling Potential
Broader classification of stages	Design stage					Operational stage							End-of-Life stage			

Table 1 Life cycle stages in construction works from BSEN15978

As shown in Table 1, the life cycle stages in construction work stated in BSEN 15978 are as follows-
The **production phase** encompasses of extracting, transporting and manufacturing the construction materials. A large amount of water and energy are consumed during this stage.
The **construction stage** involves the realisation of a structure which consumes energy during the process. The energy consumed can be either due to transport of the materials or products on the site or the energy consumed due to the on-site activities.
The **use stage** is usually the longest stage in a building's life cycle. It includes maintenance and repair and at times refurbishment. The energy consumed at this stage consists of the operational energy required for the different activities of the building and the operational water use.
The **end-of-life** stage means the end of service life of a building or a product. In a linear economy, this stage is the demolition and waste disposal. The energy consumed is majorly due to the demolition work and the related transportation costs.
The **beyond end-of-life** is critical in a circular economy. This stage considers the reuse, recycling and recovery potential of the building and its components.

2.2.3 Re-life options

There have been several approaches that address the re-life options. The 10R framework by Potting et al. (2017) describes a framework for 10 re-life options. They comprise of 2 preventive options R0 and R1 and 8 reutilization options. The rule of thumb is, the higher up you go in the ladder (from R9 to R0), the less environmental impact it creates, hence more circular the strategies. The short loops keep the products closer to its user and functions, the medium loops upgrade the products, in the long loops the products lose their original functions.

Product recovery seeks to obtain materials and parts from old or outdated products through recycling and remanufacturing in order to minimise the amount of waste sent to landfills. Table 2 suggests the product recovery hierarchy proposed to reduce the usage of virgin materials by considering the different re-life options. As seen in Table 2, in the context of circular economy, the option of re-conditioning and re-manufacturing is regarded as a more sustainable and environmentally friendly option compared to the option of landfill.

When it comes to circularity, a closed loop supply chain (CLSC) is the key. Guide and Van Wassenhove defined CLSC as “the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time.” (Guide & Wassenhove, 2009).

INCREASE IN CIRCULARITY ↑	Objectives	Re-life Options	Description	
	• Design phase • Most sustainable • Adds value • Responsible use and manufacturing	R0 Refuse	Prevent the use of products and raw materials in the creation.	SHORT LOOPS
		R1 Rethink	Reconsider ownership, use, and maintenance of products.	
		R2 Reduce	Decrease the use of raw materials in products and services.	
	• Consumption phase • Optimal Use • Preserve and Extend the life of the product	R3 Reuse	Secondary use of products by another owner for the same intended purpose.	MEDIUM LOOPS
		R4 Repair	Maintain and repair existing products for extended use.	
		R5 Refurbish	Restore and improve products to a satisfactory condition for extended use.	
		R6 Remanufacture	Make more products with the same purpose with discarded products or parts.	
		R7 Repurpose	Make new products with a different purpose using discarded products or parts.	
	• End-of-Life or return phase • Capture and retain value • Use waste as a resource	R8 Recycle	Process waste into new products or materials that can be used for new products.	LONG LOOPS
		R9 Recover	Process waste to recover energy.	
	• Loss of resources • Value lost • Environmental pollution	Landfill or Incineration	Not utilising end-of-life materials in any way	

Table 2 The 10R framework adapted from Potting et al. (2017)

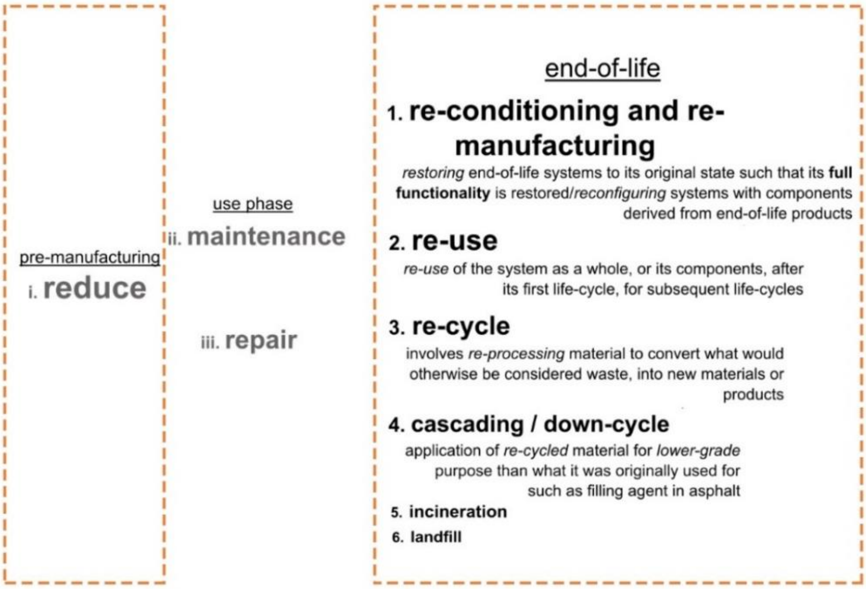


Figure 5 Product recovery hierarchy proposed with the aim to reduce the usage of virgin materials to produce new products and component by Hartwell et al., 2020

The basis to achieve a closed-loop supply chain is reverse logistics, the idea which focuses on enabling the products and materials back to the point of manufacturing or at other points during the life cycle of the product (Sillanpää & Ncibi, 2018). According to Schultmann and Sunke, the stages of reverse logistics can be distinguished into: collection, inspection/ selecting/sorting, reprocessing, and redistribution. These processes form a part of beyond EoL scenario and are taken into consideration while calculating the environmental impacts.

2.2.4 Conclusions

A building consists of various layers which helps in designing systems that are circular. The 10R strategy acts as a design guide and a starting point for considering circularity. As seen in Table 2, in a circular economy, disassembly and demount ability is promoted more than demolition. The life cycle stages in construction work can be classified into Product stage, Construction process stage, use stage, End-of-life stage and the beyond end-of-life stage which is pivotal in closing the loop for a circular built environment. This stage deals with minimising the waste. The research focuses on the End-of-life and beyond stages.

No.	Rs	Definition	Grouping the Rs
1	Repair	To bring the product to its working condition.	minor action for next/ same use
2	Refurbish	To bring the product close enough to the original condition. Thus it requires remanufacturing.	minor action for next/ same use
3	Reuse	Original purpose, no repair/ refurbishment is included in reuse.	the use might remain similar
4	Remanufac-ture	A product is built from individual components(Can be reused, re-furbished components) to match the customer expectations. This is almost like a new product.	major action for the next use
5	Repurpose	Different purpose than the original and involves refurbishment and repair.	describing the next use
6	Recycle	Process of converting the waste materials into something new.	the use might remain similar

Table 3 The 10R framework definitions and grouping by author

The Table 3 illustrates the definitions of the different Rs which are considered in Table 2. As stated in Table 3, the Reuse and Recycle are considered at the EoL of a system and indicate that the use might remain similar. Hence these two are further considered in the project as the EoL conditions. The Repair and Refurbish include minor action for the next or same use. Remanufacture and Repurpose describe the next use or include a major action before the next use.

2.3 Façade Circularity

2.3.1 Context

A façade system contributes to a total of 20% cost of construction (BES Consultants, 2022) and an embodied carbon of about 10-20% (BES Consultants, 2022). It has an effect on the operational energy of the building. The life span of a façade is around 30 years. (Brand, 1994). This implies that a façade reaches its end of life more often compared to the structure and needs to be replaced or maintained. The different scenarios at the end of life of a façade should be considered at the design phase itself (Rose et al., 2018; Hartwell et al., 2020). This will support in achieving strategies for facades which create less waste.

2.3.2 Product level circularity

Different circularity levels in a building act as a guide for the designers. As seen in Figure 4, Brand defined different building layers of change. He defined the skin as a layer.

Figure 6 specifies different circular building product levels for the façade as defined by Beurskens & Bakx (2015). The building product levels starts with 'building', which represents the building as an assembly of all the building systems. These systems are based on the sharing layers of change from Brand (1994). The building is further classified into four sharing layers. The Skin is divided into sub-systems and then into components and elements.

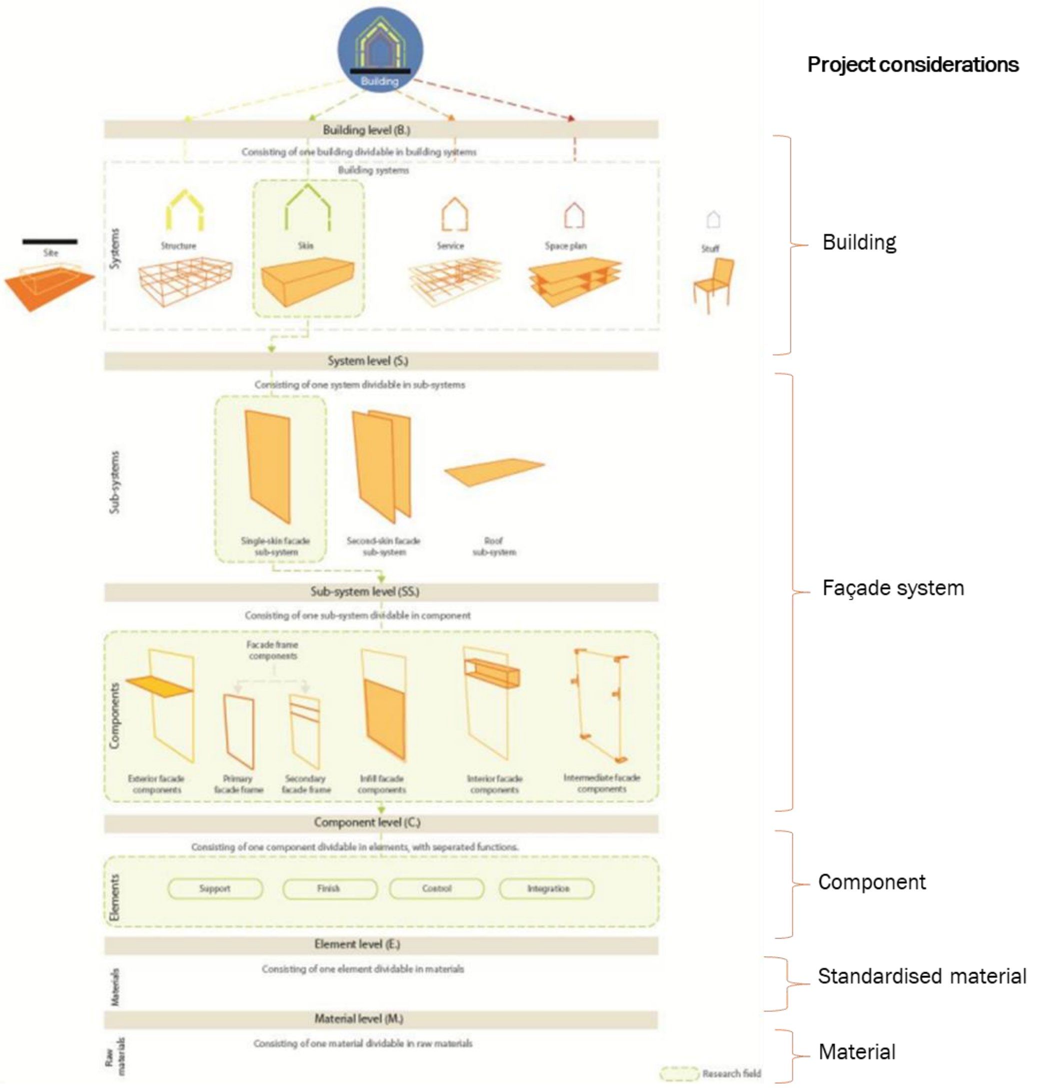


Figure 6 Circular building product levels - Specified for skin by Beurskens & Bakx (2015)

2.3.3 End-of-Life in a façade

The EoL of a façade system means the end-of-service life. The end-of-service life can be either the end of technical service life or the end of functional service life. The end of technical service life of a system refers to a point at which the system can no longer fulfil its intended function due to factors such as wear and tear and degradation. This implies that even if the system physically exits, it is no longer suitable for its original purpose.

On the other hand, the end of functional service life of a system refers to the point at which a system no longer needs to perform its intended function. The façade system can reach the end of its functional service life when there is a change in the use of the space, change in the regulations, client wants to change the exterior look of the structure which results in the change of demounting of the façade system.

Thus, the term end-of-life can be either the end-of-technical service life or the end-of-functional service life. The project takes into account the end-of-technical service life which considers the technical service life of a façade system. The technical service life of a façade system is 30 years (Brand, 1994). The project considers the end of technical service life for the project and not the end of functional service life because of the uncertainties in the end of functional service life.

2.3.4 Conclusions

The nature of the façade system is getting complicated in the recent times with additions of new functions. The focus of the project is based on system level. The division of the system of the skin into sub-systems, elements and materials should be considered while designing a façade system. The division of the system in different categories helps in accessing the circularity at multiple levels. The project considers the system, component, standardised material and material as the four different levels. To access the circularity of the system, the report will look into different scenarios for the end-of-technical service life of the façade system.

2.4 Stakeholders in the façade industry

2.4.1 Context

As quoted in the Massive Online Open Course titled Circular Economy for a Sustainable Built Environment (n.d.), *"Circularity is about collaboration between the disciplines. A constructive dialogue between stakeholders can allow a more integrated design that can deliver circular solutions."*

Figure 7 illustrates the involvement of different stakeholders in the façade industry at different stages during the life cycle of the façade system (Klein, 2013). The Façade Builder is involved in the architectural design, execution design, manufacturing and assembly stages and occasionally involved in repair and maintenance of the façade system. Thus, from the figure it is clear that the Façade Builder is not involved in the EoL stage and the scope of the Façade Builder is limited till the assembly stage and repair stage.

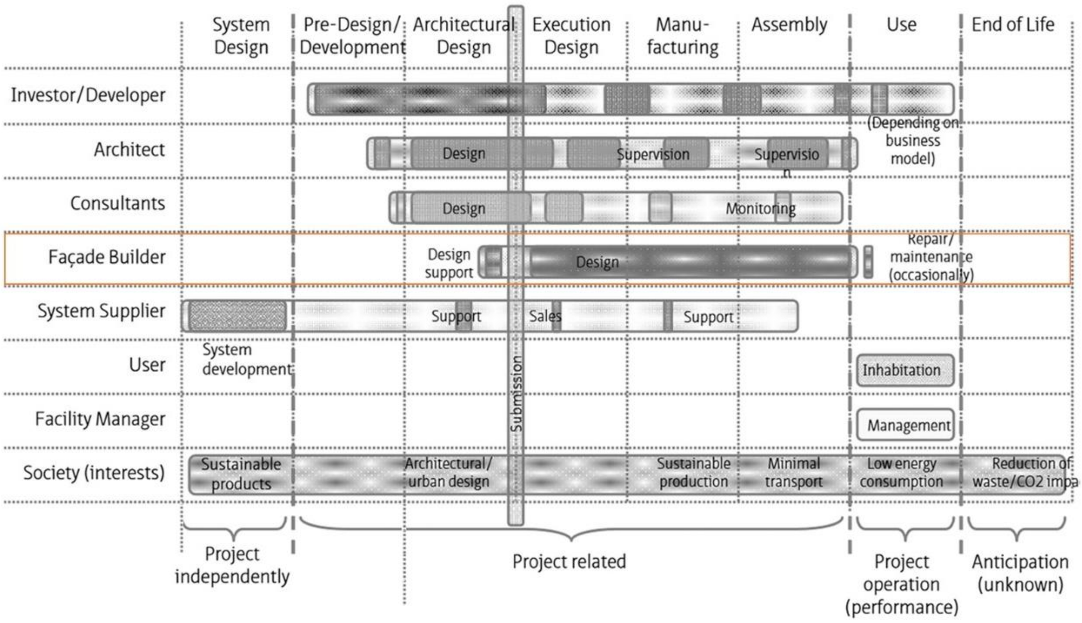


Figure 7 Facade stakeholders at different life stages by Klein (2013)

2.4.2 Stakeholder interactions

The major stakeholders involved in the façade supply chain are the client/ developer, architect, main contractor, façade contractor, material extraction, material processor and the demolition contractor. Figure 8 identifies the links between these different stakeholders and elaborates on what product or information is exchanged between these stakeholders. It is clear that the façade Consultant receives the material/ products from the material processor and there is an exchange of a design brief between the façade consultant, main contractor, client/ developer and building owner. If the system is demolished, then the EoL is handled by the demolition contractor and the unsorted scarp is sent to the waste industry/ landfill, the high-value materials are sent to the recycling facility and the systems/ components that can be reused are sent to the salvage yard. The high-value recycled material scrap is sent to the material processors to make standardised materials. In case of direct reuse of the systems/ components of a façade system, the client/ developer uses these materials in the new façade system. These are the trends in the current practices.

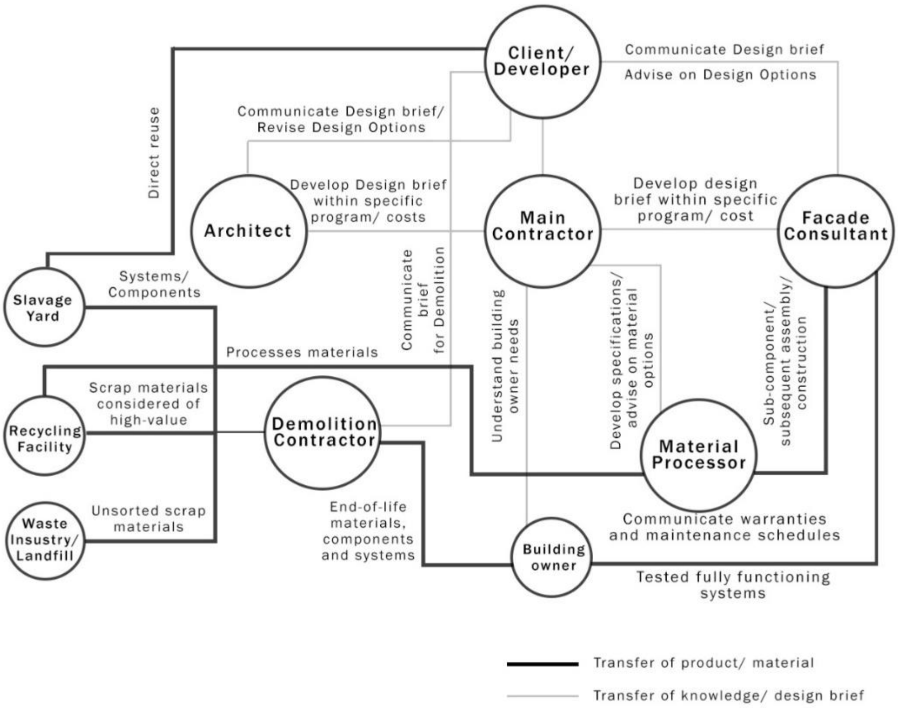


Figure 8 Stakeholder map showing stakeholders involved in the façade supply-chain and existing flows of knowledge and products/services by Hartwell et al. (2021)

The key challenges to achieve circularity in the façade sector involves a wide range of economic, technological and risk-based factors. As discussed in the literature by Hartwell (Hartwell et al., 2021), apart from the information exchange in a façade system, the other real-world challenges at the EoL of a façade system to achieve circularity are -

1. **Designing for high value recovery of EoL**: The supply-chain is not incentivised to formally include the deconstruction stage as an important factor in the original design process.
2. **Recovery of existing system and constituent materials**: There is a lack of take-back infrastructure and a negative perception about recovered/ remanufactured products. The façade contractors lack the ability to provide assurance about their product. Thus, the demolition contractors have little incentives to optimise the recovery of the components and materials in the system.
3. **Designing with reuse products**: A façade system often has a high value at the design stage, but at the end-of-service life, it is considered as one of the least valuable elements. The freedom for design in the reused structure is limited because of the specific dimensions and performance-oriented design of the façade. Stakeholders may be unprepared to adapt to the different technological processes involved in deconstruction.
4. **Designing with recycled materials**: There is a lack of information on the product/ material, thus it becomes difficult for the designers to design from recycled material. Some stakeholders involved in the design phase like the façade contractor, architect and the client want a specific appearance for their structure, this can be compromised while using recycled materials.

2.4.3. Conclusions

Circularity is about collaboration between different stakeholders throughout the lifecycle stages of a façade system. Throughout the life cycle of a façade, product and information are exchanged between various stakeholders. As highlighted by Hartwell et al., (2021), the major challenges to tackle the EoL of façade system include designing for high recovery of EoL, recovery of existing system and constituent materials, designing with reuse products and designing with recycled materials. These challenges can be addressed by the façade designers at the design stage itself. In order to address the problems stated by (Hartwell et al., 2021) certain business models should be studied and implemented to achieve the circularity of the façade system towards their EoL.

2.5 Circularity Assessment Methods

2.5.1 Context

There are different Circularity Assessment Methods used to evaluate the circularity of the materials in the system. These methods focus on resource efficiency, waste reduction and the use of renewable materials. They take into account the extent to which renewable and recycled materials are incorporated into the products or processes. The different material circularity assessment methods are mentioned in the sub-sections.

2.5.2 Material Circularity Index (MCI)

The Material Circularity Indicator (MCI) is developed by Ellen MacArthur Foundation and measures the circularity of the material flows of a product. It gives a value between 0 and 1 where higher values indicate higher circularity. It is a useful method to compare designs of multiple products on a scale from linear to circular. It uses the input in the production process from virgin, recycled and reused materials, it measures how long the product is being used which takes into account the repair/ durability of the products along with the considerations of different business models. The MCI also measures the destination of the material after its use and which components are collected for reuse. It takes into account the recycling efficiency after use.

The indicator is based on the following four principles –
1. Feedstock form the reused or recycled sources.
2. Reuse component or materials after the use of the products.
3. Extend the lifecycle of the products
4. Intensify the use of products

The Circularity Indicator is based on the following inputs –
1. Raw material inputs
2. Utility during use phase
3. Destination after the use phase
4. Efficiency of recycling

2.5.3 Life Cycle Assessment (LCA)

The life cycle stages in the European markets are defined by EN 15978 and EN 15804. These standards can be included in the LCA. LCA is a standardised, science-based tool for quantifying the impact in order to assess lifetime environmental impact.

The LCA measures the environmental impact of a product through every phase of its life – from production to waste (or recycling, etc.) (UNEP AND SETAC, 2002) It is an environmental tool used to qualitatively analyse the life cycle of products within the context of environmental impact. All material and energy flows throughout the life cycle of a product are summed up. The LCA assessment can be used to compare different life cycle scenarios of the building. The results of the LCA assessment of the building can be validated by comparing them to the result of a similar building.

LCA consists of four fundamental steps –
1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

The five important steps of a product life cycle from cradle-to-grave include raw material extraction, manufacturing and processing, transportation, usage and retail and waste disposal. The cradle-to-cradle approach consists of an additional step of benefits and loads beyond the system boundaries. The Figure 9 illustrates the different stages of Life Cycle Assessment as listed in BSEN15978. The Cradle-to-cradle approach is adopted in the project since the project is focused on the End-of-Life and Beyond End-of-Life stages.

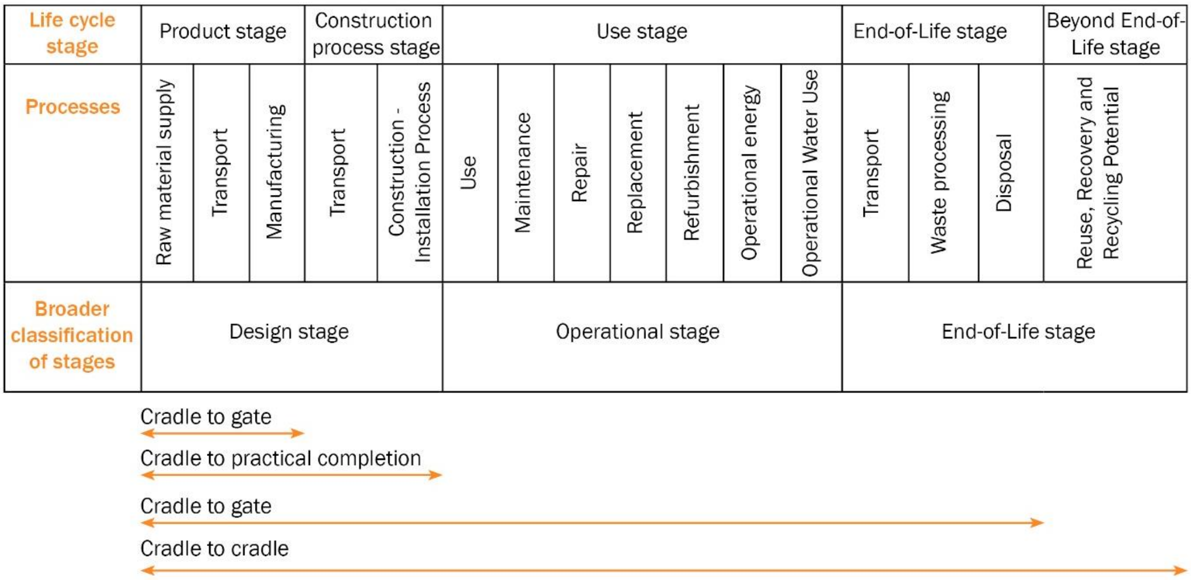


Figure 9 Life cycle stages in construction works from BSEN15978

The difference between LCA and MCI is their focus areas. Where the LCA looks into the environmental impact of the product during its life cycle, comparing different scenarios, the MCI is only concerned with the materials that are used in the system and the materials that are returned from the system. Hence it majorly focuses on the quantity of materials used in a system. Where the LCA balances the environmental impacts of the input and output of the material processes during the life cycle of the product, the MCI concentrates mainly on the use of recycled or reused materials for the production of the product and the reuse and recycling possibilities at the end of use of the product.

2.5.4 Material Flow Analysis (MFA)

As described by Brunner and Rechberger (2016), MFA is described as a "systematic assessment of the state and change of material flow and stock in space and time." MFA is a detailed analysis of flow of all the materials within a system boundary. MFA represents an empirical and intuitive support for decisions concerning the environmental management of natural resources and waste. The MFA measures the input and output flows of materials to a system within a specific place and timeframe. The input flows equal the output flows plus the additional materials stored in the system. The primary focus of MFA is to calculate the flow of materials in terms of volume and mass as input and output values in a system as opposed to the LCA's purpose of calculating the environmental impacts.

MFA is a detailed analysis, while MCI provides ways to use materials efficiently. MFA allows the researchers to trace inputs, outputs, waste, and emissions from the beginning to the end of a process by keep track of measurements of characteristics like flows, processes and stocks. MFA measures the input of natural resources, use of recyclables and the loss of valuable material.

MFA does not take into consideration the reduced quality of secondary materials, compared to the quality of primary materials. Hence it does not take into account down-cycling of the materials. In MFA, another important aspect of the Circular Economy is missing which is the measurement of the reduction of emissions. It focusses on the material flows within the system. (Elia, Maria, & Tornese, 2017).

2.5.5 Building Circularity Index (BCI)

The Life Cycle Assessment developed by Alba Concept's in 2015 measures the circularity potential of a new or existing building. It combines the various measurement methods for environmental impact and circularity in one integrated tool. While other measuring methods like the MCI and MCA focus on the raw materials and material use, the BCI also attempts to provide insights into building detachability. BCI specifically focuses on the circularity of buildings. It takes into consideration the factors like the material use, recyclability along with disassembly and adaptability of the building. BCI has an approach of 'cradle-to-grave' and not 'cradle-to-cradle'. It does not take into consideration the benefits beyond the EoL as considered by LCA's cradle-to-cradle approach.

As stated in BCI Gebouw (2022), the BCI provides insight into the following performances-
1. Environmental Performance Buildings
2. Environmental Cost Indicator
3. Paris Proof indicator
4. Global Warming Potential
5. Construction Stored Carbon
6. Material Circularity Index
7.Percentage of bio-based material
8. Percentage of non-virgin material

2.5.6 Conclusions

No.	Assessment method	Advantage	Disadvantage
1	MCI	1. Takes into account material inputs and outputs. 2. Focused on evaluating specific products and systems.	1. Does not take into account the complexity of the circularity since it does not take into account the aspects like biodiversity, toxicity and human health impacts 2. Does not take into account the CO2 emissions thus the results showcase a high score for the materials with a high recycled content. 3. Only focused on calculating the quantity of the input and output of materials in a system.
2	LCA	1. Takes into account the entire life cycle of the building. 2. Calculates the environmental impacts based on different indicators. 3. Includes stages regarding EoL processing impacts and benefits beyond the EoL stages.	1. Complex and time consuming. 2. Requires an extensive database to obtain accurate results.
3	MFA	1. MFA is a detailed analysis of flow of all the materials within a system boundary.	1. Does not calculate the environmental impacts but calculates only the input and output flows as quantities in a system.
4	BCI	1. Offers information about the building detachability along with the input and output of materials in the system.	1. Only takes into account a cradle-to-grave approach and not cradle-to-cradle approach. 2. It does not consider benefits beyond system boundaries.

Table 4 Comparison of the different circularity assessment methods

The different circularity assessment methods were analysed and LCA was chosen as the assessment method majorly because it takes into account the EoL stage and Beyond EoL stage and calculates the environmental impacts of these stages along with the manufacturing stage. Since these stages are important to tackle the research gap, LCA was further used as an assessment method for the project.

3 Case Study and Case Development

The section exhibits the AEGiR façade renovation project as a case study and derives different passive and active components required to satisfy the operational energy demands. The components of the AEGiR project are studied further to develop a case in the context of the Netherlands. The case developed in the context of the Netherlands aims to meet the country's energy performance criteria for housing renovation projects by adding an additional envelope layer to the existing houses.

3 Case Study and Case Development

3.1 AEGiR project as a Case Study

3.1.1 Introduction

Europe aims at achieving climate neutrality by 2050, a net zero economy through the deep decarbonisation of all the sectors (European Commission,2015.). The number of newly constructed buildings is falling. Most of this building stock will still be standing in the year 2050. The old, non-renovated buildings are usually less energy efficient since they require more energy to keep indoor environmental conditions, Thus, there is also an increase in the energy bills of those households. If the indoor conditions are not on the comfort range, it may lead to health problems. The AEGiR project tries to tackle this issue through the strategy of renovation.

AEGiR stands for DigitAl and physical incremental renovation packaGes/ systems enhancing envIronmental and energetic behaviour and use of Resources. The AEGiR façade is an industrialised, prefabricated plug and play system. Such a system not only provides modularity and flexibility but also reduces the time required for the renovation process to a minimum. The project intends to achieve circular material flows by using industrialised and modular system and aims to provide affordable solution according to the needs of the inhabitants.

3.1.2 AEGiR Renovation concept

The primary reason for renovation is to enhance the aesthetics followed by performance and remediation (Martinez et at., 2015). The number of newly constructed buildings is falling in the Netherlands, and this has led to a market rise of 50% for restoration and renovation projects (ABN AMRO, 2014). Thus, the focus on renovation projects is increasing. According to Ebbert (2010), the reasons for a renovation can be due to building immanent factors, legal reasons or economic reasons.

The degree of intervention for 'Renovation' can cover a range of measures consisting from a cosmetic renovation to a complete demolition. These are summarised in the Figure 10 below.

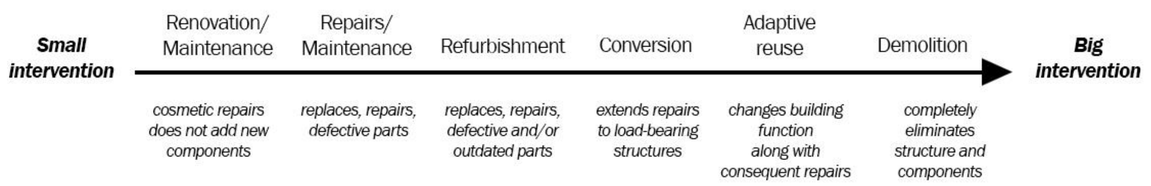


Figure 10 Degree of intervention to the building (Konstantinou, 2014)

Figure 11 Renovation strategies (Konstantinou, 2014; Henry, 2018)

As seen in the Figure 11, the renovation of the envelop can have three renovation strategies. The Add-in strategy considers adding a layer of insulation from the inside to meet the energy demands, the Wrap-it strategy aims to wrap the existing structure with an additional layer of components and the Replace strategy replaces the building envelop of the existing building.

The AEGiR project takes into consideration the renovation strategy of Wrap-it. It wraps the entire envelope with an additional components layer. The project comprises of a modular façade system, a modular roof system and energy generating components. The thesis project focuses only on the modular façade system.

3.1.3 AEGiR façade system

The AEGiR façade system has active and passive components. The façade structure, insulation and façade cladding, act as the passive components. The solar panels, ventilation ducts and the active windows act as the active components. The active and the passive components together act as a façade ensemble.

The components of the AEGiR façade system are shown in the figure below.

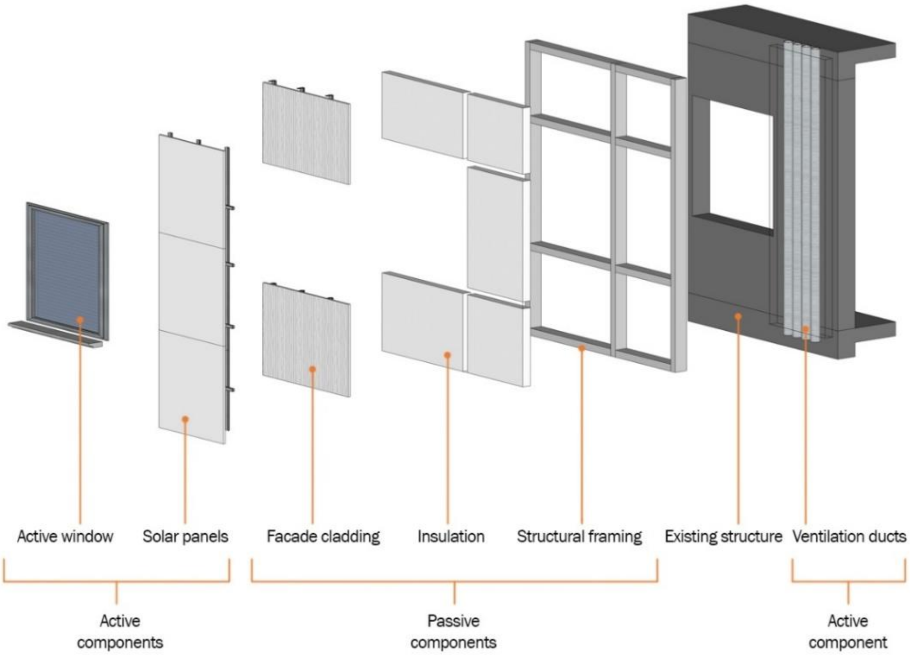


Figure 12 Components of the facade system

The façade is built externally to the existing façade. The externally built façade structure comprises of a mullion and transom system that acts like a structural frame making the system a self-supporting system. The other components in the system comprise of the façade cladding, insulation, ventilation ducts, solar panels and the active window which are mounted on the existing structure along with the façade structure.

3.1.4 Conclusions

The AEGiR project aims to achieve circularity of the added systems. It helps to achieve energy goals by adding active components like solar panels and the ventilation system and passive components like insulation which helps to increase the Rc value. The cladding system helps to improve or change the aesthetics of the façade and a structural system which assists to mount the new façade and take the load of the components.

The thesis project takes forward the concept of façade project and develops a case in the context of the Netherlands. The thesis uses the components used in the AEGiR in order to achieve the renovation goals. The wrap-it approach is adopted to develop the designs for a façade system for renovation.

The concepts from the AEGiR that are carried forward are-

1. Circularity of the additional envelop.
2. The components taken into account for AEGiR
3. Prefab, industrialised envelop system.
4. The new system follows a wrap-it approaches.

For the further steps, a case is developed in the context of the Netherlands based on the existing literature related to the housing stock in the Netherlands. This developed case in the context of the Netherlands is used as a base to develop different design variants of the new façade system and the variants are further tested.

3.2 Case development

3.2.1 Considerations for the existing structure

The case that is developed is used as a base to further develop different preliminary façade design variants to conduct research. These design variants are elaborated in the next chapter in detail.

The Netherlands has an ambition to become fully circular by 2050 (European Commission,2015.). The Dutch housing forms an important part of the Dutch building stock. To reduce the operational energy demand of the housings in the Netherlands, they are renovated. The early Dutch housing which was built to tackle the housing crises after the World War II constructed between 1946 to 1969 followed a prefab and industrialised construction technique (Van Thillert, 2002). This housing makes up around one-third of the total Dutch housing stock. The lifespan of these houses is more than the original intended lifespan of 50 years. These housings no longer comply with the energy requirements (de Vreeze, 2001; Liebregts & van Bergen, 2011).

The developed case is a post-war housing unit in the context of the Netherlands. The structural system considered is a RCC framed structure. The Rc value of the existing façade system is 2.53 m^2K/W (Voorbeeldwoningen, 2011). Thus, an additional Rc value of 2.23 m^2K/W is required to satisfy the current energy demands.

3.2.2 Considerations for the new façade system

While developing different design variants for the façade system, it was considered that the material and dimensions of the solar panels and the ventilation system are kept constant. The façade structure, insulation, façade cladding, window frame and the support system for the solar panels and the support system for the façade cladding change in materiality and dimensions for different design variants.

The performance criteria like thermal performance of the façade system, thermal comfort, acoustic performance, energy performance, daylight conditions and the Rc value are kept constant for all the design options.

3.2.3 Conclusions

The existing structure is renovated with a façade system incorporating components similar to AEGiR project.

<u>Constant criteria</u>

The following criteria are kept constant while developing different design variants –
1. Thermal comfort
2. Acoustic performance
3. Energy Performance
4. Daylight conditions
5. Rc value of the insulation

<u>Constant components</u>
The following components are kept constant with respect to materiality and dimensions while developing different design variants -
1. Solar panels
2. Ventilation system

<u>Variable components</u>
The following components vary in materiality and dimensions of the standardised materials for the different design variants-
1. Façade cladding
2. Insulation
3. Façade cladding

4. Façade cladding support
5. Solar panel support
6. Window frame

Taking the above-mentioned constant criteria into account, a preliminary design for the three panel modules was developed taking into consideration the components involved. The preliminary design panels are explained in the next chapter.

Further, the constant and the variable components were considered to develop multiple variants of the preliminary design.

4. Design Process

The Design Process consists of developing a basic design scheme for the façade system. Different panel designs which satisfy different façade functions along with the function of generating the energy are considered in this section. A study of different materials is conducted with respect to their lifespans and possible end of life scenarios as a part of the design process. Different design scenarios and variants are developed taking into consideration the study of materials.

4 Design Process

4.1 Preliminary Design

The project focused on the preliminary design decision making and guides the façade designers to take decisions considering the various EoL scenarios.

The designed system is a prefab system with transom and mullions acting as the main structural system for the prefab panels. The prefab panel is hung to the structural system of the existing building by a bracket which is mounted on the structural system of the existing building beforehand.

Three different façade modules were developed to include different components and they satisfy various functions of a façade system. The first module (Panel A) consisted of a façade structure, insulation, façade cladding and imparts an aesthetical aspect to the façade system. The second module (Panel B) had an opening and consisted of façade structure, insulation, façade cladding, active window. The third module (Panel C) focused on including the active components and has façade structure, insulation, ventilation system and solar panels.

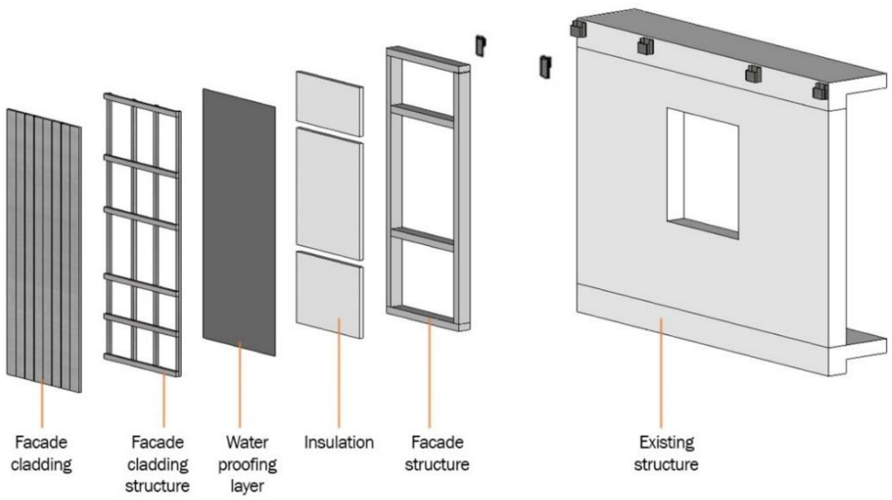


Figure 13 Panel A by author

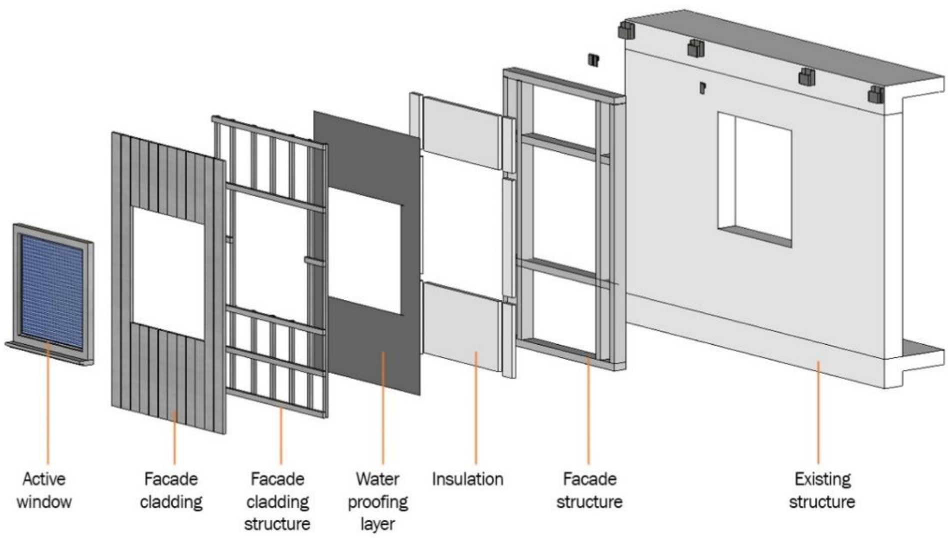


Figure 14 Panel B by author

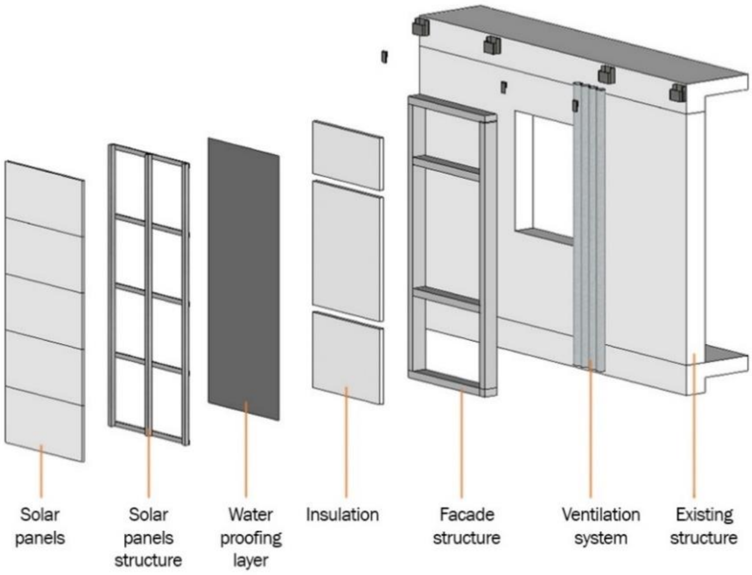
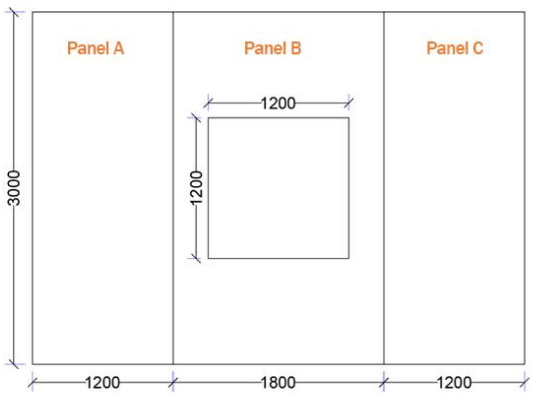


Figure 15 Panel C by author



Components in panel A, B and C

	Panel A	Panel B	Panel C
Facade structure	✓	✓	✓
Insulation	✓	✓	✓
Facade cladding	✓	✓	
Active windows		✓	
Solar panels			✓
Ventilation ducts			✓

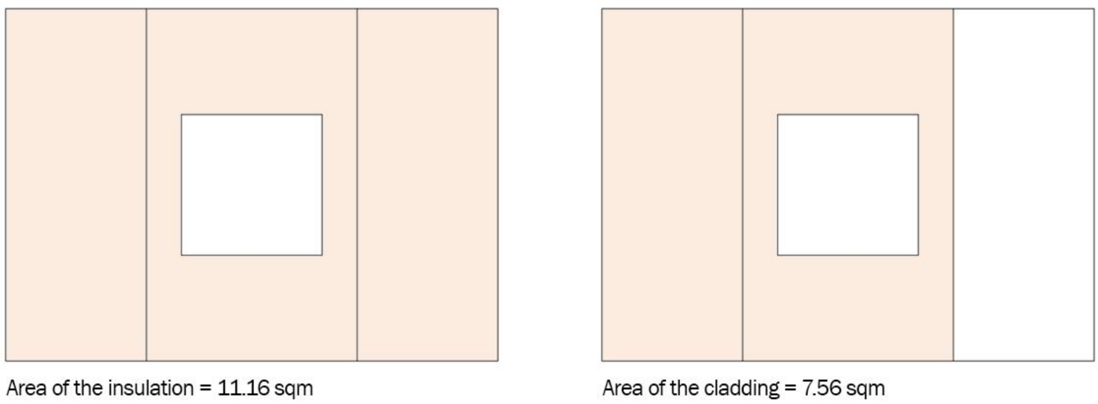


Figure 16 Dimensions of the Panels and Components considered in each panel by author

The next step involves a study of different materials for the components considered which takes into account the end of technical service life scenarios and technical lifespans of the standardised materials.

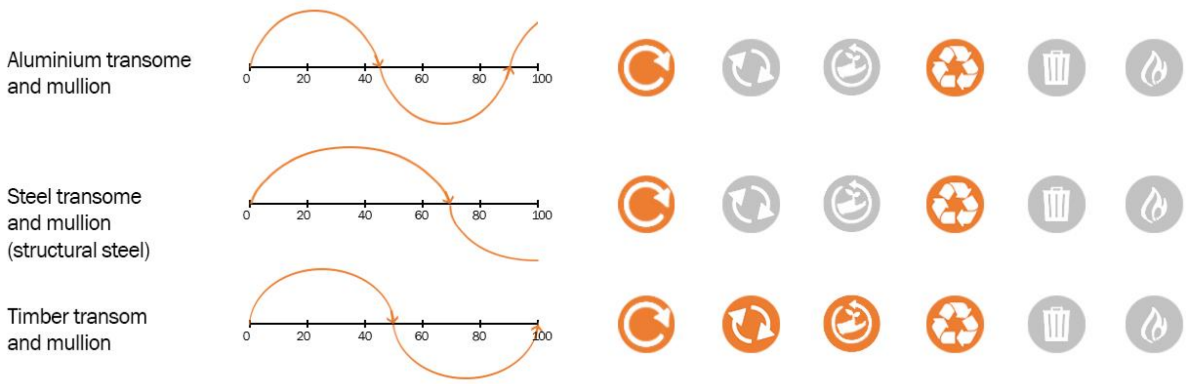
4.2 Material Study

4.2.1 Material study based of the standardised materials

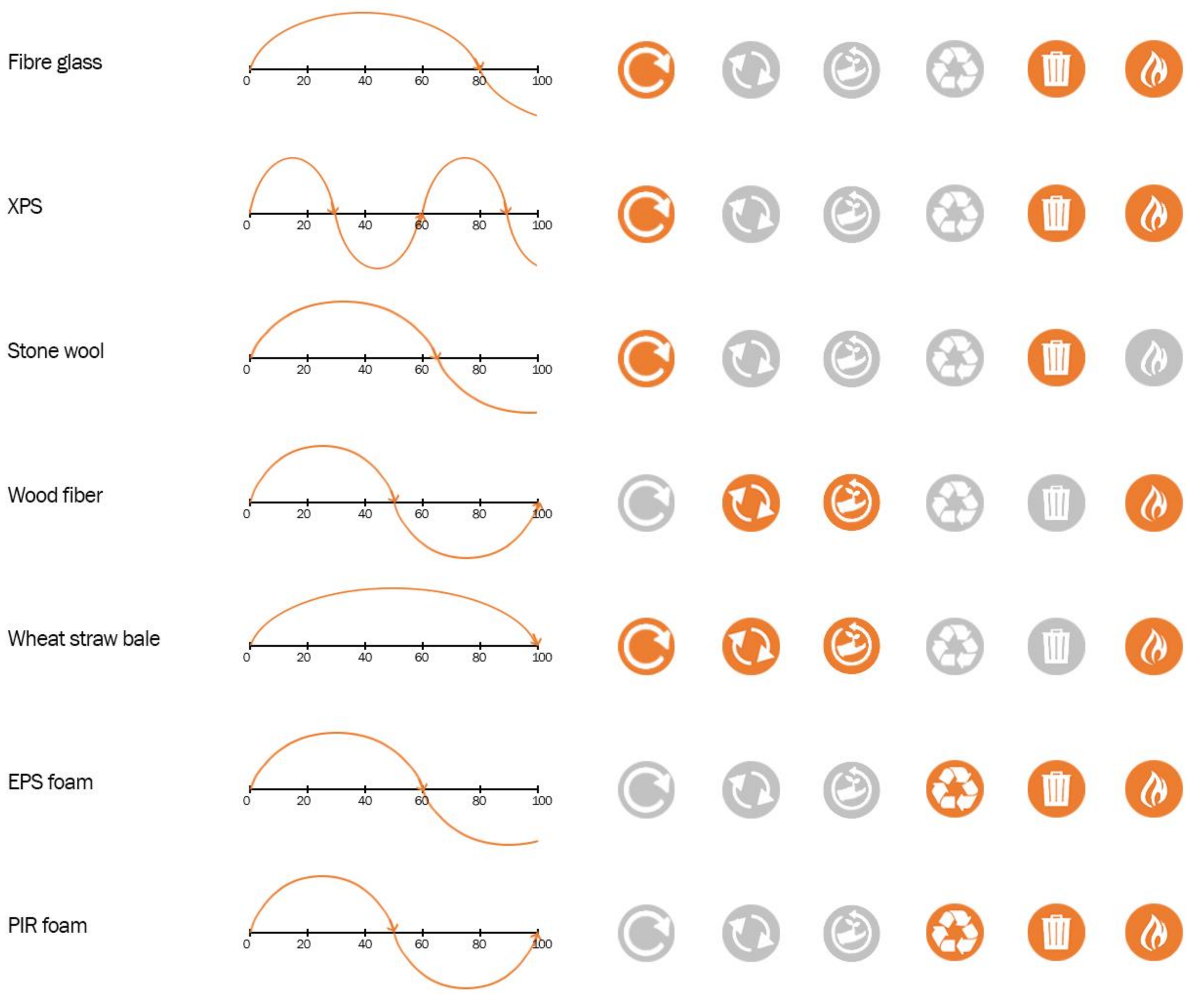
Different standardised materials were analysed with respect to their End-of technical service life and their lifespans to develop various scenarios. The technical lifespans are taken from Nationale Milieudatabase.

Material **Lifespan (years)** **End of life**

Façade structure



Insulation



Façade cladding

Fair-faced brickwork

Fibre cement board

Natural stone cladding

Glavanised steel cladding

Aluminium facade cladding panel

PVC platic

Clay plaster with flax-fibres

Rammed earth

Timber weatherboarding

Ventilation system

Steel ducts

Fans

Solar panels

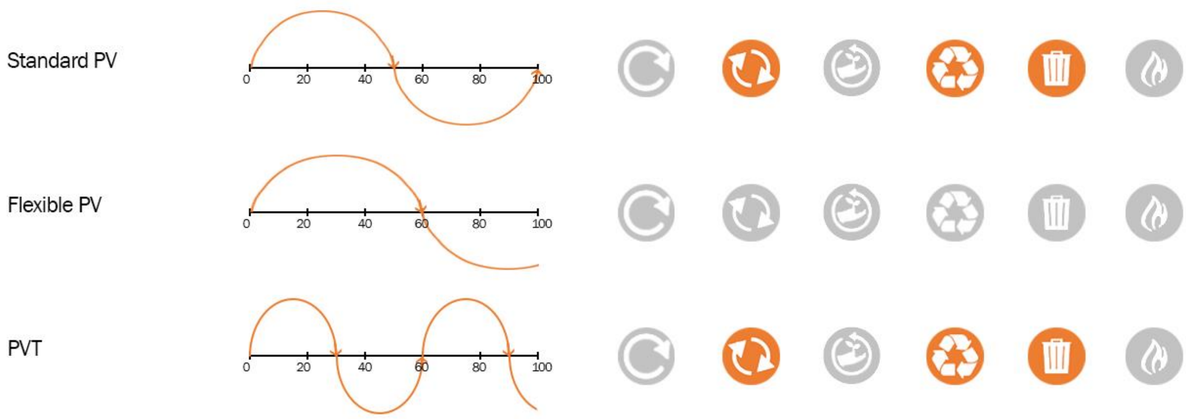


Figure 17 Lifespans and End-of-life scenarios of different components by author

It was found that there are some standardised materials that have a lifespan more than 60 years i.e. two technical life cycles of a façade system with each cycle consisting of 30 years. Some standardised materials have a lifespan which is less than 60 years but more than one technical life-cycle of a façade system. Hence, the scenarios for the technical materials were classified into - Standardised materials and components with a long life-span (life-span more than 60 years) and Standardised materials and components with a short life-span (life-span more than 30 years but less than 60 years). The third scenario is for the biological materials. Most of the standardised biological materials have a short-lifespan.

4.2.2 Conclusions

The following three scenarios were drawn from the standardised material and End-of-Life market scenarios-

1. Long lifespan standardised materials (standardised materials and components with lifespan more than 60 years)
2. Short lifespan standardised materials (standardised materials and components with lifespan more than 30 years but less than 60 years)
3. Bio-based materials (standardised materials and components made from biological resources)

Since, the EoL scenario of reuse is considered at the top of the R-ladder to achieve circularity, it is found that it is possible to use the standardised materials with a longer lifespan for multiple technical life cycles of a façade system. The shorter lifespan standardised materials will majorly have to be recycled or recovered for energy at their EoL. The long lifespan standardised materials can be grouped together to achieve reuse of the system as a whole instead of a reuse on a standardised material level. The end of technical life plays an important part in taking decisions regarding a design since the standardised materials can be fed back into the same system or other system. Since, different standardised materials have different lifespans and EoL scenarios, different design variants are designed and evaluated for their environmental impacts and market-based material and installation costs. These environmental impacts and costs help to analyse the choice of materials and their EoL conditions across different variants.

For a circular façade renovation, different design options of the façade system are developed and evaluated based on the key performance indicators. The different design options are called as the variants. The different variants take into account the different technical lifespans of the standardised materials and their EoL scenarios. These scenarios and variants are elaborated in the next chapter.

4.3 Development of scenarios and design variants

4.3.1 Design scenarios and Design variants

When a façade system reaches the end of its technical service life, it is either reused, recycled or recovered depending on its wear and tear and degradation. A decision regarding these factors which needs to be taken at the design stage is based on the lifespans of the components in the facade system. The façade design scenarios are developed taking into consideration various EoL scenarios and lifespans of the components.

The long lifespan standardized technical materials scenario refers to a system developed such that the maximum material in the system is reused at the end of first technical service life. The second scenario is developed taking into account the materials that have a shorter lifespan. At the end of first technical service life, these materials are majorly recycled. Bio-based system aims to achieve biodegradability at the end of the first technical service life. The bio-based system takes into consideration maximum use of bio-degradable materials. Thus, each system that is developed either tries to maximize reuse, recycle or biodegradability.

Construction techniques and materials have an impact on the EoL conditions of the system. Thus, the variants take into account the different circular design strategies which are based on the selection of construction materials and techniques. Within the scenarios, different variants are nested which emphasize on the different circular design strategies like using traditional materials, low-cost standardized materials and materials with low production energy.

The circular design strategies are elaborated below-

1. Traditional materials–These are the standardized materials which are manufactured using the available local materials and are used traditionally. This is important towards EoL because it is easier to repair or refurbish these materials since the raw material and the construction technique are easily available. The labour is also skilled in the application of the construction techniques. After the EoL this concept of local materials can be extended wherein the local materials are the materials/ components or systems that are sourced from the surrounding areas of the construction site are reused.

2. Low-cost standardized materials –Economic materials and construction techniques refer to the materials and techniques that are available at a cheaper cost. These materials have a reduced material cost, processing and manufacturing cost, less resource consumption. Economic construction involves using the resources efficiently so that the material and the construction cost less over time.

3. Low material production energy – The standardized materials made from these variants have a low material production energy required. These materials are the materials that have not undergone heavy processing in the standardized material manufacturing stage. They refer to the application of materials in the system in their natural form. These are majorly materials that are made from a single material/ material with simple construction solutions for easy separation during recycling process.

By taking into account the above-mentioned factors, different variants were developed. The developed design variants are considered for a lifespan of over 90 years. Where in one lifespan is assumed to be of 30 years.

4.3.2 Developing the design variants

Taking into account the above-mentioned criteria, different standardised materials were considered to develop the different variants. The table below entails the list of standardised materials considered for developing the different variants -

	Traditional materials	Low-cost standardised materials	Low material manufacturing energy	
Facade fraction name	**Variant 1**	**Variant 2**	**Variant 3**	Long-life span standardised materials
Facade structure	Structural steel I section	Steel box section	Structural steel I section	
Insulation	EPS	Fibre glass	Stone wool	
Facade cladding	Clay click bricks	Fibre cement board	Natural stone cladding	
Facade cladding frame	Steel sheet for click bricks	Steel hollow box section	Steel hollow box section	
Solar panel frame	Steel box and U section	Steel hollow box section	Steel hollow box section	
Window frame	Wooden frame	Aluminium	Steel	
Facade fraction name	**Variant 4**	**Variant 5**	**Variant 6**	Short-life span standardised materials
Facade structure	Aluminium extrusion profiles	Aluminium extrusion profiles	Aluminium extrusion profiles	
Insulation	XPS	PIR foam	Glass wool	
Facade cladding	Galvanised steel sheet	Aluminium facade cladding panels	PVC Plastic	
Facade cladding frame	Steel hollow box section	Aluminium extrusion profile	Aluminium extrusion profiles	
Solar panel frame	Steel hollow box section	Aluminium extrusion profile	Aluminium extrusion profiles	
Window frame	Steel	Aluminium	Aluminium	
Facade fraction name	**Variant 7**	**Variant 8**	**Variant 9**	Bio-based standardised materials
Facade structure	Pine wood	Pine wood	Steel channels	
Insulation	Wood fibre	Wheat-straw bale	Rammed earth	
Facade cladding	Facade wood panel	Clay plaster with flax fibre	-	
Facade cladding frame	Pine wood	Steel mesh	-	
Solar panel frame	Pine wood	Pine wood	Steel angle sections	
Window frame	Pine wood	Pine wood	Pine wood	

Table 5 Selected materials for various components by author

Variant 1: Long lifespan standardised materials with modern traditional insulation and cladding system

As the name of the variant suggests, Variant 1 consists of standardised materials with long lifespans. The façade structure consists of structural steel sections since they have a long lifespan. The materials used for the insulation and the cladding system are traditional materials that have been used in the Netherlands. The insulation material consists of EPS, and the cladding is a brick cladding system. At the end of the first lifecycle (assumed to be of 30 years), the components - façade structure, insulation and the façade cladding are reused. Same is the case with Variants 2 and 3.

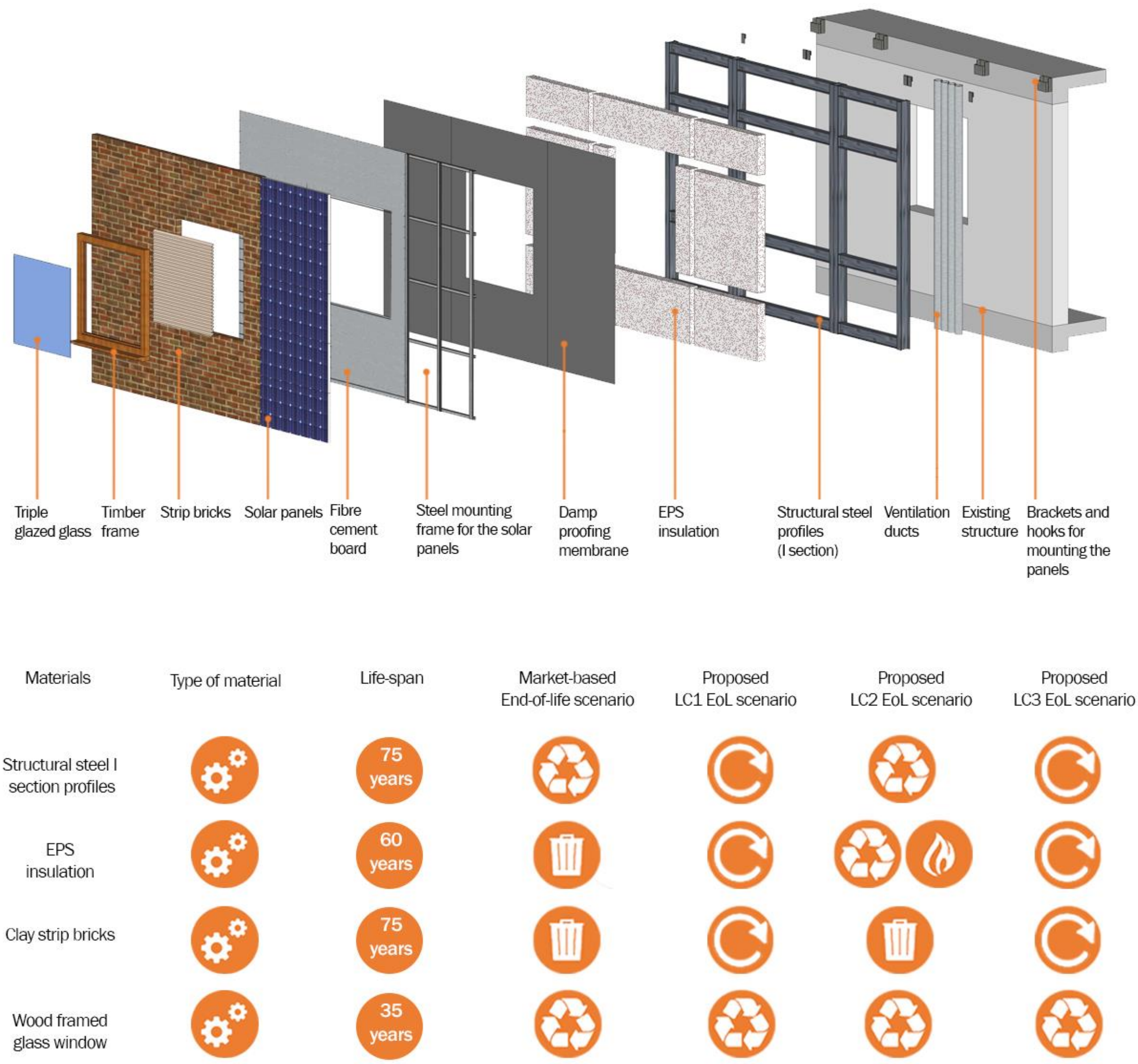


Figure 18 Variant 1 by author

Variant 2: Long lifespan standardised materials with low-cost insulation and cladding standardised materials

The variant 2 comprises of steel as the façade structure element and along with that glass wool insulation which is a cheap insulation compared to the other insulations is used. The façade cladding consists of flat fibre cement panels which are cheaper than the other cladding materials with a higher lifespan.

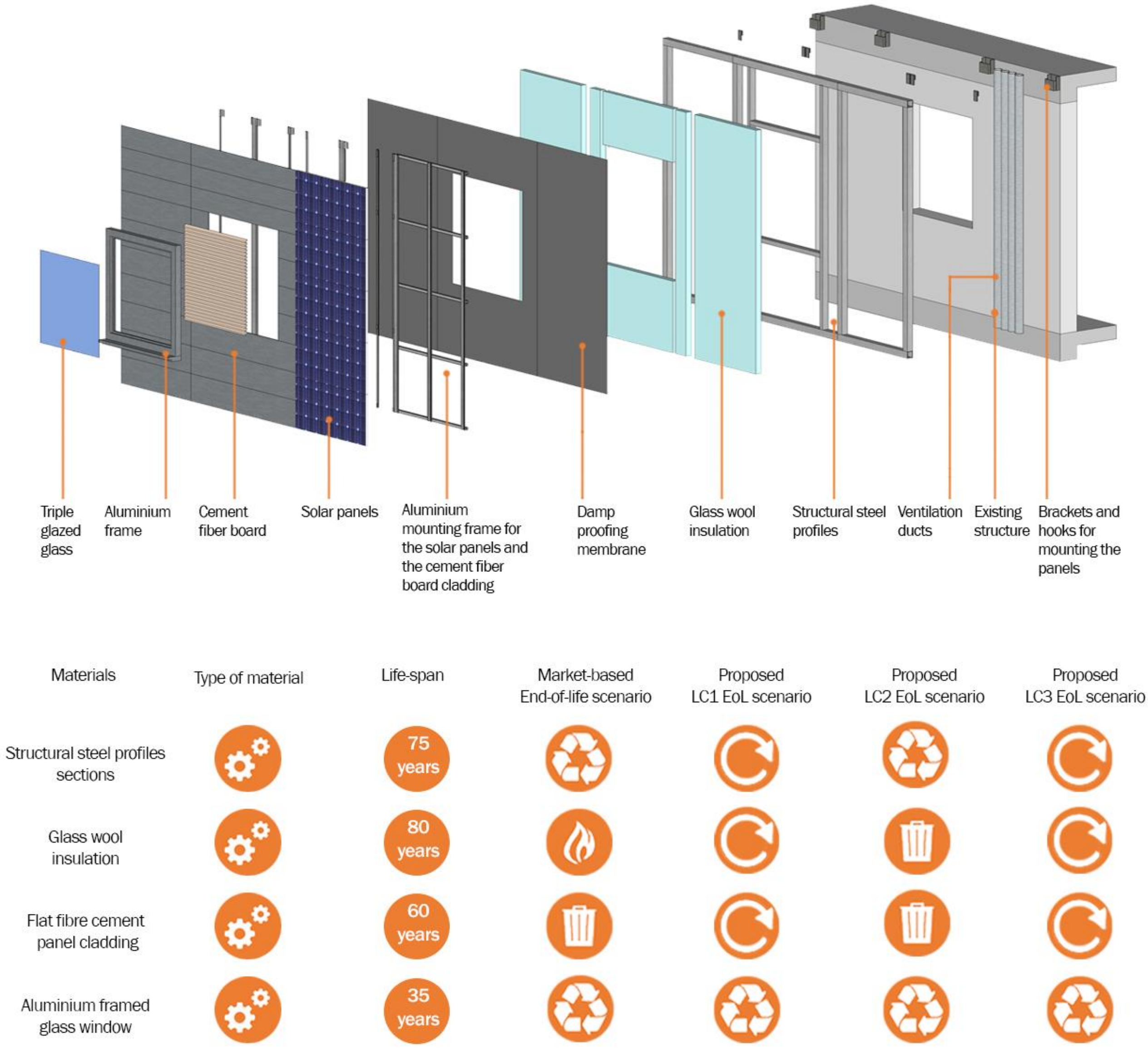


Figure 19 Variant 2 by author

Variant 3: Long lifespan standardised materials with low material production energy

As the name of the variant suggests, the materials used in this variant are such that the materials required to manufacture the standardised materials do not require a high amount of material production energy. In these cases, even though the energy required to manufacture the standardised materials can be high, the material itself does not require a high energy for production. The insulation material is made from rockwool and the cladding material is made from natural stone. The structural system is kept constant as the Variant 1 and Variant 2.

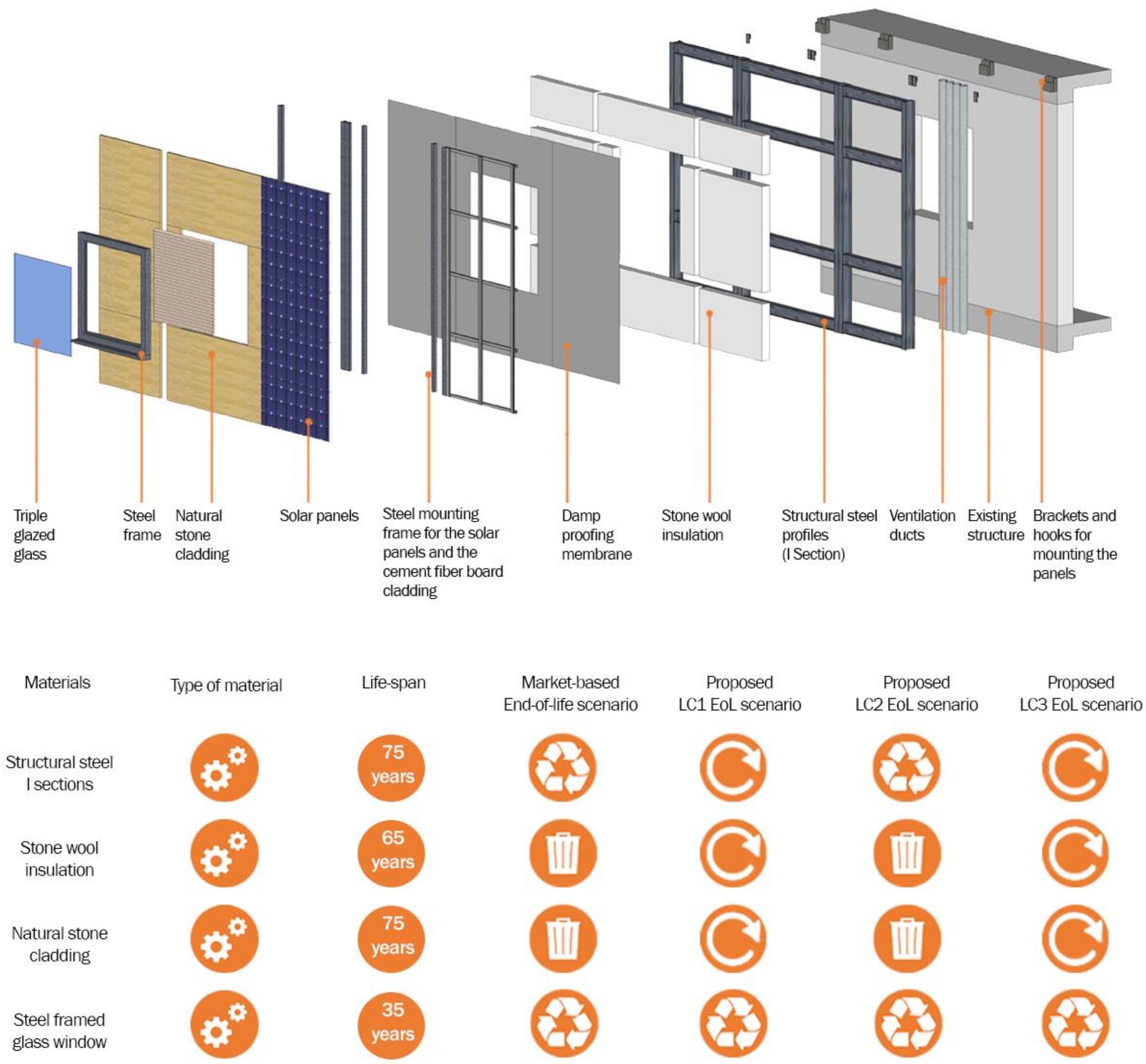


Figure 20 Variant 3 by author

Variant 4: Short lifespan standardised materials with modern traditional insulation and cladding system

As the name suggests, this variant takes into consideration the modern traditional materials having a short lifespan. These materials include XPS insulation for the insulation and corrugated steel for the cladding system. The window is a steel framed window system. The figure below illustrates the proposed EoL conditions which are the most circular options. For the Variants 4,5 and 6 the façade structure, the insulation and the cladding are recycled at the end of first technical life.

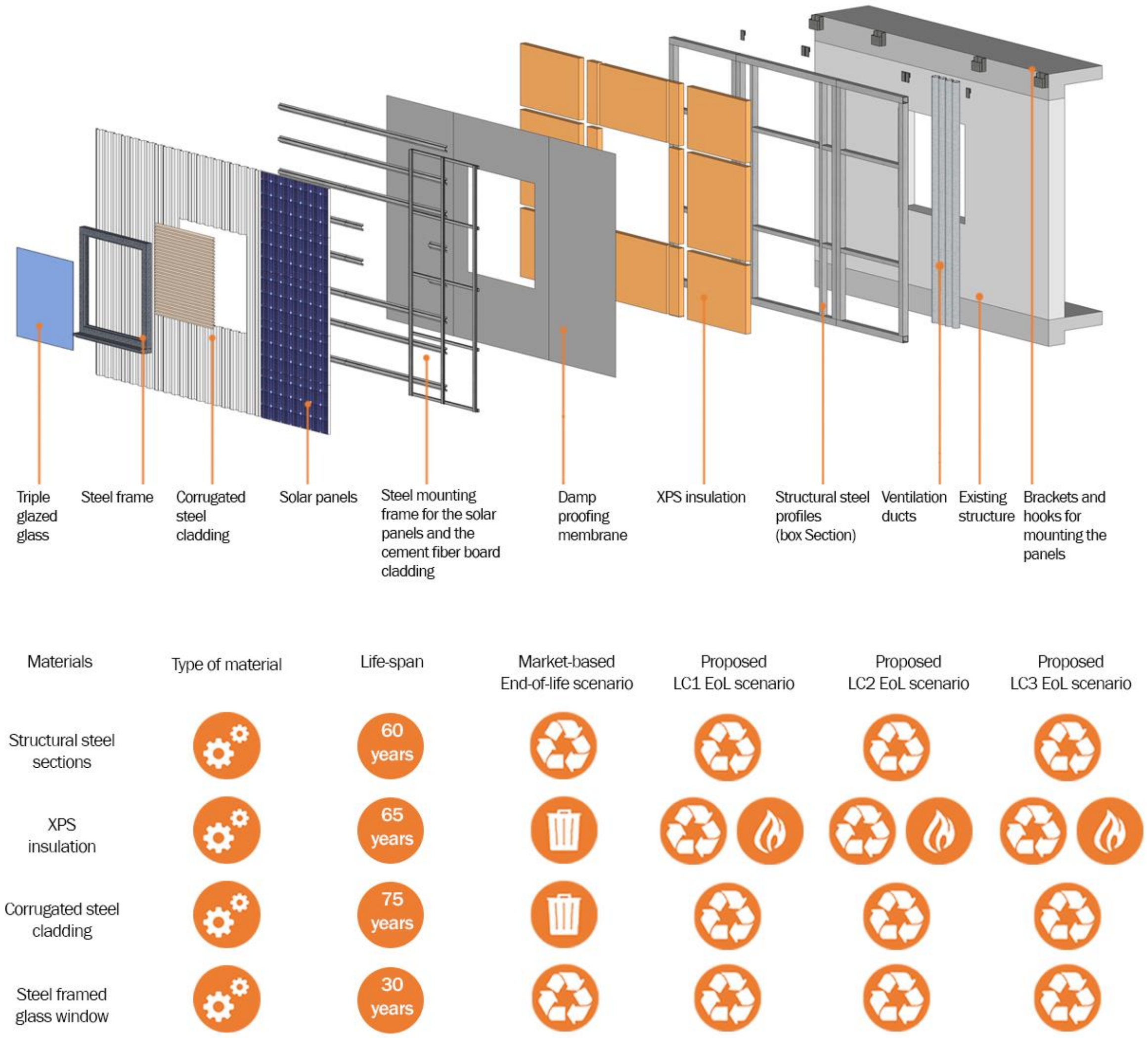


Figure 21 Variant 4 by author

Variant 5: Short lifespan standardised materials with low-cost insulation and cladding standardised materials

This variant consists of aluminium façade cladding since it is a low-cost material and PIR foam as the insulation material along with aluminium windows. Though the manufacturing cost of aluminium is higher, it is cheaper with respect to installation and maintenance expenses compared to steel.

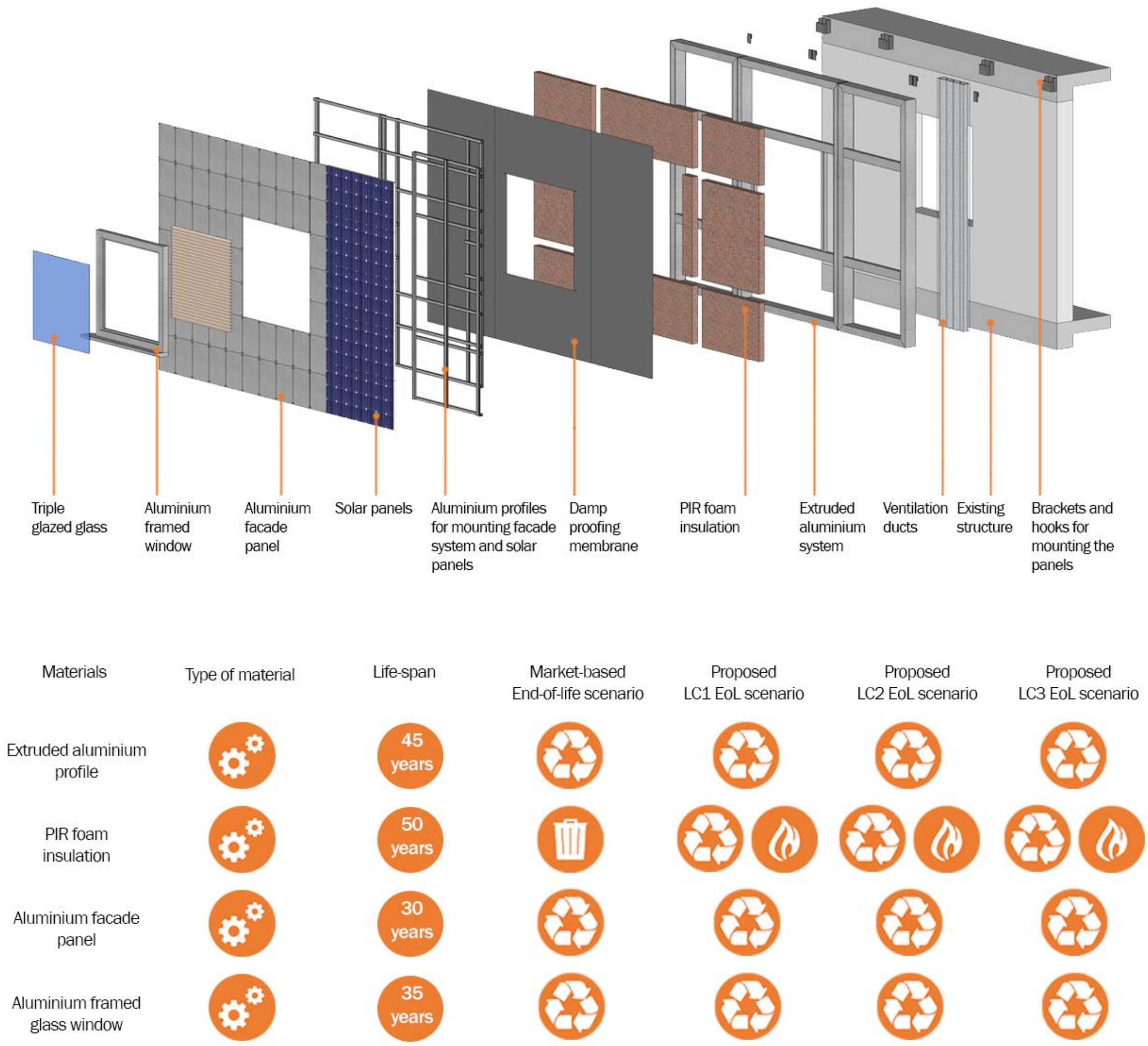


Figure 22 Variant 5 by author

Variant 6: Short lifespan standardised materials with low material production energy

Plastic cladding as the façade cladding, Fibre glass insulation and aluminium facade structure are used in this variant since their material manufacturing energy is low.

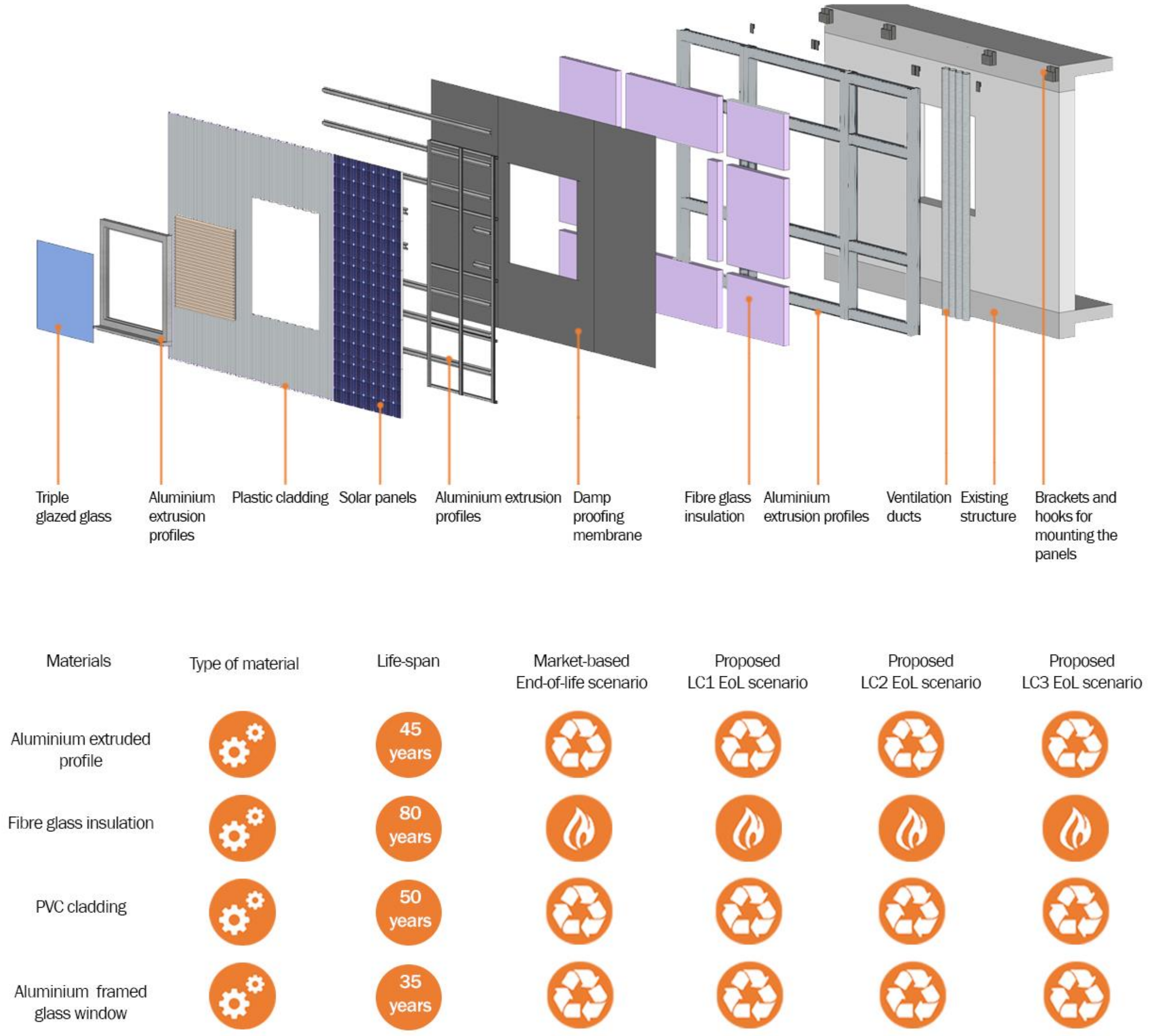


Figure 23 Variant 6 by author

Variant 7: Bio-based standardised materials with modern traditional insulation and cladding system

This variant consists of the traditional materials like wood, wood fibre insulation, wooden façade structure and wood framed window.

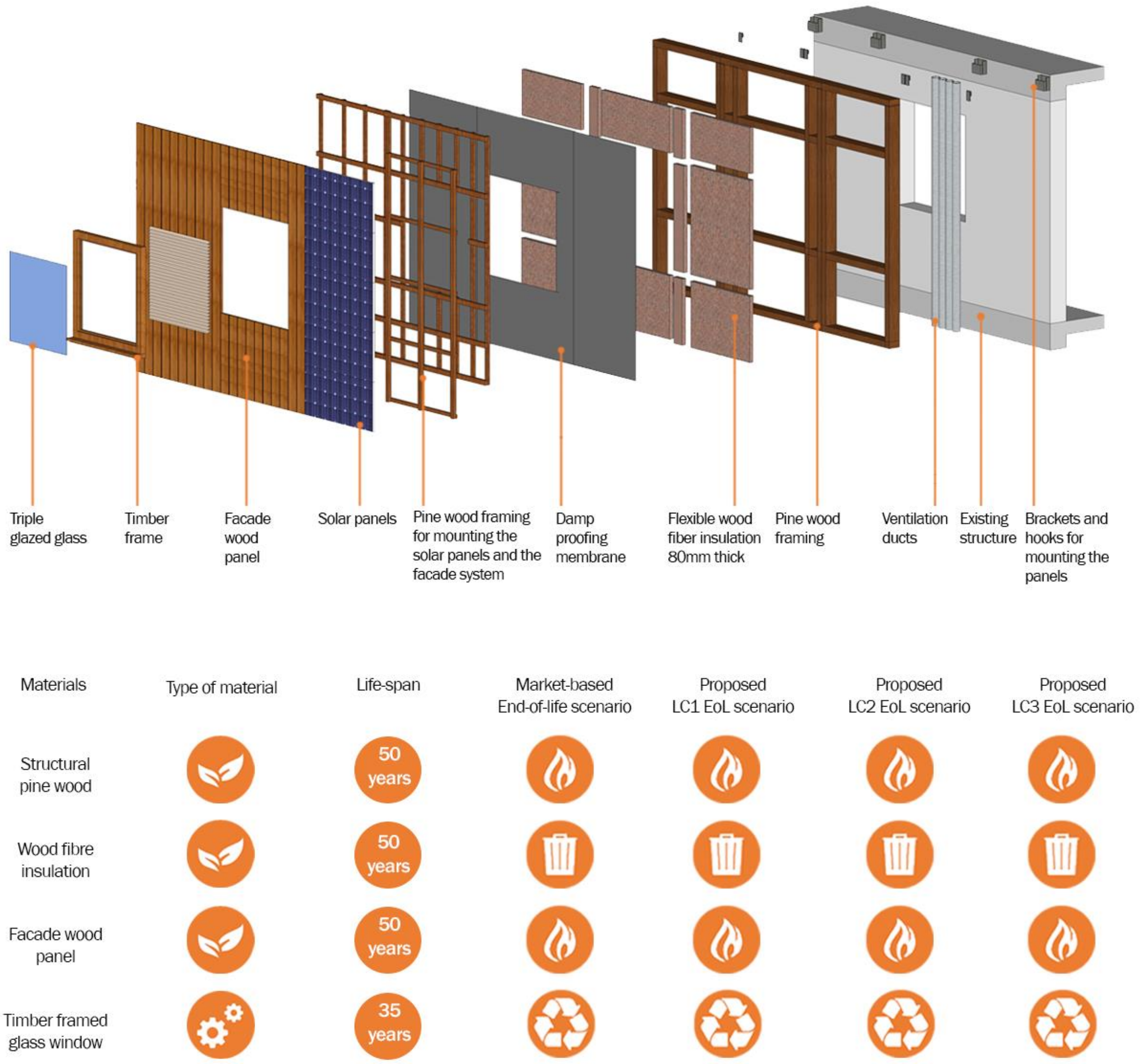


Figure 24 Variant 7 by author

Variant 8: Bio-based standardised materials with low-cost insulation and cladding standardised materials

As the name of the variant suggests, the variant is a low-cost variant amongst bio-based materials. It consists of wheat straw bale insulation with clay plaster and pine wood as the structural system. At the end of life, based on the market scenarios the actions are taken in this particular variant.

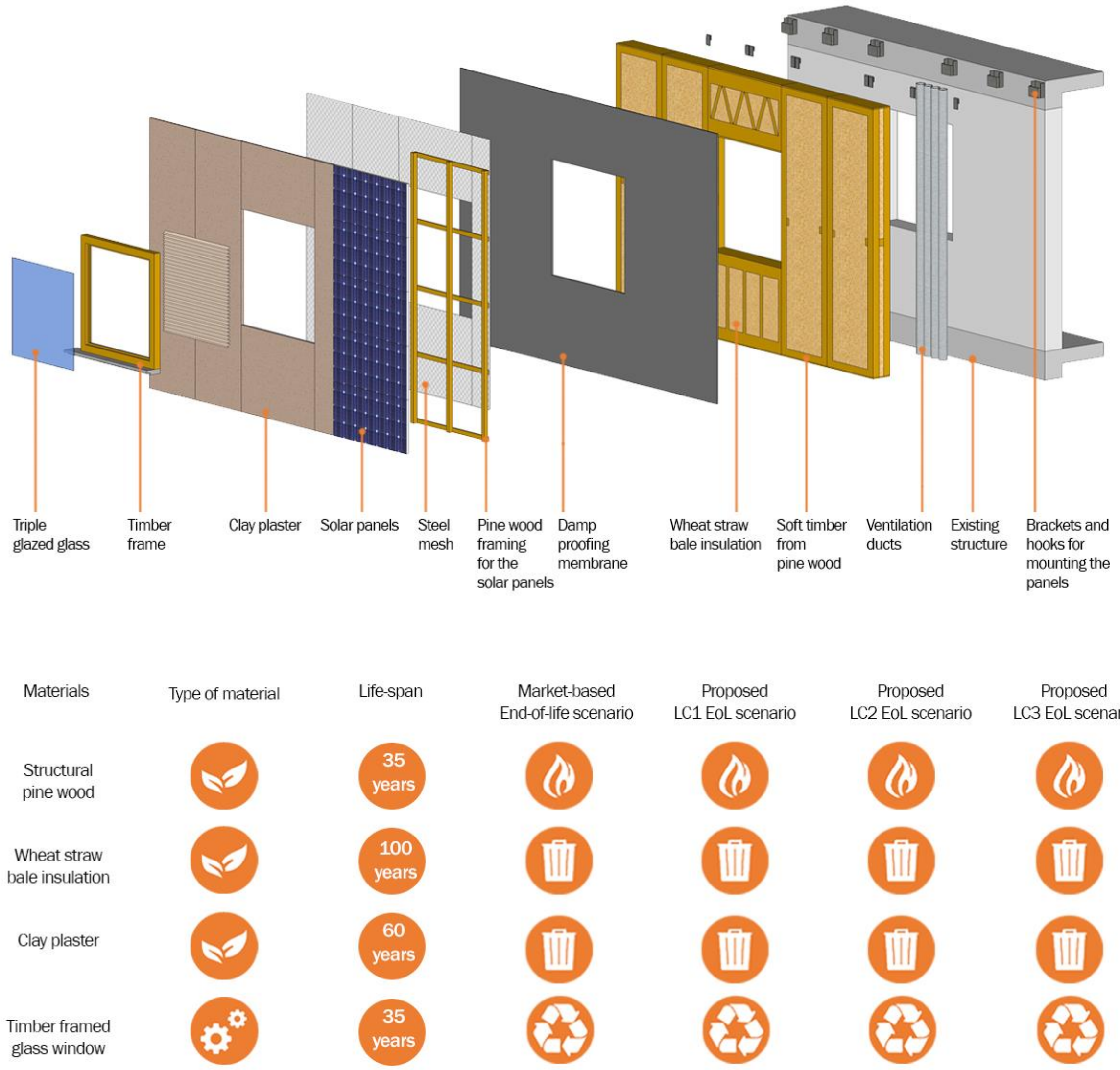


Figure 25 Variant 8 by author

Variant 9: Bio based standardised materials with low material production energy

The bio-based variant has low cost of material production since it consists of rammed earth as the material which is a biodegradable material. The wall requires strong steel supports; hence steel is used as a façade structure.

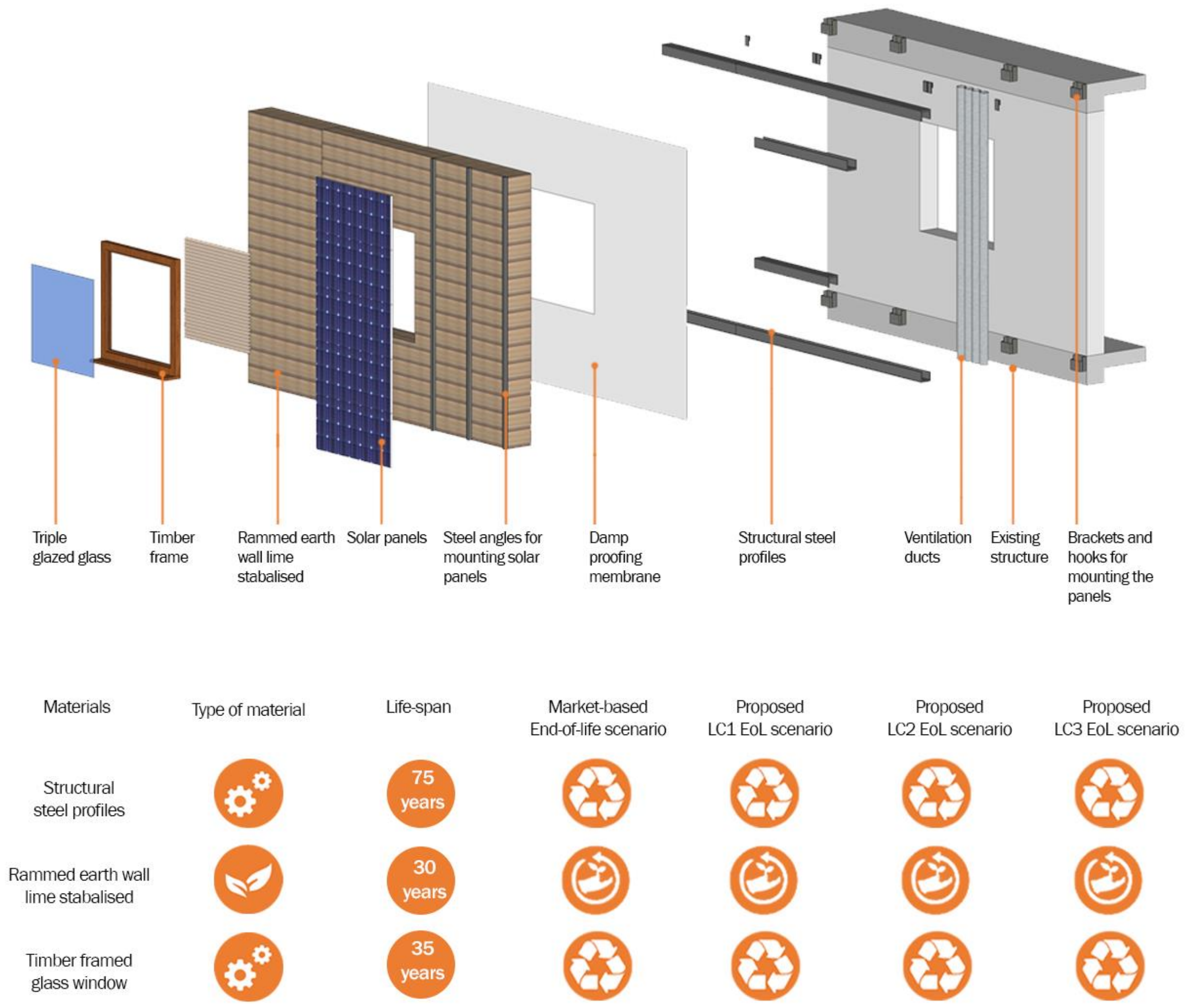


Figure 26 Variant 9 by author

4.3.3 Material quantification of the variants

Variant 1

Component	Standardised material	Density (kg/ cubic m)	Mass (kg)	Volume (cubic m)
Façade structure	Structural steel profile section	7850	550.7	0.07
Insulation	EPS insulation panels	20	2232	111.6
Façade cladding	Click bricks	1430	810	0.566
Façade cladding support	Fibre cement boards	1300	130	0.1
Solar panel support	Structural steel profile section	7850	16.15	0.002
Window	Aluminium frame window	1.44 sqm area		

Variant 2

Component	Standardised material	Density (kg/ cubic m)	Mass (kg)	Volume (cubic m)
Façade structure	Structural steel profile section	7850	550.7	0.07
Insulation	Glass wool insulation with fibre glass	100	83.7	0.837
Façade cladding	Flat fibre cement panels for cladding	1354	60.93	0.045
Façade cladding support	Structural steel profile section	7850	16.75	0.002
Solar panel support	Structural steel profile section	7850	16.15	0.002
Window	Aluminium frame window	1.44 sqm area		

Variant 3

Component	Standardised material	Density (kg/ cubic m)	Mass (kg)	Volume (cubic m)
Façade structure	Structural steel profile section	7850	550.7	0.07
Insulation	Stone wool insulation	60	5.34	0.089
Façade cladding	Natural stone cladding	2515	284.195	0.113
Façade cladding support	Structural steel profile section	7850	16.15	0.002
Solar panel support	Structural steel profile section	7850	16.15	0.002
Window	Aluminium frame window	1.44 sqm area		

Variant 4

Component	Standardised material	Density (kg/ cubic m)	Mass (kg)	Volume (cubic m)
Façade structure	Extruded aluminium profile	2700	223.81	0.083
Insulation	XPS insulation	38	42	1.105
Façade cladding	Galvanised steel	7000	51	0.007
Façade cladding support	Structural steel hollow section	7850	34.02	0.004
Solar panel support	Structural steel hollow section	7850	16.15	0.002
Window	Steel frame window	1.44 sqm area		

Variant 5

Component	Standardised material	Density (kg/ cubic m)	Mass (kg)	Volume (cubic m)
Façade structure	Extruded aluminium profile	2700	223.81	0.083
Insulation	Glass wool insulation	100	83.7	0.837
Façade cladding	PVC façade cladding	1650	95	0.057
Façade cladding support	Extruded aluminium profile	2700	33.41	0.012
Solar panel support	Extruded aluminium profile	2700	16.15	0.006
Window	Aluminium frame window	1.44 sqm area		

Variant 6

Component	Standardised material	Density (kg/ cubic m)	Mass (kg)	Volume (cubic m)
Façade structure	Extruded aluminium profile	2700	223.81	0.083
Insulation	PIR insulation	45.45	50	1.1
Façade cladding	Aluminium façade cladding	2710	7.56	0.003
Façade cladding support	Extruded aluminium profile	2700	33.41	0.012
Solar panel support	Extruded aluminium profile	2700	16.15	0.006
Window	Aluminium frame window	1.44 sqm area		

Variant 7

Component	Standardised material	Density (kg/ cubic m)	Mass (kg)	Volume (cubic m)
Façade structure	Softwood timber	474	208.56	0.44
Insulation	Wood fibre	50	45	0.9
Façade cladding	Façade wood panel	110	130	1.18
Façade & solar panel support	Softwood timber	474	73.95	0.156
Window	Wood frame window	1.44 sqm area		

Variant 8

Component	Standardised material	Density (kg/ cubic m)	Mass (kg)	Volume (cubic m)
Façade structure	Softwood timber	474	310	0.654
Insulation	Wheat straw bale	104	250	2.404
Façade cladding	Clay plaster with flax fibre	1300	295	0.227
Solar panel support	Steel section	7850	14.35	0.002
Window	Wood frame window	1.44 sqm area		

Variant 9

Component	Standardised material	Density (kg/ cubic m)	Mass (kg)	Volume (cubic m)
Façade structure	Structural steel profile	7850	362	0.046
Façade cladding, Insulation	Rammed earth wall	1830	1500	0.819
Façade cladding support	Structural steel hollow section	7850	14.35	0.002
Solar panel support	Structural wood	474	60	0.126
Window	Wood frame window	1.44 sqm area		

Table 6 Material quantities of all the variants by author

4.3.4 Selected assessment methods and tools selection

Different assessment methods were analysed and Life Cycle Assessment (LCA) was chosen as the assessment method since it takes into account the environmental impacts of the entire life cycle of a system. The impacts caused at the Manufacturing and construction stage along with the environmental impacts caused at the EoL stage and beyond EoL stage are considered in LCA. Thus, the method was chosen after a comparison with the other methods to access circularity as shown in subsection 2.5.6.

OneClickLCA was chosen as a tool to assess the impact of the standardised materials in the systems and its benefits beyond the system boundaries. The specific tool was chosen because of its advantage of being able to measure the circularity at standardised material level and its ability to group these standardised materials to evaluate the impacts of the system. The tool also provides the results about Building Circularity. The tool is based on the Level(s) and Building Circularity Indicator to compute the impacts, benefits of the standardised materials in the system and beyond the system boundaries and to calculate the circularity index of the system.

5. Evaluation

The Evaluation section involves the elaboration of the assessment method that is chosen and the key performance indicators that are evaluated for every variant. The method of evaluation is elaborated in this section and different input considerations are mentioned. The multiple lifespan approach followed for the process of evaluation is elaborated in this section. Further, the section conducts and analysis of the results.

5 Evaluation of the variants

5.1 Method of evaluation

5.1.1 Life Cycle Assessment

The diagram below represents the different stages of LCA and highlights the stages that are taken into account while evaluating the variants.

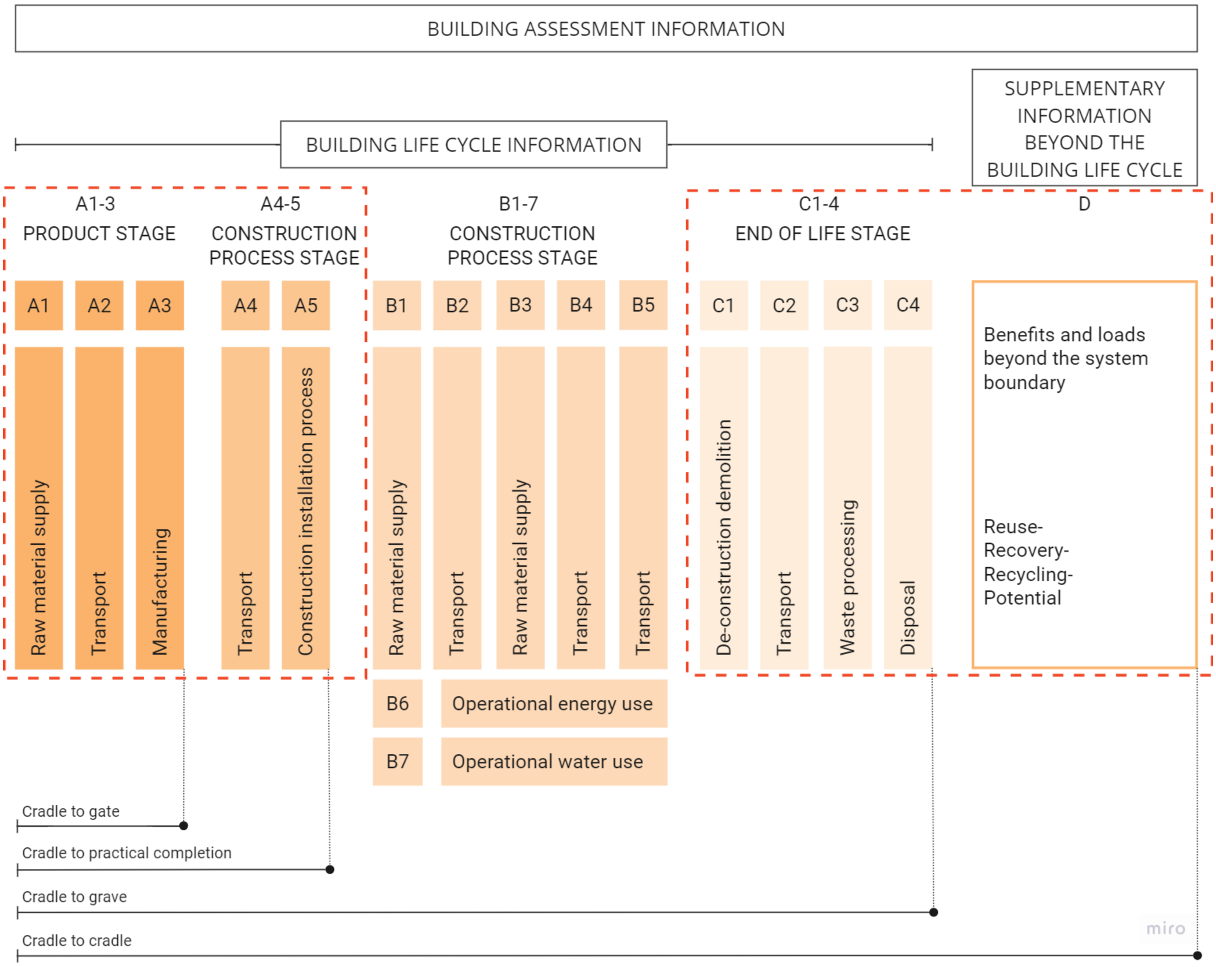


Figure 27 Life Cycle Stages from OneClick LCA

The OneClick LCA software is compliant with EN15978 standard, ISO 21931-1 and ISO 21929 and the data requirements of ISO 14040 and EN 15804 (OneClickLCA, 2021a)

The stages included in LCA are as follows-

- **A1:** Raw material extraction and processing. Processing of secondary material
- **A2:** Transport to the manufacturer
- **A3:** Manufacturing

Modules A1-A3 includes provision of all materials, products, and energy, as well as waste processing and disposal. In the thesis, these stages are different for different variants since they are highly dependent on the choice of material.

- **B1 to B7:** Use stage, repair, replacement, refurbishment, maintenance stage, operational energy and water use are considered in these stages. These stages are kept constant for all the variants.
- **C1:** De-construction, demolition

- **C2:** Transport to waste processing
- **C3:** Waste processing for reuse, recovery and/or recycling
- **C4:** Disposal

C1-C4 stages deal with the End-of-Life scenarios of the various variants. They include provisions for transport of all the materials, products and related energy and water use. The thesis does not take into account the impacts of the stage C1, but it is assumed that all the variants will be de-constructed and not demolished after they have reached the end of technical service life.

- **D**: Reuse, recovery and/or recycling potential, expressed as net impacts and benefits.

As per EN 1504+A2, the following equation is used to calculate the net benefits and loads beyond the system boundaries:

$$e_{\text{module D1}} = (M_{\text{MR out}} - M_{\text{MR in}}) \left(E_{\text{MR after EoW out}} - E_{\text{VMSub out}} \cdot \frac{Q_{\text{R out}}}{Q_{\text{Sub}}} \right)$$

Equation 1 Calculation of the net benefits and loads beyond the system boundaries as per EN1504+A2

$M_{\text{MR out}}$ - Amount of scrap content exiting the system.
$M_{\text{MR in}}$ - The amount of scrap content fed into the system.
$E_{\text{MR after EoW out}}$ -The amount of emissions, resources and waste from material made from recycled scrap material.
$E_{\text{VM Sub out}}$ - The amount of emissions, resources and waste from material made from primary materials.
$Q_{\text{R out}}$ / Q_{Sub} - Coefficient of quality difference, where QR out corresponds to material made of recycled material and QSub to material made of primary material.

5.1.2 Building Circularity Index

The building circularity tool by OneClick LCA allows tracking, quantifying different materials included in the system. It helps in getting a holistic picture of the circularity as well as a detailed breakdown per material in the system. It calculates the percentage of materials entering that are recovered in the system and the percentage of materials returned.

Renewable, Recycled, or Reused contents

This section calculates the percentage of renewable, recycled, or reused materials in the resource. They are calculated as percentage of share in the system by mass.

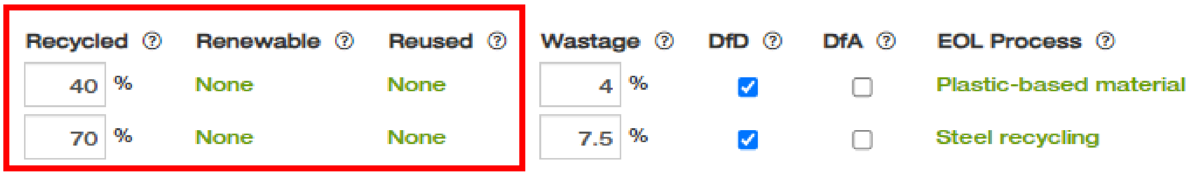


Figure 28 OneClick LCA interface showing Renewable, Recycled, or Reused contents

Design for Disassembly and Design for Adaptability

This allows you to check if the materials installed can be disassembled or adaptable for future use. This score does not affect the circularity score in the tool.

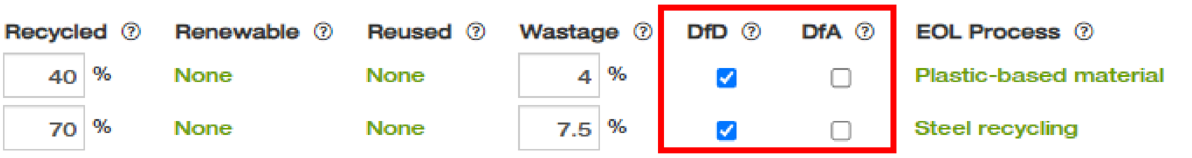


Figure 29 OneClick LCA interface showing options for Design for Disassembly and Design for Adaptability

End of Life processes

These processes are based on the material type. It is possible to select different end of life processes in the drop-down menu.

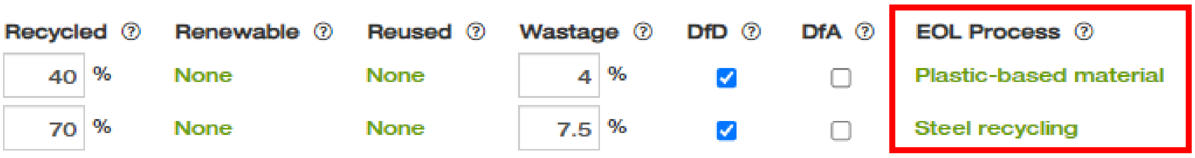


Figure 30 OneClick LCA interface showing the option to select different EOL Process

5.1.3 Key Performance Indicators

The following table represents the various key performance indicators that are analysed for evaluating the results-

No.	KPI	Unit of measurement	Description
	Environmental impact indicators		
1	Global Warming Potential	CO2eq	Global warming potential is a relative measure of how much heat a greenhouse gas traps in the atmosphere.
2	Biogenic Carbon Storage	CO2eq bio	Biogenic Carbon Storage is the process of capturing and storing atmospheric carbon in living organisms and biomass.
3	Ozone Depletion Potential	kg CFC11eq	Describes the potential damage caused to the stratospheric ozone layer. Chemical refrigerants used in older air conditioning systems often have a higher ODP.
4	Acidification Potential	kg SO2eq	Acidifying emissions that result in a lower pH-value of water and soil, decreasing the nutrient availability and intake of plants.
5	Eutrophication Potential	kg PO4eq	Nutrient emissions (nitrogen and phosphorus) that increase the flow of nutrients to ecosystems, causing algae growth in waters.
6	Formation of Ozone of lower atmosphere	kg Ethenee	Formation of Ozone of lower atmosphere occurs when pollutants like nitrogen oxides and volatile organic compounds react with sunlight.
7	Abiotic Depletion Potential for non-fossil fuel resources	kg Sbe	Abiotic depletion refers to the global reduction of non-living, or abiotic, natural re-sources, such as mineral, metal and fossil resources.
8	Abiotic Depletion Potential for fossil fuel resources	MJ	
	Material costs		
1	Material market price	Euros	This is the regional market based cost of the standardised materials.
2	Typical labour cost for installing the material	Euros	This is the regional cost considered for installing a standardised material.

Table 7 Key Performance Indicators derived from OneClick LCA by author

5.2 Input considerations

The material flows were analysed for a period of 90 years which consisted of three life cycles with each life cycle of 30 years. It was considered that the design of the system is the same for all the lifecycles. The EoL considerations for each of the materials were taken into account as discussed in sub-section 2.2.3. The details regarding the inputs for materials chosen, their quantities, service life, material wastage along with their EoL process selected can be found in the appendix.

Figure 31 indicates the different EoL conditions considered for the various scenarios. The long lifespan materials used for LC1 are virgin standardised materials that are considered to be reused on a different site after 30 years, thus LC2 utilises reused components or standardised materials. For the LC3, the standardised materials for the components considered in the system are recycled or virgin standardised materials. The short lifespan variants use the components made from virgin materials for LC1 followed by a combination of recycled and virgin materials for LC2 and LC3. The bio-based variants follow a similar material and component flow as short lifespan variants.

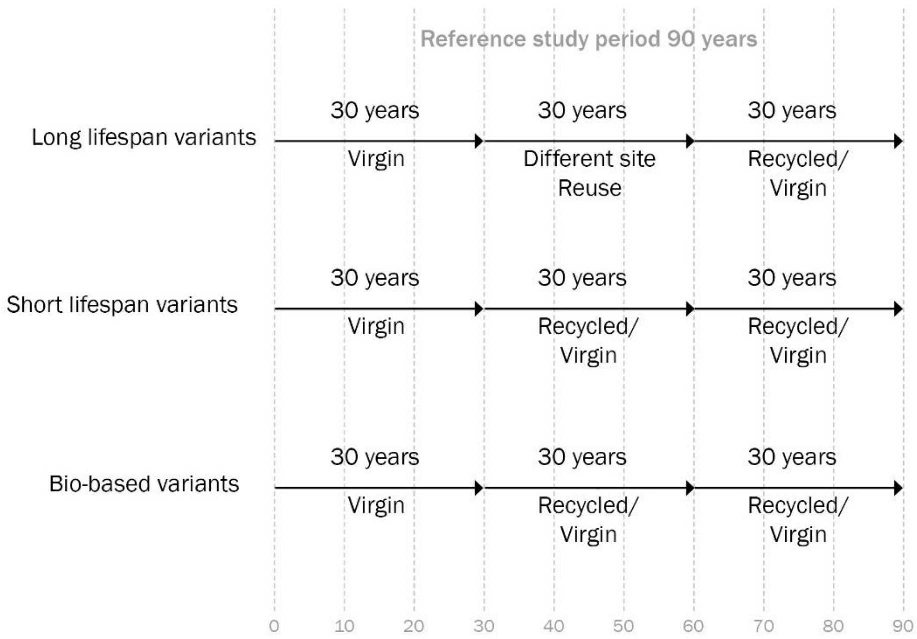


Figure 31 Materials used over 90 years lifespan for each of the design scenarios by author

Scenario 1:

The following flowcharts indicate the material flows for different lifecycle stages taken into consideration for each of the variants. The decisions regarding the EoL of materials at the end of each technical cycle is mentioned along with their relation for the next use stage.

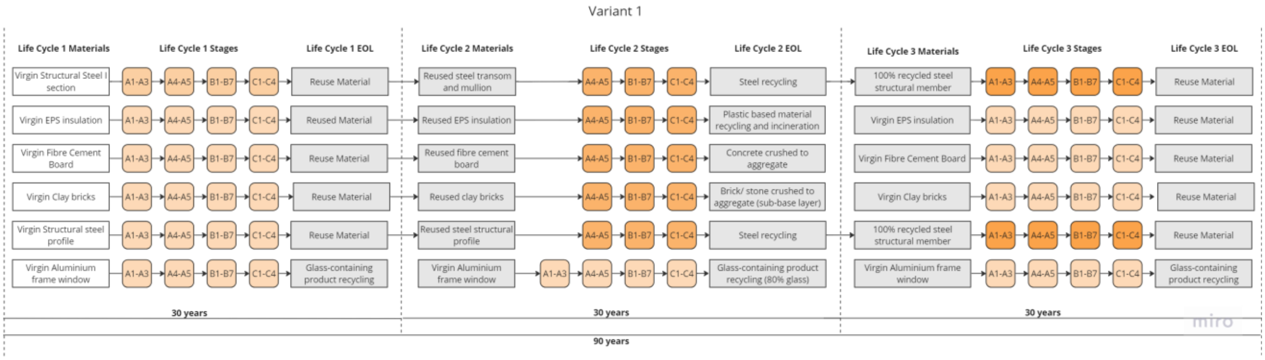


Figure 32 Variant 1 over 90 years by author

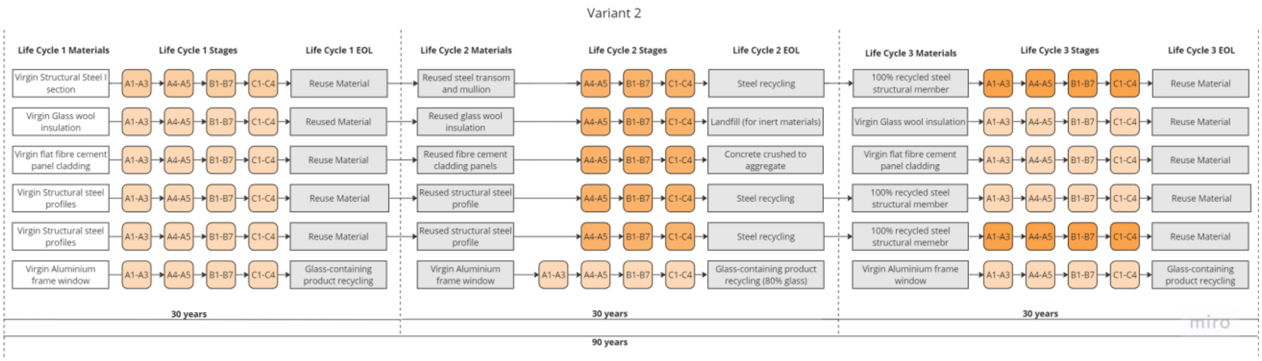


Figure 33 Variant 2 over 90 years by author

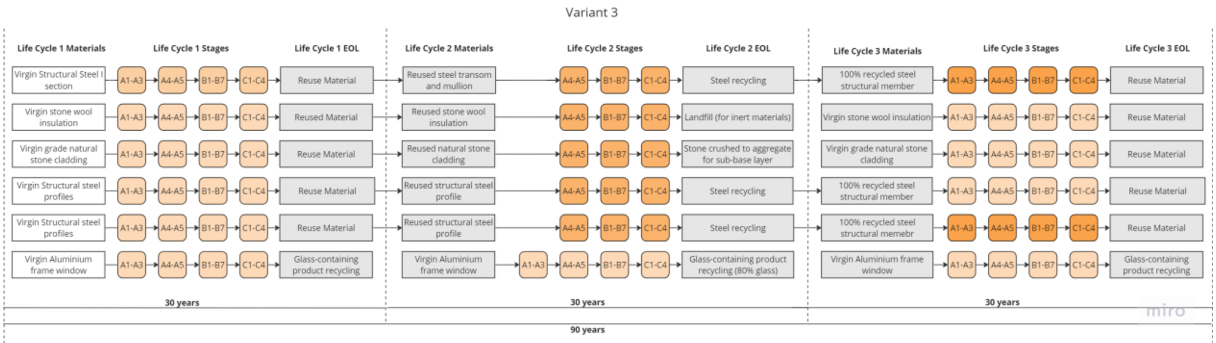


Figure 34 Variant 3 over 90 years by author

Note: The different colours indicate the different environmental impacts of the stages. The stages with the same impacts have the same colour.

A1-A3 Production stage   A4-A5 Construction process stage   B1-B7 Use stage   C1-C4 End-of-Life stage

In the first three variants, virgin materials are utilized in the first life cycle which are subsequently reused after 30 years. The scenario assumed here is a different site reuse. At the EoL of the second lifecycle, the components are dealt with based on the market-based practices for the specific standardised materials of the components. For the third lifecycle, a mix of recycled and virgin materials is used, with components being reused once again after another 30 years, hence the EoL for the third life cycle is reuse.

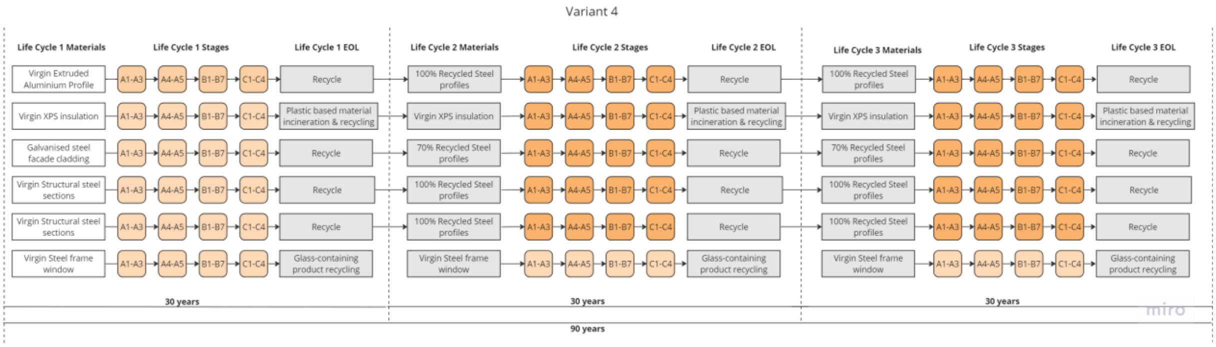


Figure 35 Material flow chart of variant 4 over 90 years by author

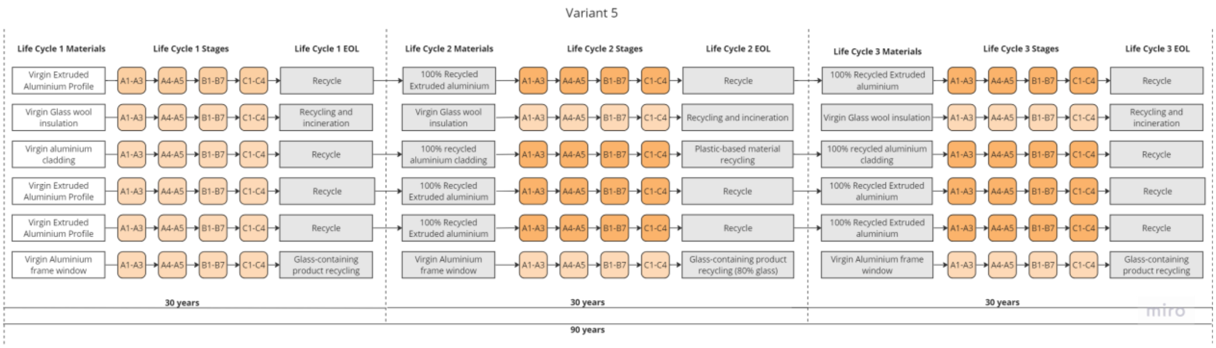


Figure 36 Material flow chart variant 5 over 90 years by author

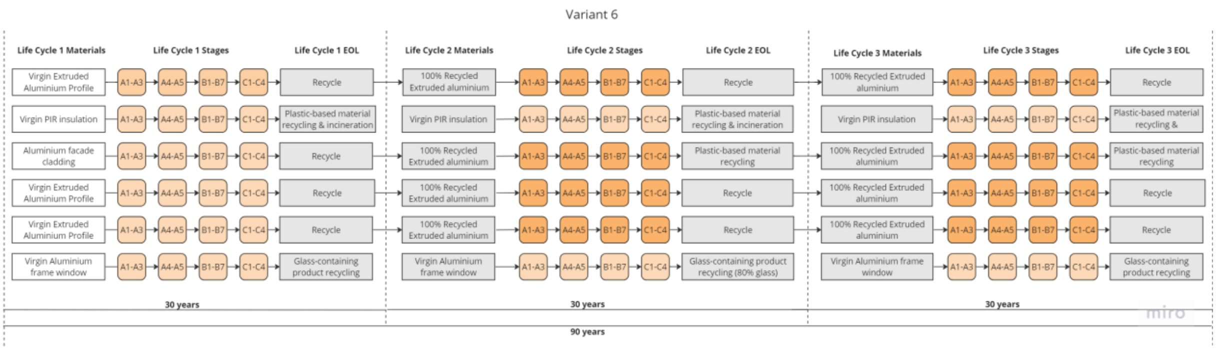


Figure 37 Material flow chart variant 6 over 90 years by author

Note: The different colours indicate the different environmental impacts of the stages. The stages with the same impacts have the same colour.

A1-A3 Production stage
A4-A5 Construction process stage
B1-B7 Use stage
C1-C4 End-of-Life stage

The Variant 4,5 and 6 which are characterised by short lifespan materials, a consistent pattern emerges in the EoL processing at the end of the first life cycle. The majority of the components in the system are recycled with the recycled materials being utilised in the manufacturing of the new components for the second life cycle. Thus, for the second life cycle, recycled components are prominently used and recycling occurs at the end of each cycle.

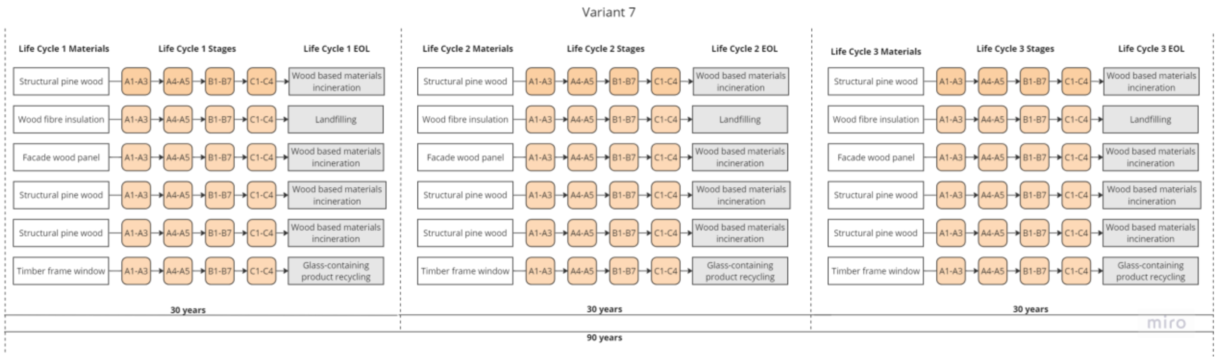


Figure 38 Variant 7 over 90 years by author

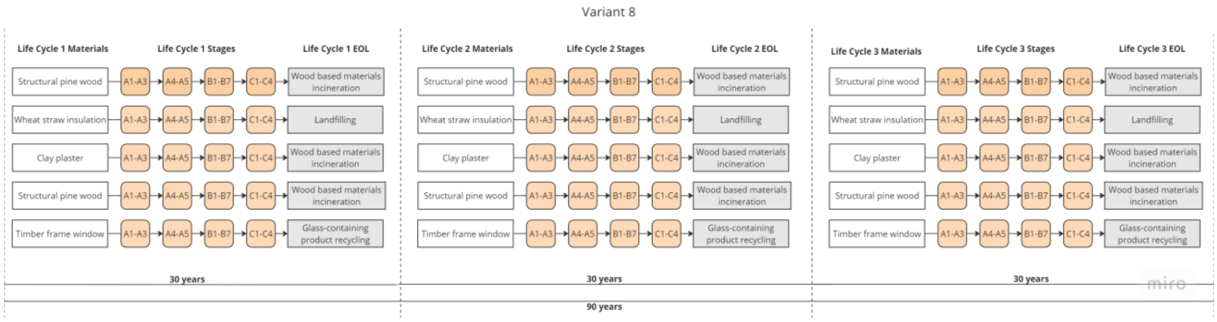


Figure 39 Variant 8 over 90 years by author

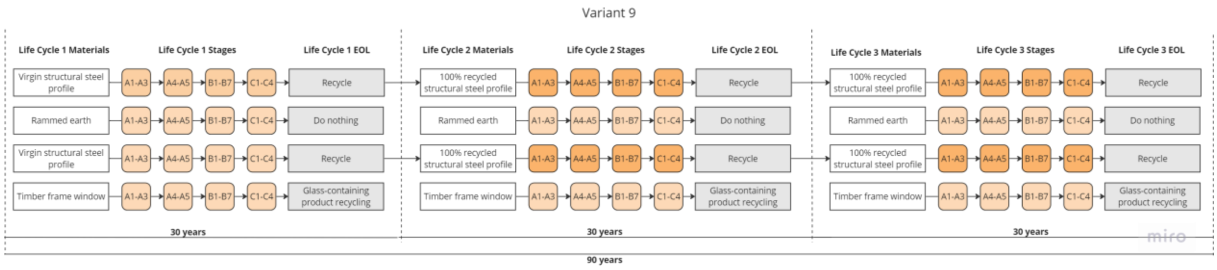


Figure 40 Variant 9 over 90 years by author

Note: The different colours indicate the different environmental impacts of the stages. The stages with the same impacts have the same colour.

A1-A3 Production stage   A4-A5 Construction process stage   B1-B7 Use stage   C1-C4 End-of-Life stage

In these bio-based variants, upon reaching the end of first life cycle, the standardised materials are treated according to the marked-based EoL. The market-based scenarios are mentioned in the flowcharts above. Subsequently, for each of the life cycle, virgin materials are used and at the EoL are dealt with depending on the market-based EoL. The EoL is dependent on the available technology.

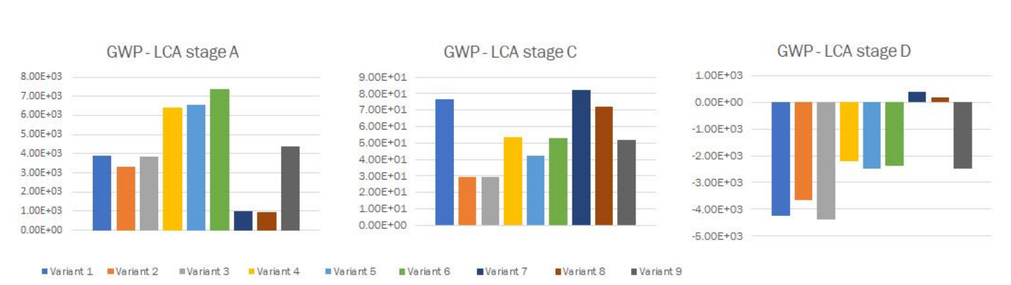
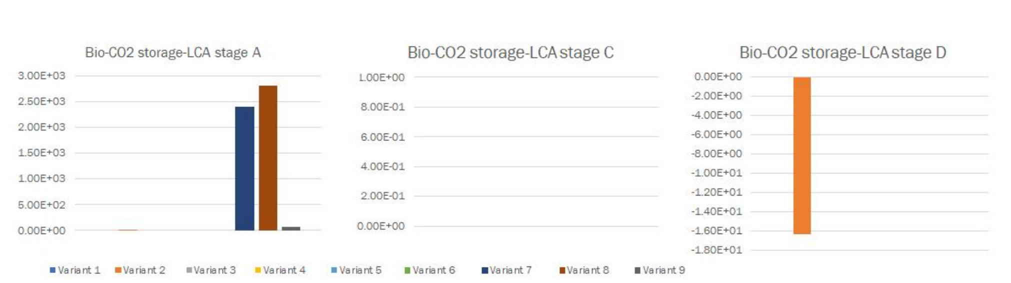
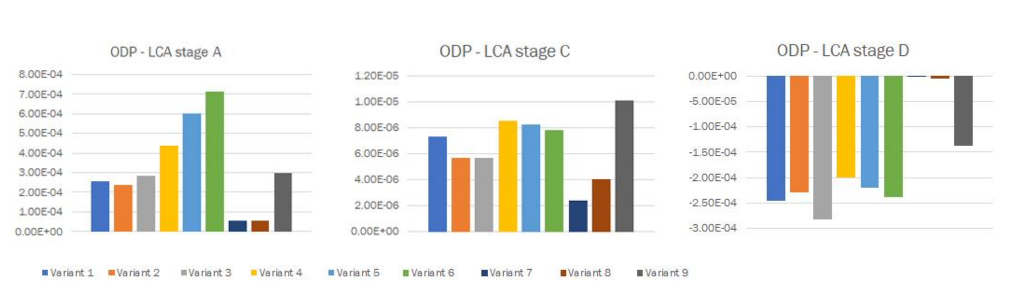
5.3 Results

5.3.1 Environmental Key Performance Indicators

Table 8 illustrates different graphs of different KPIs at Stage A, C and D for a span of 90 years. It is observed that at Stage A, the most impact in many of the KPIs is created by the Variant 6 and the least impact is created by Variant 7 for most of the KPIs. For Stage C, which is the EoL stage, Variant 7 has the least impact for all the other KPIs except the GWP and the most impact is created by Variant 7 for GWP and by Variant 1 for the other KPIs. Variant 3 has the least GWP impacts. For Stage D, Variant 3 has the most GWP benefits and Variant 1 has the least benefits.

Amongst all the KPIs, the stage A impacts are more for the long lifespan variants. The stage C GWP impacts are more for the bio-based variants and the impacts of the other KPIs are more for the short lifespan materials. Module D results show that the most benefits are obtained when the long lifespan materials are used followed by the short lifespan materials and then by the bio-based materials.

As per these results, long lifespan materials have a higher material use benefits since their EoL processes are more circular and the bio-based materials cause a significantly lower environment impact. If the bio -based materials are durable and have a circular EoL their GWP impacts at Stage C can significantly be reduced. According to the available technology, the GWP impacts at the EoL of the bio-based materials are significantly higher than the long lifespan materials. The bio-based variants perform better than the other variants with respect to ODP, AP, EP, POCP, ADPE and ADFP at Stage C. Since, the bio-based materials cannot be returned back to the facade system, they are downgraded and result in CO2 emissions and do not gain material benefits equivalent to the long lifespan or the short lifespan materials.

1	Global Warming Potential (GWP)	
2	Biogenic Carbon Storage (Bio-CO2 storage)	
3	Ozone Depletion Potential (ODP)	

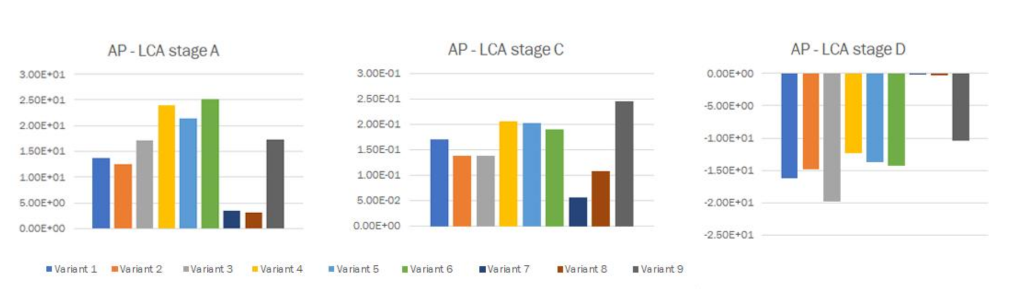
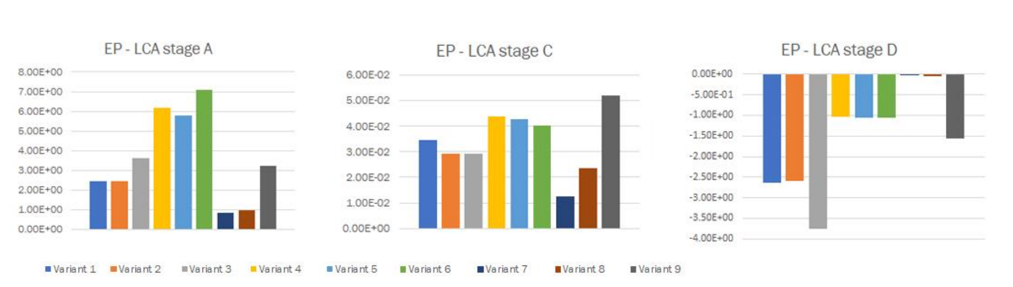
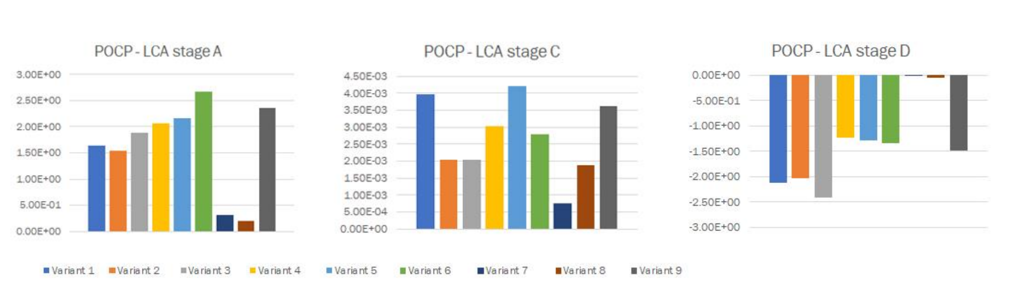
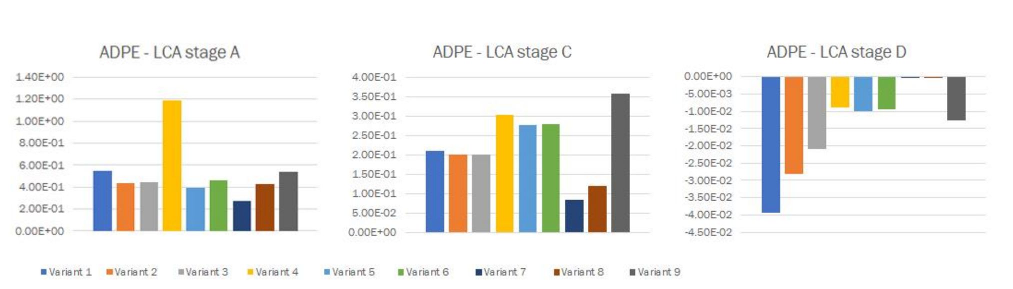
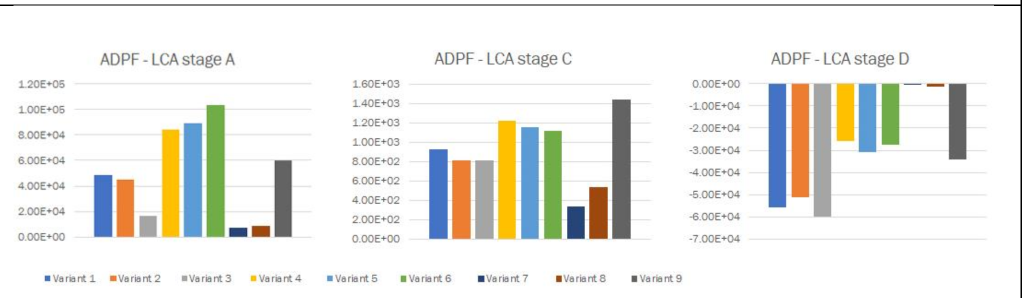
4	Acidification Potential (AP)	
5	Eutrophication Potential (EP)	
6	Formation of Ozone of Lower Atmosphere (POCP)	
7	Abiotic Depletion Potential for Non-fossil Fuel Resources (ADPE)	
8	Abiotic Depletion Potential for Fuel Resources (ADPF)	

Table 8 Environmental Key Performance Indicators Results

5.3.2 Environmental impacts (kg CO2 eq/m2) and Building Circularity

The table below illustrates the environmental impacts and Building Circularity as measured by OneClick LCA for the different design variants.

Variants	Variant name	Environmental impact (kg CO2 eq/ m2)	Building Circualrity
Long lifespan variants	Variant 1	92	67%
	Variant 2	82	63%
	Variant 3	92	60%
Short lifespan variants	Variant 4	140	76%
	Variant 5	116	73%
	Variant 6	135	72%
Bio-based variants	Variant 7	34	75%
	Variant 8	29	53%
	Variant 9	83	12%

Table 9 Results of Environmental impacts and Building Circularity of all the variant by author

Table 9 indicates that Variant 8, which is composed of biological materials like pine wood, straw bale insulation and clay plaster generates the least GWP impact per sq.m. The bio-based variants have less environmental impact compared to the long lifespan materials followed by the short-lifespan materials.

The circularity index for the short lifespan materials is more than the other variants. The process of recycling at the EoL helps in creating circular EoL for short lifespan materials. The process of recycling helps in closing the loop. The long lifespan materials help in slowing the loop by the process of reuse at the EoL stage. The bio-based materials have less circularity rate since the materials used in those variants are either landfilled or incinerated generating CO2 emissions.

5.3.3 GWP impacts of stages A, C and D over 90 years and 300 years

It is observed that the GWP impacts during the first life cycle are greater for the short lifespan variants (Variant 4, Variant 5 and Variant 6) followed by long lifespan variants (Variant 1, Variant 2 and Variant 3) and bio-based variants (Variant 7, Variant 8 and Variant 9). The life cycle 2 impacts are the least for the variants with a long lifespan. The introduction of a reuse cycle for the second life cycle for the long lifespan variants decreases the GWP impact by 89%. While, for the third lifecycle, a decrease of 56% is observed compared to the first lifecycle, the major reason for this is the use of recycled materials in the system for the third life cycle as compared to the virgin materials used for the first life cycle. For the short lifespan variants, the GWP impacts decrease by 88% for the second life cycle and thereafter the GWP impacts are constant for the consecutive cycles. In case of the bio-based variants (Variant 7, Variant 8 and Variant 9), the impacts for each lifecycle remain constant.

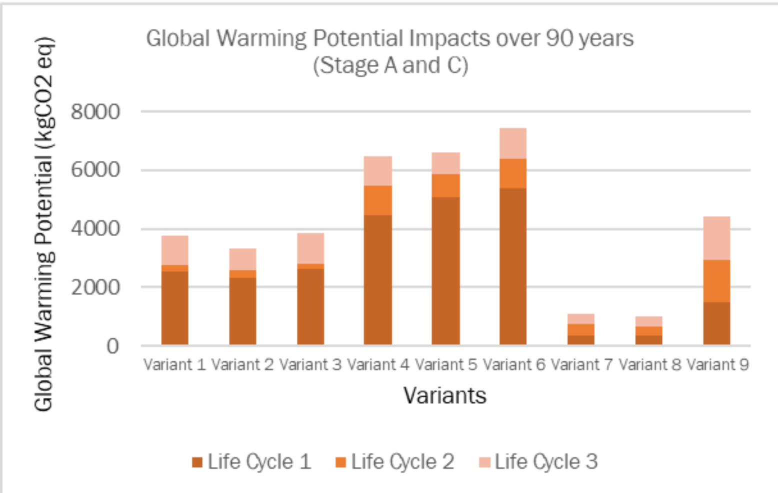


Figure 41 Global Warming Potential Impacts of each Variant in 90 years lifespan by author

The GWP impacts are high when virgin materials are used. The GWP impacts are reduced by using the recycled materials. If the GWP impacts produced during the manufacturing and construction stage by using the recycled materials are high, then the preferred choice would be to use virgin materials. The GWP impacts are less when the system/ components of the system/ standardised materials in the system are reused. The GWP impacts of the reuse cycle can be further reduced by opting for on-site reuse, thereby eliminating the transportation impacts. A further reduction in the overall GWP impacts can be observed if the strategies of reuse and recycle are combined. This will reduce the impacts over the years.

When considering 300 years impacts, the variants with long lifespan materials and the bio-based materials exhibit a similar trend of increase in the GWP impacts. The impacts for various lifecycles can be reduced by reusing at the EoL and using the standardised materials that can be recycled multiple times. Thus, for the technical materials, it is necessary to combine the circular strategies for slowing and closing the loop. In case of the bio-based variants, a less impact is created during each cycle even though the virgin materials are used it is because of the less GWP at the manufacturing stage.

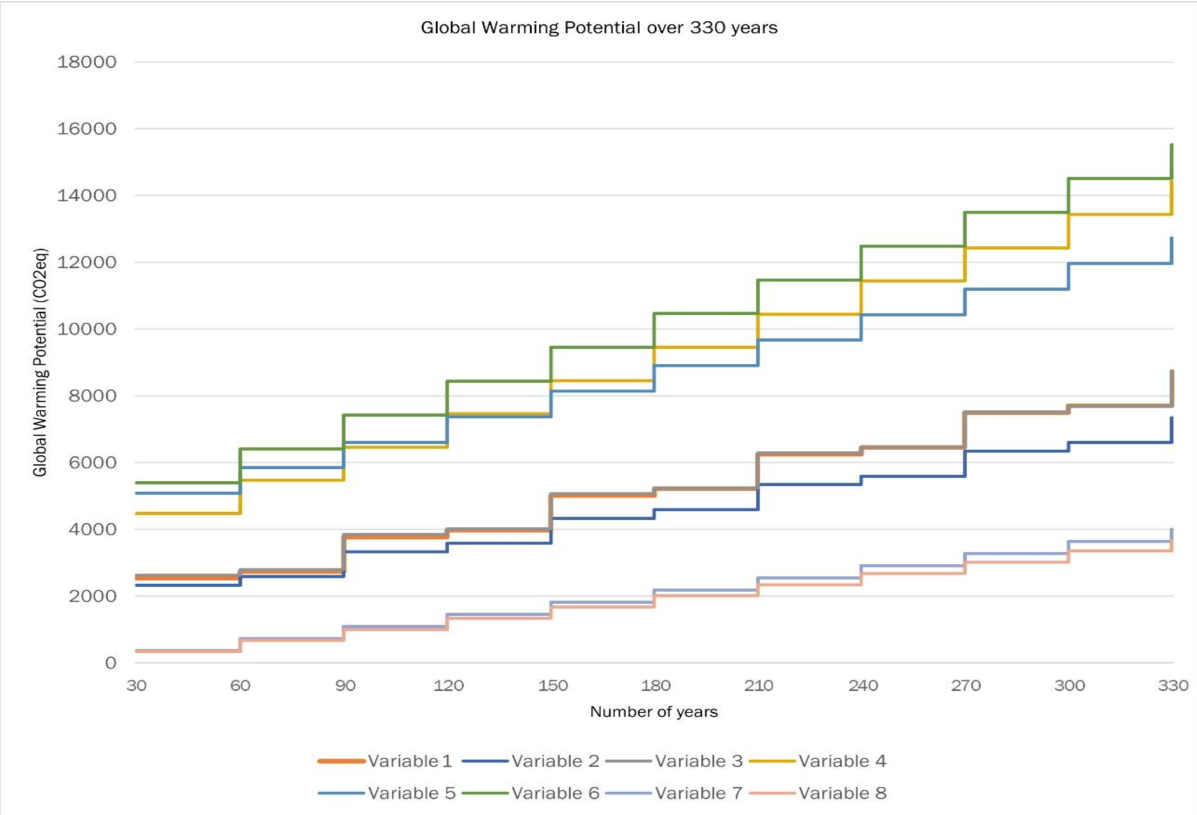


Figure 42 Impact of the selected materials over a span of 330 years by author

5.3.4 GWP impacts of stage C (EoL) over 90 years

While considering the impacts of the EoL stage, it can be seen that the impacts of the materials which are bio based are more as compared to impacts caused by the technical materials with a long lifespan or short lifespan. This implies that the current market scenarios for EoL processes for bio-based materials should be revised. It is advisable to use bio-based materials with a longer lifespan and materials that help in closing the loop. Incineration is not a preferred option.

The long lifespan Variant 1 the bricks end up getting crushed and added to the sub-base layer, the EPS insulation is incinerated, thus the EoL processing impact is more at LC2 compared to the other two long lifespan variants which have a more circular EoL compared to Variant 1.

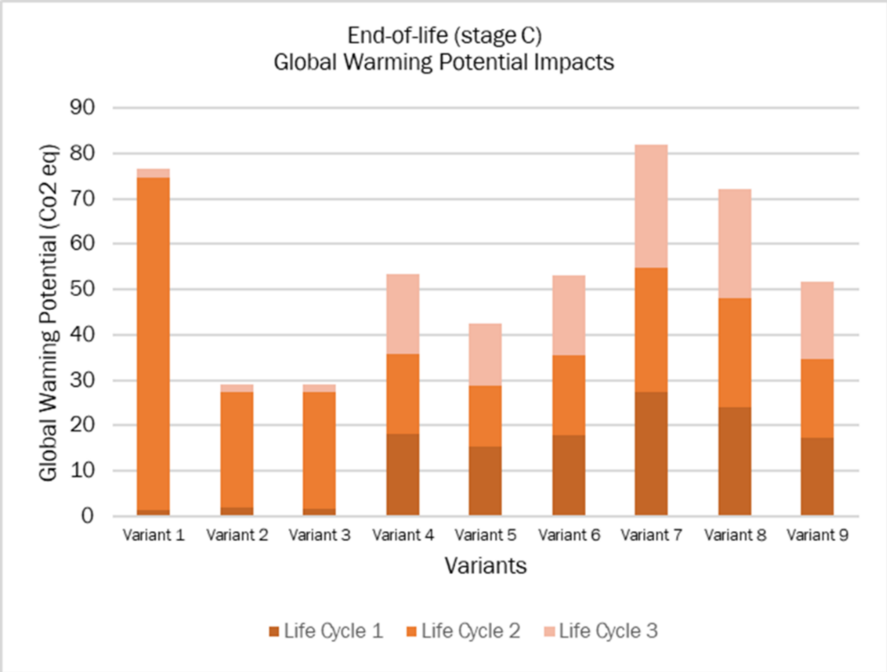


Figure 43 EoL (stage C) GWP of different variants by author

5.3.5 Market based material cost comparison over 90 years

The figure below illustrates the market-based material costs of the variants. The material costs of the long lifespan variants (Variants 1,2 and 3) and the bio-based variants (Variants 7, 8) are high compared to the short lifespan materials for the LC1. The material costs for the long lifespan variants are low since the same materials are used for the LC2 for these variants. The costs of the materials for the bio-based variants and the low lifespan variants remain constant for all the three lifecycles.

Materials with a longer lifespan often have a higher initial cost compared to those with a shorter lifespan. However, over a period of 90 years, the overall costs evens out, making them equally cost-effective in the long run.

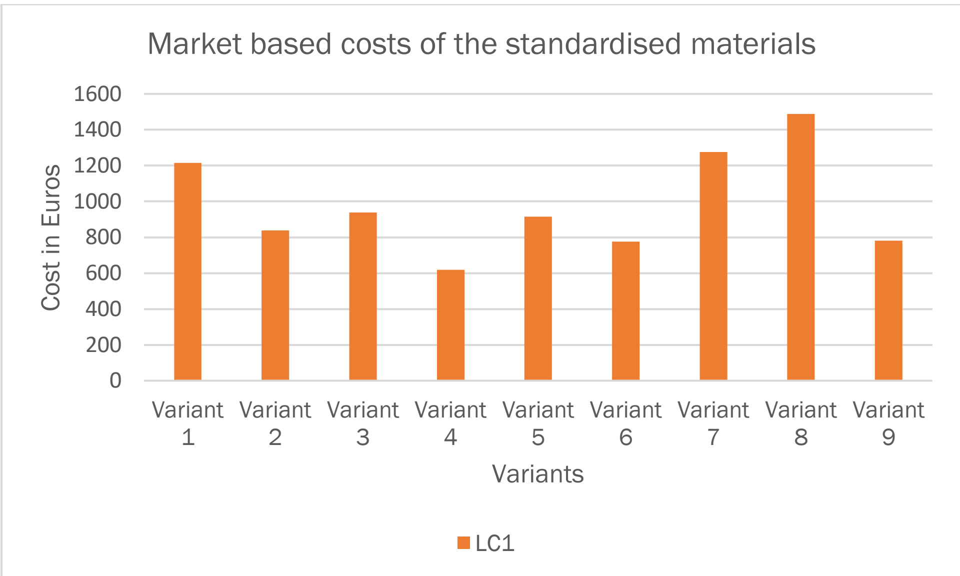


Figure 44 Market based costs of the different systems for the initial lifecycle by author

5.4 Results conclusions

The environmental performance increases significantly by adapting the strategies to close and slow the loop. The impacts will be even lesser if the bio-based materials are more durable and have a circular EoL processing method and are available in the Netherlands. Maximizing the overall lifespan of the components, incorporating multiple use cycles and using bio-based or recycled materials lead to lowest material consumption, environmental impacts and waste. The best performing façade as analysed by the stated KPIs combines long lifespan materials and non-virgin materials along with multiple use cycles.

1. When designing circular components all future cycles need to be considered, understanding the building component as a composite of parts and materials. The impacts of the bio-based variants are observed to be the least according to the LC1 results. This is due to the low manufacturing energy of the materials in the system. Conversely, for LC2, materials with a long lifespan exhibit minimal impact because the materials are not manufactured again. Thus, for LC2, the long lifespan materials perform better than the bio-based variants. **In circularity, to accurately assess the impacts, it is necessary to take into account a multiple lifespan approach rather than a single lifespan approach.**

2. For LC2 of the technical variants, the percentage of the recycled and reused content in the system affected the environmental impacts. **Use of more reused and recycled content in the system created less environmental impacts.**

3. The long lifespan variants and the short lifespan variants are considered more circular than the bio-based variants. This is because a larger portion of the materials in the system are reused or recycled at the EoL. The short lifespan variants had materials that could be recycled multiple times; hence these variants are more circular. The long lifespan variants and the biobased variants are downcycled hence are less circular. **Thus, lifespan and EoL play an important role in deciding the circularity of the system. They also affect the environmental impacts that are created.**

4. The recyclability percentage and the biodegradability percentage in a system affect the global warming impacts across multiple lifecycles and also acts as a deciding factor for circularity. **Hence if the recyclability percentage and biodegradability percentage in a system is high, the circularity is high and the GWP impacts are low.**

5. The GWP impacts at the EoL of the biobased variants were seen to be high since the materials were downgraded. On the other hand, when a reuse cycle was used, the GWP impacts were less at the EoL. **Thus, the materials used in the system should have a low GWP processing energy.**

Though the above-mentioned factors are identified as the tipping points, the material manufacturing and construction stage creates more impacts than the EoL stage for all the variants. Thus, the impacts of the materials selected should be given a priority over the impacts at the EoL stage as they largely influence the overall environmental impacts.

Based on the obtained results design guidelines are established in the next section along with the information considerations.

6. Design Guidelines and Information Considerations

The section establishes information considerations and design guidelines that help to guide the façade designers during the preliminary design stage on making decisions regarding the circular EoL scenarios. These design guidelines are established based on the results established in the previous section. After determining the design guidelines, the information that influenced these guidelines become a part of the information considerations. The information considerations are governed by the different tipping points that impacted the results.

6 Design Guidelines and Information Considerations

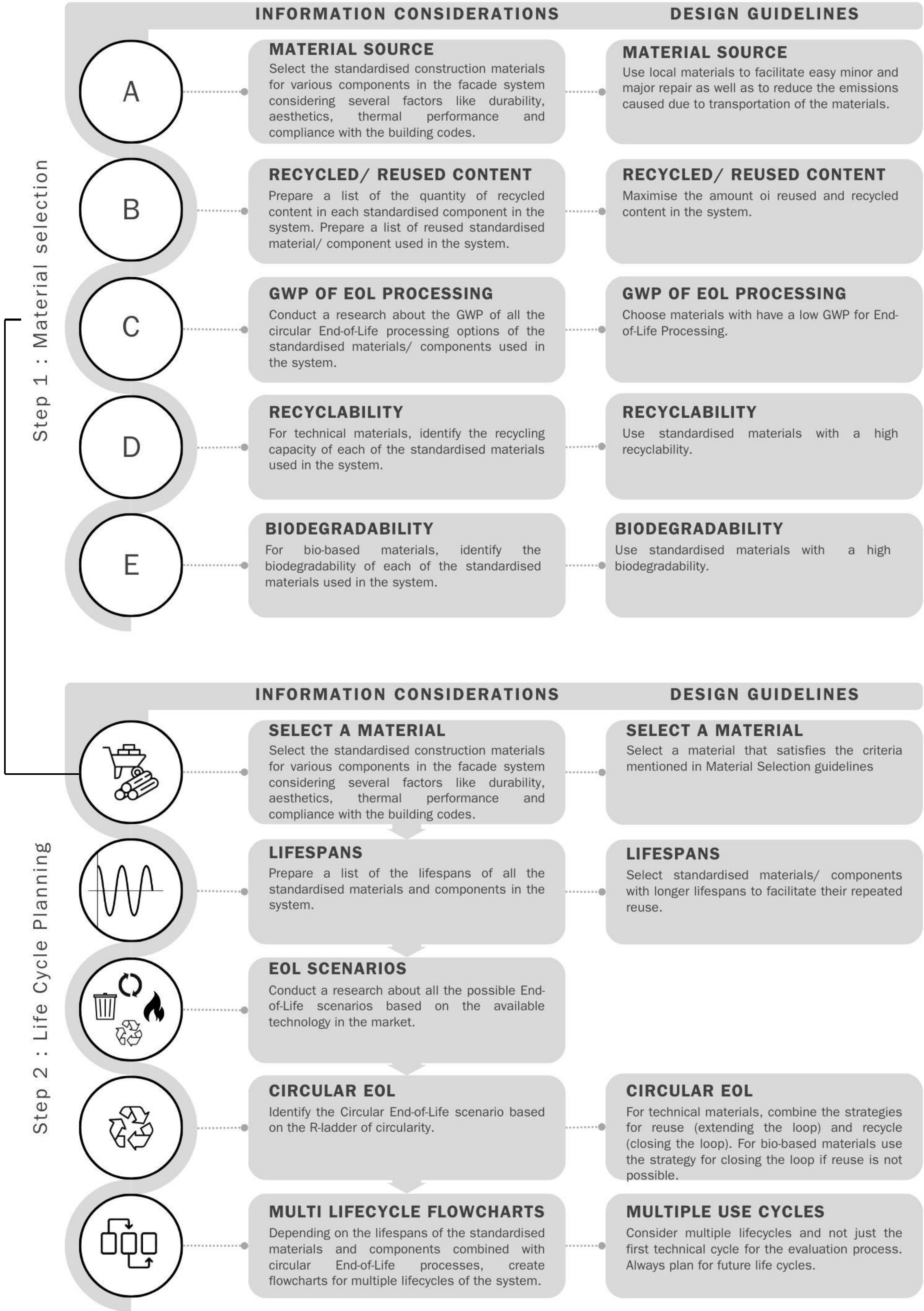


Figure 45 Design Guidelines and information considerations by author

The design guidelines and the information considerations are stated in the above figure. The design guidelines are derived from the evaluation results of the different variants and the different tipping points were identified to establish the information considerations.

To ensure the involvement of circularity in façade design, the design guidelines should be considered at the preliminary design stage by the façade designers. The information regarding the source of standardized material is important to reduce the environmental impacts during the product stage (A2). Using reused and recycled content in a system significantly affects the environmental impacts at the product stage. By maximising the use of such materials, the impacts of stages A1-A3 are substantially reduced. Therefore, it is evident that the product stage impacts can be minimized by reducing transportation distances and increasing the use of recycled and reused materials in the system. The information regarding these aspects affects the environmental impact calculations for the product stage of LCA.

To achieve a circular EoL scenario, it is necessary to use materials that have the potential for circularity. Systems with a high recyclability and biodegradability are considered as more circular. Additionally, a system with a low GWP for EoL processing is indicative of a system which is more circular. Thus, the information about the GWP for EoL processing coupled with the information regarding the quantity of material that can be recycled, the material which can be reused and the material which is biodegradable helps in evaluating the circularity of a system.

7. Guidelines Validation

This section validates the design guidelines and the information considerations by designing a façade system and comparing the results with the previously developed variants. This section marks the culmination of the research through design process and helps to establish the design guidelines and information considerations.

7 Guidelines Validation

Over a lifespan of 300 years, the overall environmental impacts for long lifespan materials and biobased materials are similar. But the GWP impacts created by the EoL stage of Variants 2 and 3 are less as compared to the other variants. These consist of long-life materials which can be used for 2 lifecycles and in real-life conditions will not be demounted from a building after 30 years which further decreases the amount of energy required for transportation of the removed system. The Variant 3 was chosen for the validation of the guidelines since the cladding system used in Variant 3 can be reused and the repurposed instead of downcycling like in case of the fibre cement boards considered in Variant 2. Further, more factors were considered which are stated in the design guidelines for the final variant.

7.1 Step 1: Material selection

The materials chosen for the standardised materials are selected based on the evaluated results and the derived guidelines. The following steps were taken in order to take the design decisions -

A. Material Source

The materials chosen for the design are manufactured in the Netherlands, thus reducing the transportation impacts along with the costs. The used materials can be locally repaired and refurbished for the next use or same use due to the availability of the material manufacturing units locally. Using locally manufactured materials helps in closing the circularity loop. The table below illustrated the various standardised materials and their material source.

Component	Standardised material	Material source
Façade structure	Structural steel profile section	Netherlands
Insulation	Stone wool insulation	Netherlands
Façade cladding	Natural stone cladding	Netherlands
Façade cladding support	Structural steel profile section	Netherlands
Solar panel support	Structural steel profile section	Netherlands

Table 10 Sources of Materials considered for the design by author

B. Recycled/ Reused Content

The design tries to maximise the recycled content in the system for the first use cycle. The initial design that considers the first life cycle (LC1) does not take into consideration reused components since the components are reused at the EoL of the first life cycle (LC1). The components are reused after the first life cycle. By maximising the use of recycled materials, less material sourcing energy is consumed and reduces material wastage.

Component	Standardised material	Recycled content (LC1)	Reused content (LC1)
Façade structure	Structural steel profile section	100%	-
Insulation	Stone wool insulation	90% slag	-
Façade cladding	Natural stone cladding	0%	-
Façade cladding support	Structural steel profile section	100%	-
Solar panel support	Structural steel profile section	100%	-

Table 11 Percentage of Recycled and Reused Content used in each standardised material in the design by author

C. GWP of EoL processing

The Re-life options stated in the circularity ladder give the options that are most circular to the least circular options. The options at the top of the ladder are more circular than at the bottom, thus causing less environmental impacts.

D. Recyclability and Biodegradability

The materials used should have high value of recyclability or biodegradability at EoL. These characteristics are essential is closing the loop in a circular economy. The design considers materials who have a high value of recyclability.

Component	Standardised material	Recyclability	Biodegradability
Façade structure	Structural steel profile section	100%	-
Insulation	Stone wool insulation	0%	-
Façade cladding	Natural stone cladding	92.6%	-
Façade cladding support	Structural steel profile section	100%	-
Solar panel support	Structural steel profile section	100%	-

Table 12 Recyclability and Biodegradability percentage of the standardised materials chosen in design by author

7.2 Design details and view

The façade system is a modular prefabricated system that is assembled on-site. The prefabricated façade system promotes time efficiency, reduces the on-site labour costs, provides quality control, minimises on-site waste, enables modular design and supports a streamlined logistics. The prefabricated panels are anchored onto the hooks that are attached to the structural system of the existing building.

The design proposal consists of three panels A, B and C that satisfy various façade functions. The panel A satisfies the function of providing thermal comfort by insulating the external walls, imparting aesthetics by having a natural stone cladding. The panel B provides light and ventilation with the help of aluminium triple glazed operable window to the indoor spaces while taking into consideration the aesthetics of the system. The panel C integrates the active functions of energy generation by the help of the solar panels and an active ventilation system. It also satisfies the requirement of providing insulation to the indoor spaces.

The system is composed of steel acting as the main façade structural system, the supports for the solar panels and for the façade cladding. The insulation is made of stone wool which has a long lifespan and the cladding system of natural stone which well known for its durability.

In the assembly process, various components made from different materials are prefabricated off-site under controlled conditions. Prior to the installation, hooks are attached to the existing structural system of the building. These hooks serve as anchor points for the modular prefabricated panels which are then mounted in place. The mounting of the panels follows a floor-by-floor approach. This enables systematic installation approach. Cranes and lifts are used to hoist the panels in place.

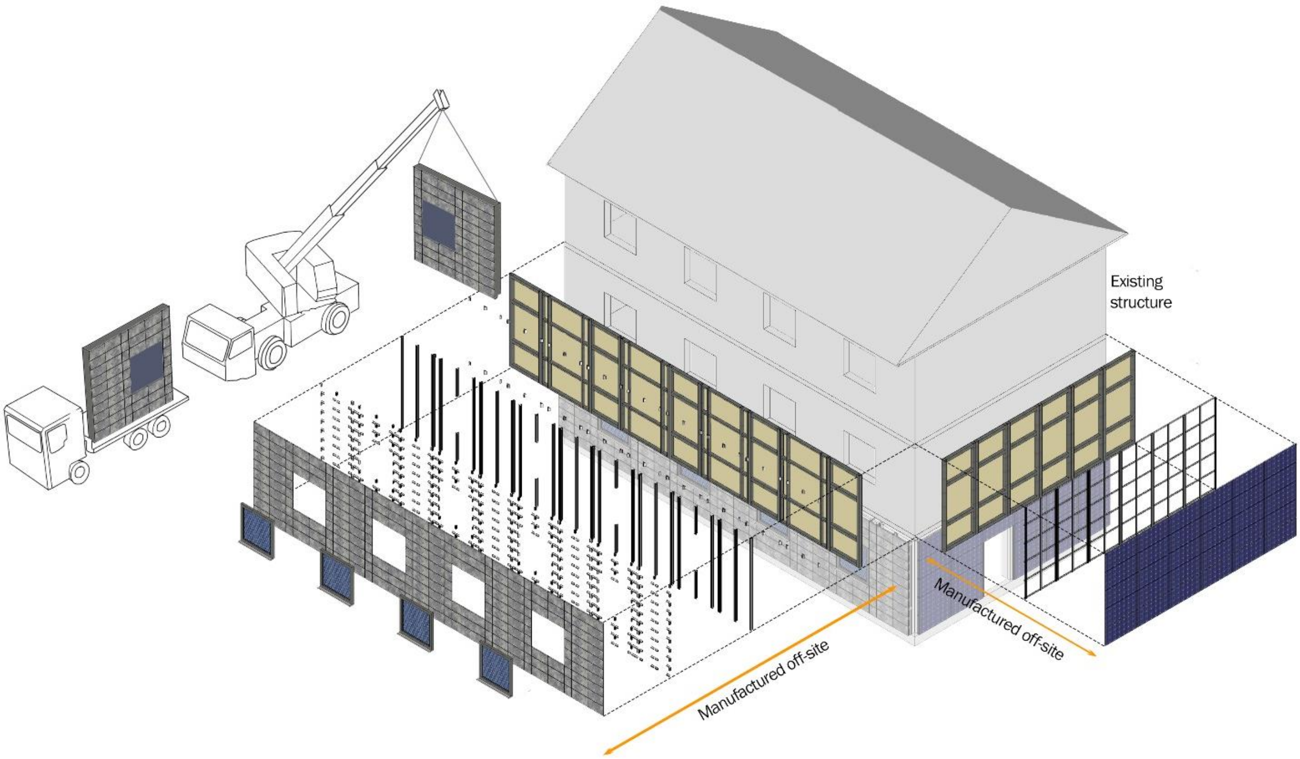


Figure 46 Assembly of the Facade system by author

Exploded views

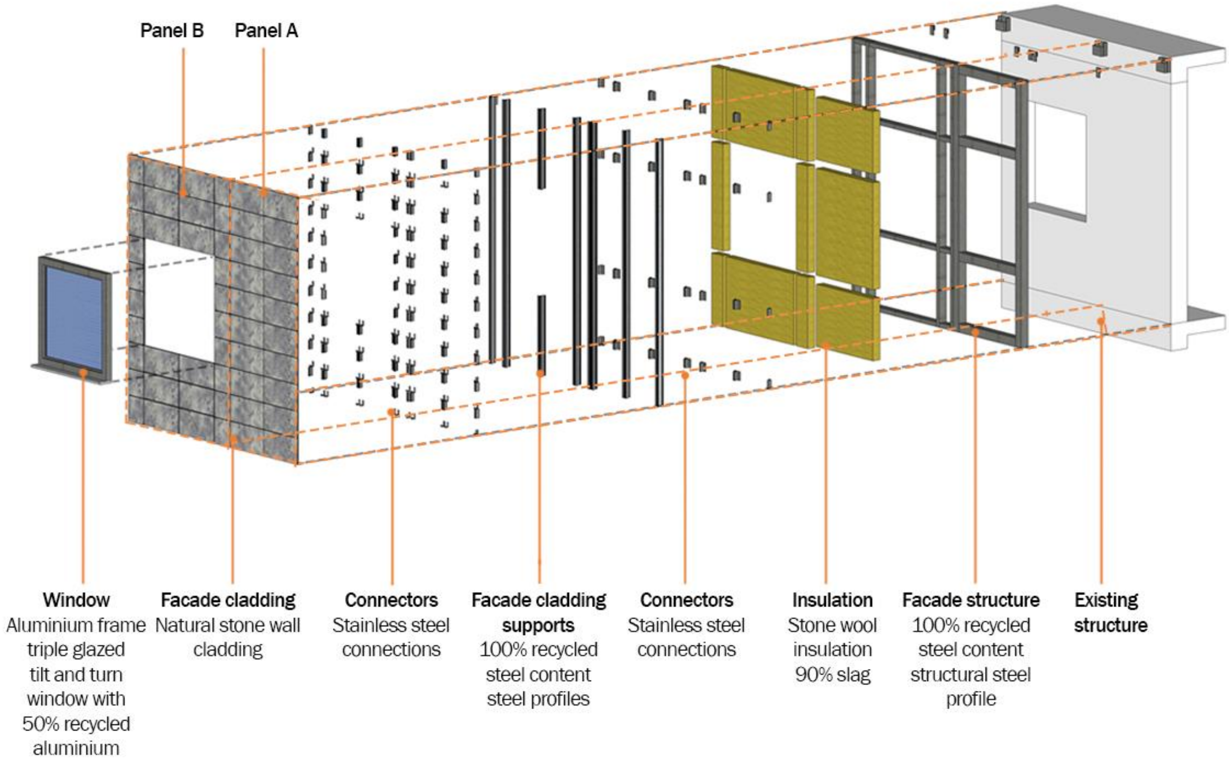


Figure 47 Exploded view of Panel A and Panel B by author

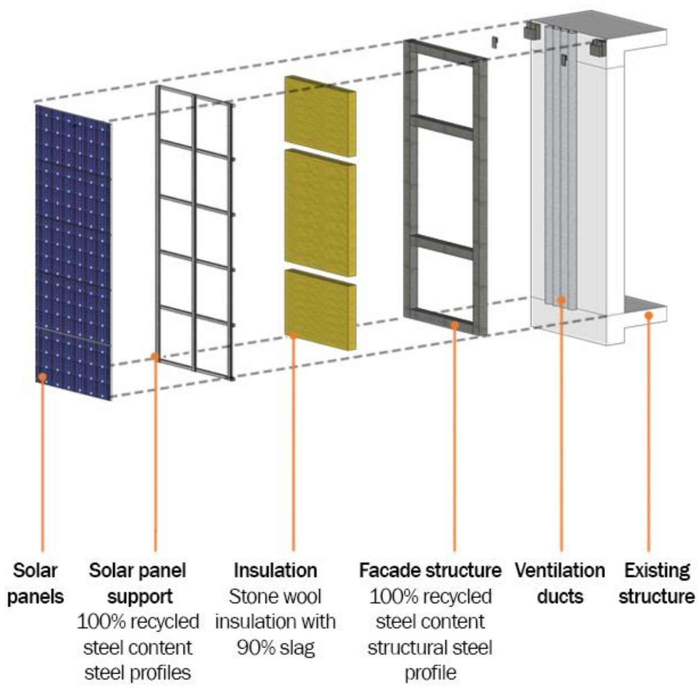


Figure 48 Exploded view of Panel C by author

Assembly sequence for panel A

The assembly sequence of the modular panel A and the mounting of the panel is illustrated below. A similar assembly sequence is followed for Panel B, the window is mounted on the prefab panel and then the prefab panel is mounted on the existing structure.

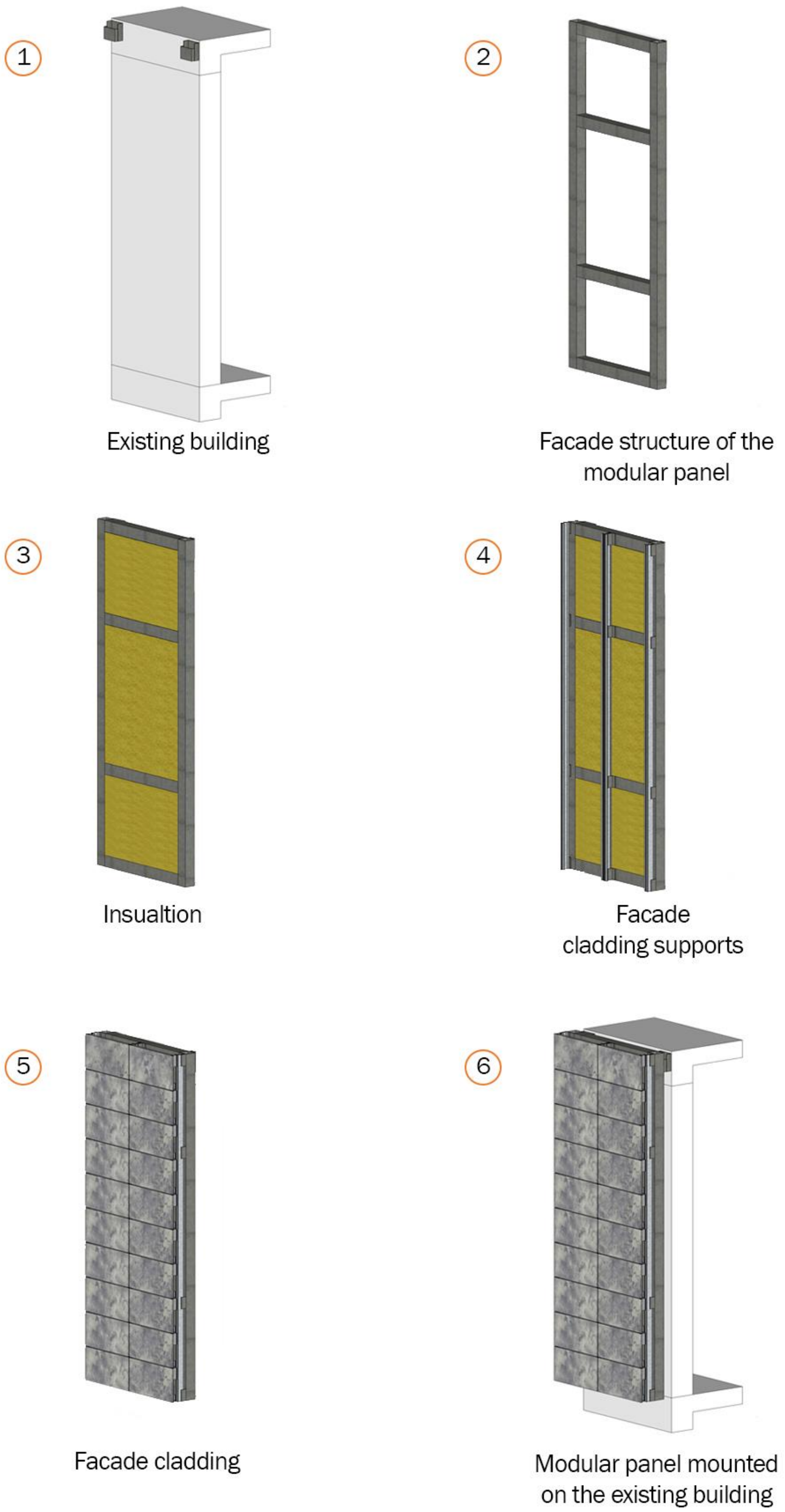
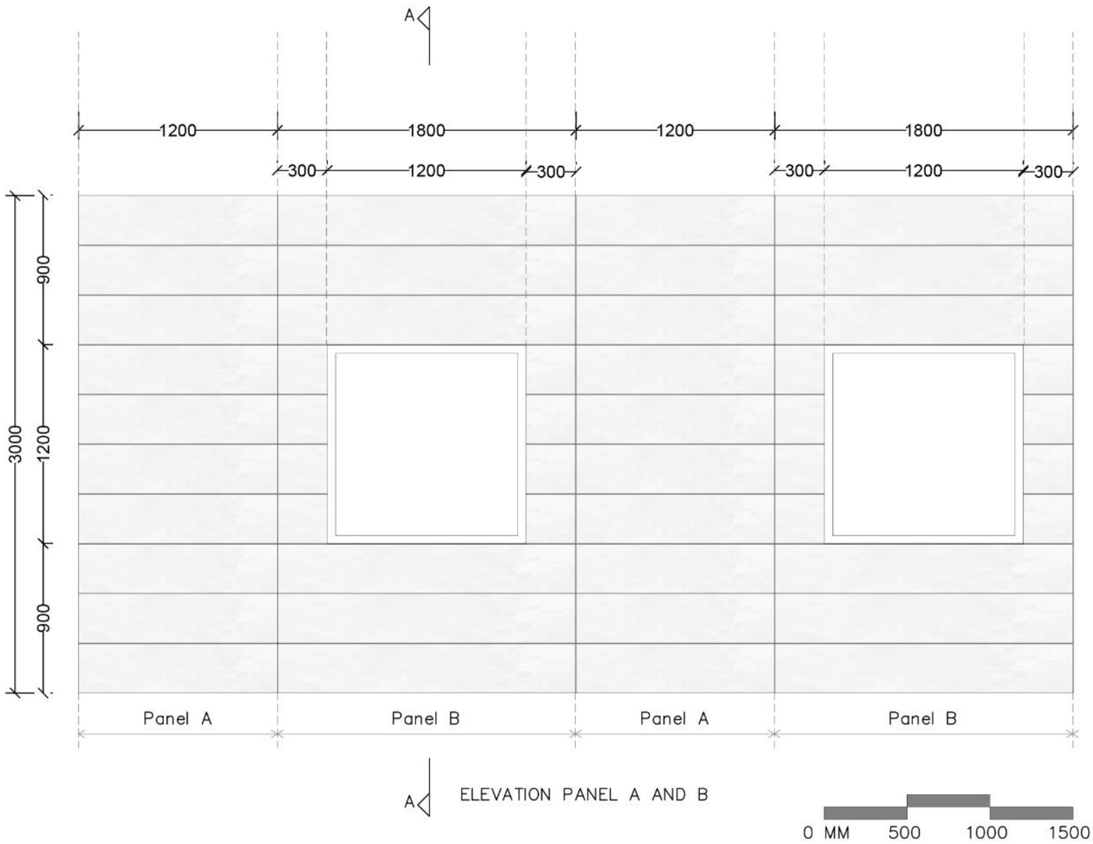


Figure 49 Assembly sequence of Panel A by author

Detail drawings



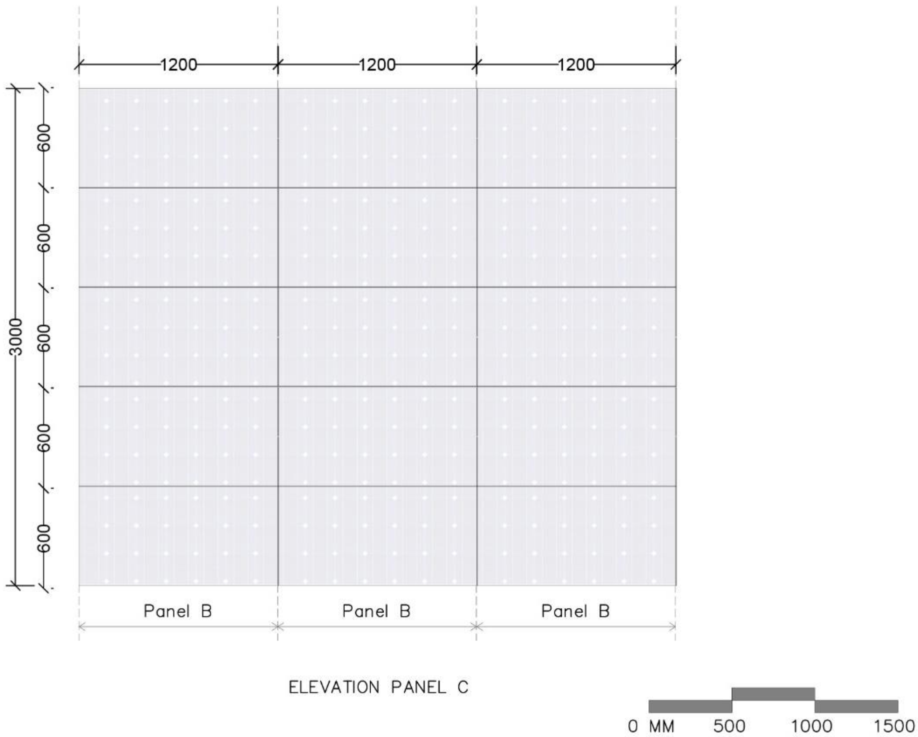
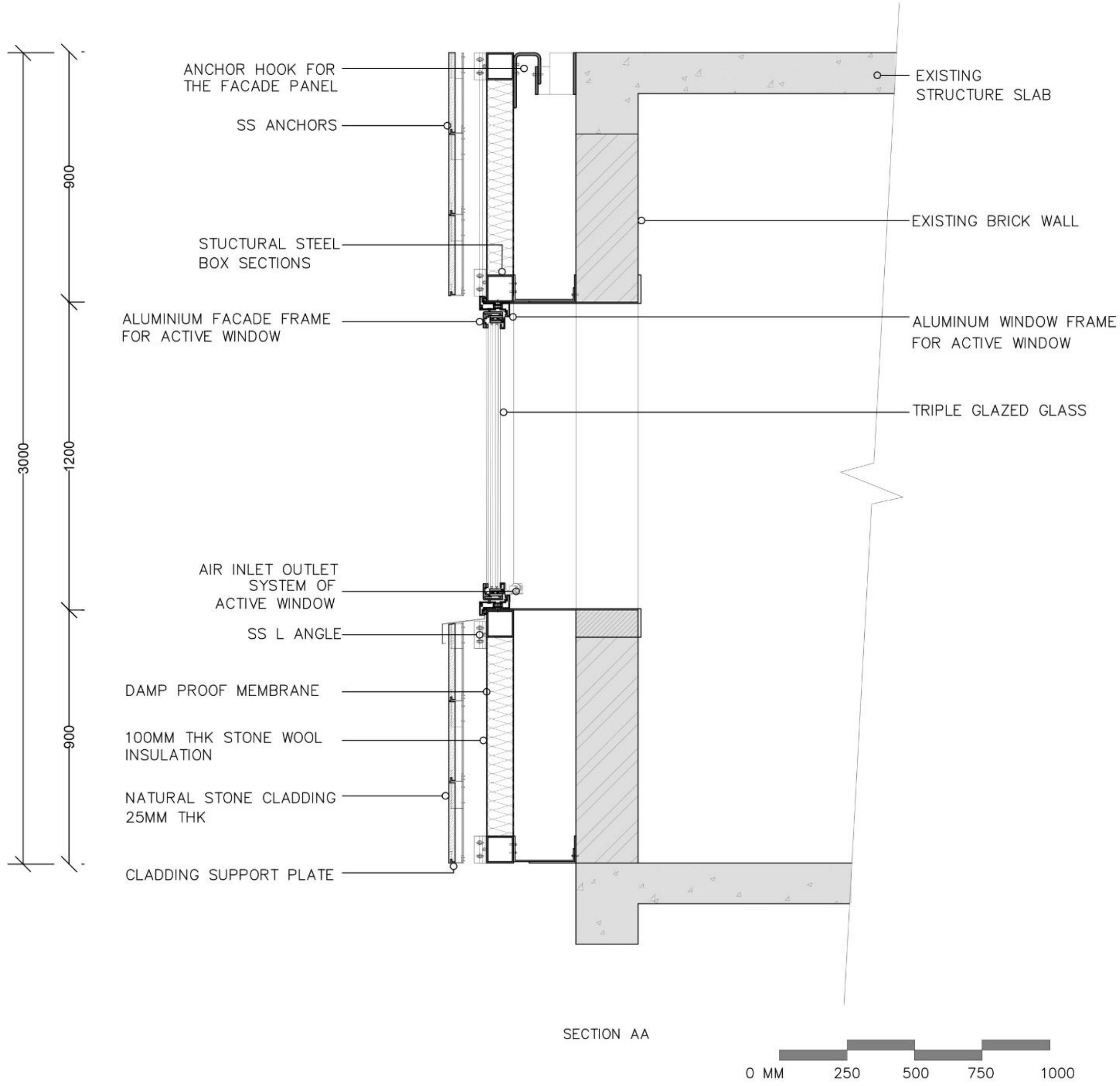


Figure 50 Elevations of Panel A, B and C by author for representation purpose only



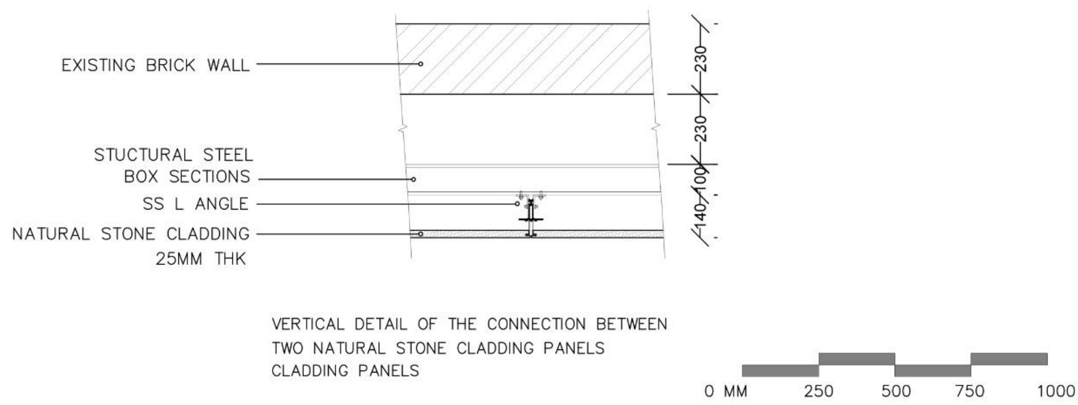
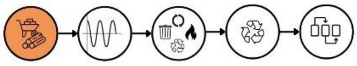


Figure 51 Section of Panel B and Details by author for representation purpose only

Details modified from Façade construction manual (Herzog, T., Krippner, R., & Lang, W. (2017))

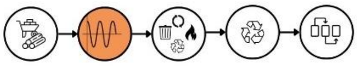
7.3 Step 2: Lifecycle Planning

7.3.1 Select a material



The materials selected for the design is a combination of materials that help in slowing and closing the loop. The materials selected have a lifespan that extends beyond the 30 years lifespan of a façade system. The other criteria used for the selection of the materials have been stated in section 6.

7.3.2 Lifespans



The technical lifespans of the selected materials play an important role in lifecycle planning since they have an impact on the EoL conditions of the components. The circular EoL process of reuse creates a less environmental impact compared to the circular alternative of recycling. The components with a longer lifespan can remain on the building for a longer time or can be reused multiple times.

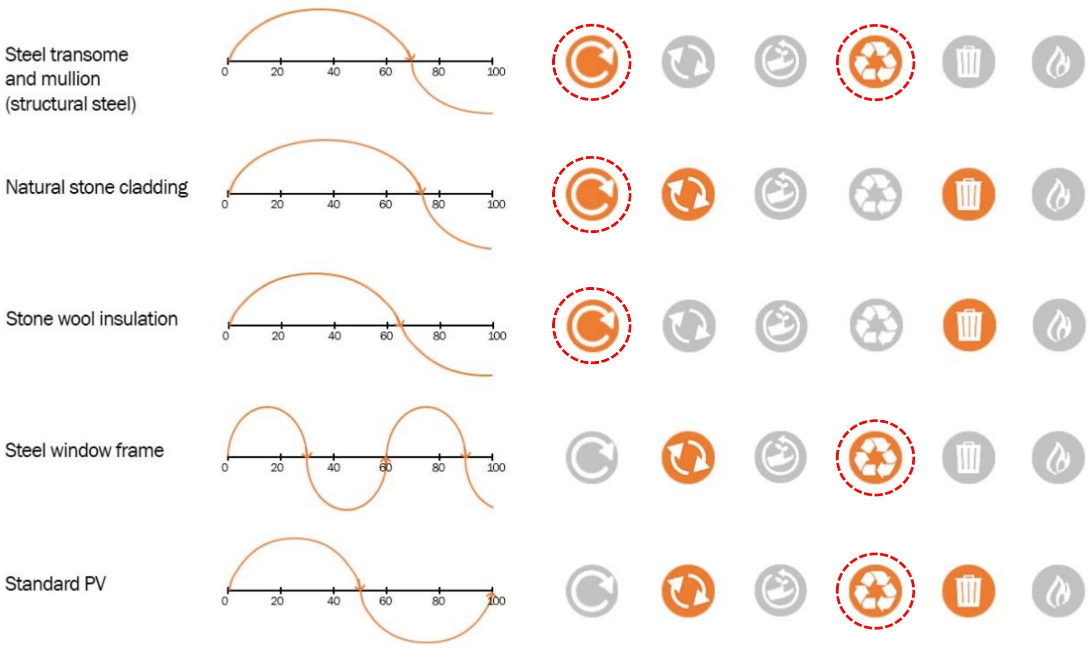
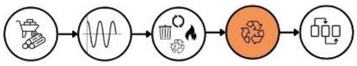


Figure 52 Standardised materials lifespans, possible EoL scenarios and circular EoL scenarios by author

7.3.3 EoL scenarios

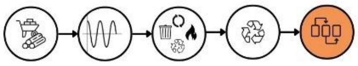
The possible EoL conditions are listed in the Figure 52. Some components have multiple potential EoL conditions, depending on their material properties and available techniques to deal with the EoL conditions. The structural steel used in the system can be reused or recycled at the EoL either can be a direct reuse of the component or reuse of the standardised materials. It can be reused on the same site or on a different site after a span of 30 years. Natural stone cladding can be reused multiple times like the structural steel or can be landfilled. The stone wool insulation can be landfilled or reused.

7.3.4 Circular EoL



The different circular scenarios are identified for each of the standardised materials. The circular EoL scenarios are highlighted with a red circle in Figure 52. The façade system for panel A is reused at the EoL of the first façade lifecycles and then recycled at the EoL of the second lifecycle. On the other hand, panel B has an active window system with the window component that needs to be replaced after 20-40 years. The other components in the panel B are reused as a system at the EoL of the first lifecycle. Panel C consists of active components that are replaced at the end of life of the first lifecycle. The structural steel and the stone wool insulation used in the system are reused for a second lifecycle.

7.3.5 Multi-lifespan flowchart



The flowchart below indicates the different lifecycle stages considered for the evaluation of the results along with different materials used in the system and the various circular EoL scenarios taken into consideration.

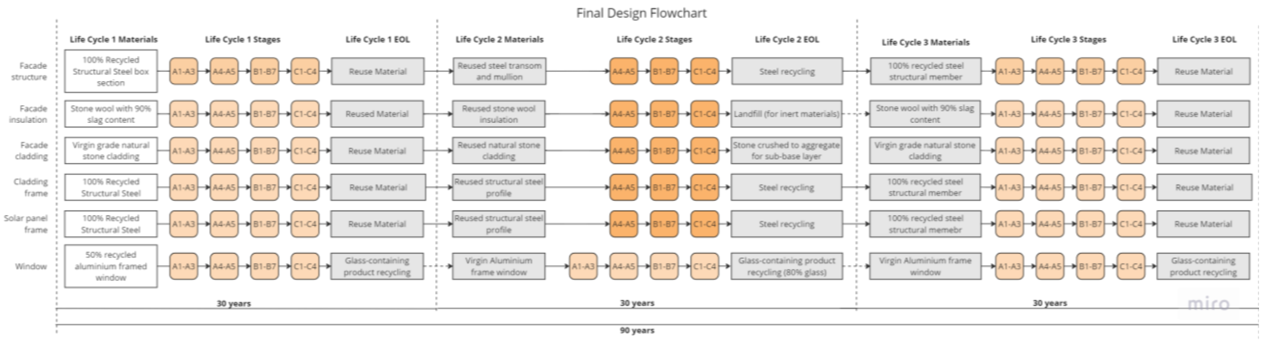


Figure 53 Multi-lifespan flowchart

7.4 Evaluation results

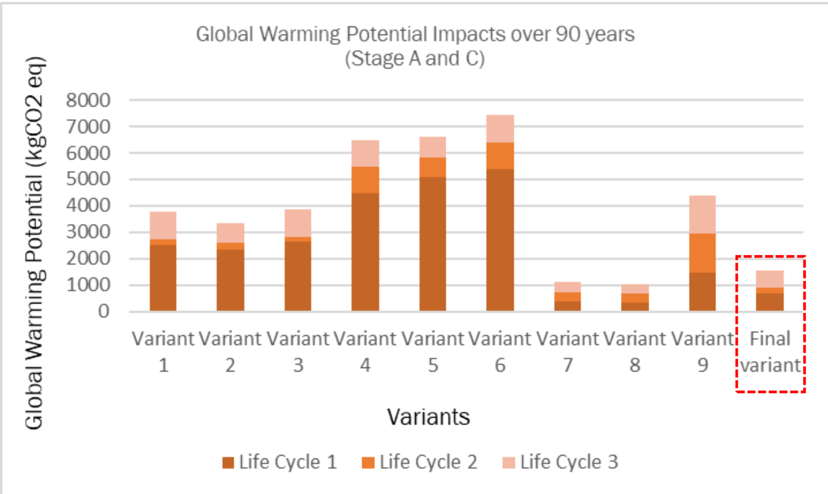


Figure 54 GWP impact over 90 years (Stage A and Stage C)

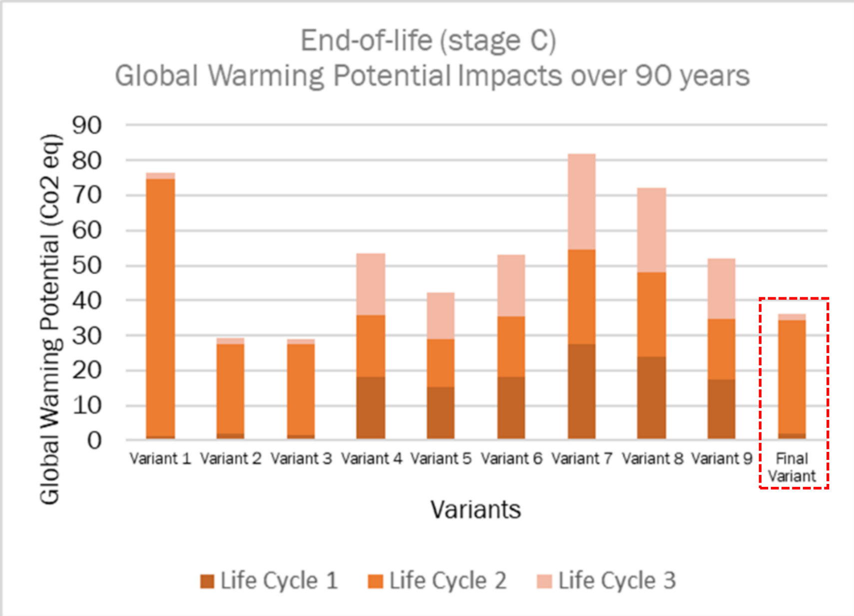


Figure 55 GWP impacts of stage C over 90 years

Figure 54 indicates that the impacts of GWP impacts are significantly reduced by integrating the design guidelines stated in section 6 in the façade design. A decrease of GWP impact of 50% was observed compared to the average value of long lifespan materials in the final design which helps to validate the proposed guidelines. The circularity percentage of the new design is 55% which is higher than the circularity percentage of bio-based materials and a 34 kgCO2 eq/m2 of the embodies carbon value which is lower than the long lifespan and short lifespan variants and the biobased variant 9 (rammed earth system) and equal to the variant 7 (timber system). The cost of the final variant is equivalent to the cost of the Variant 3 or less since recycled materials are used in the system. While the ODP, AP and POCP impacts are higher than the long lifespan variants, the other environmental indicators have less impacts.

Since most of the environmental indicators perform well, the next step involves preparing a flowchart that indicated the different circular EoL considerations for the final variant.

7.5 Recommended circular End-of-Life scenarios

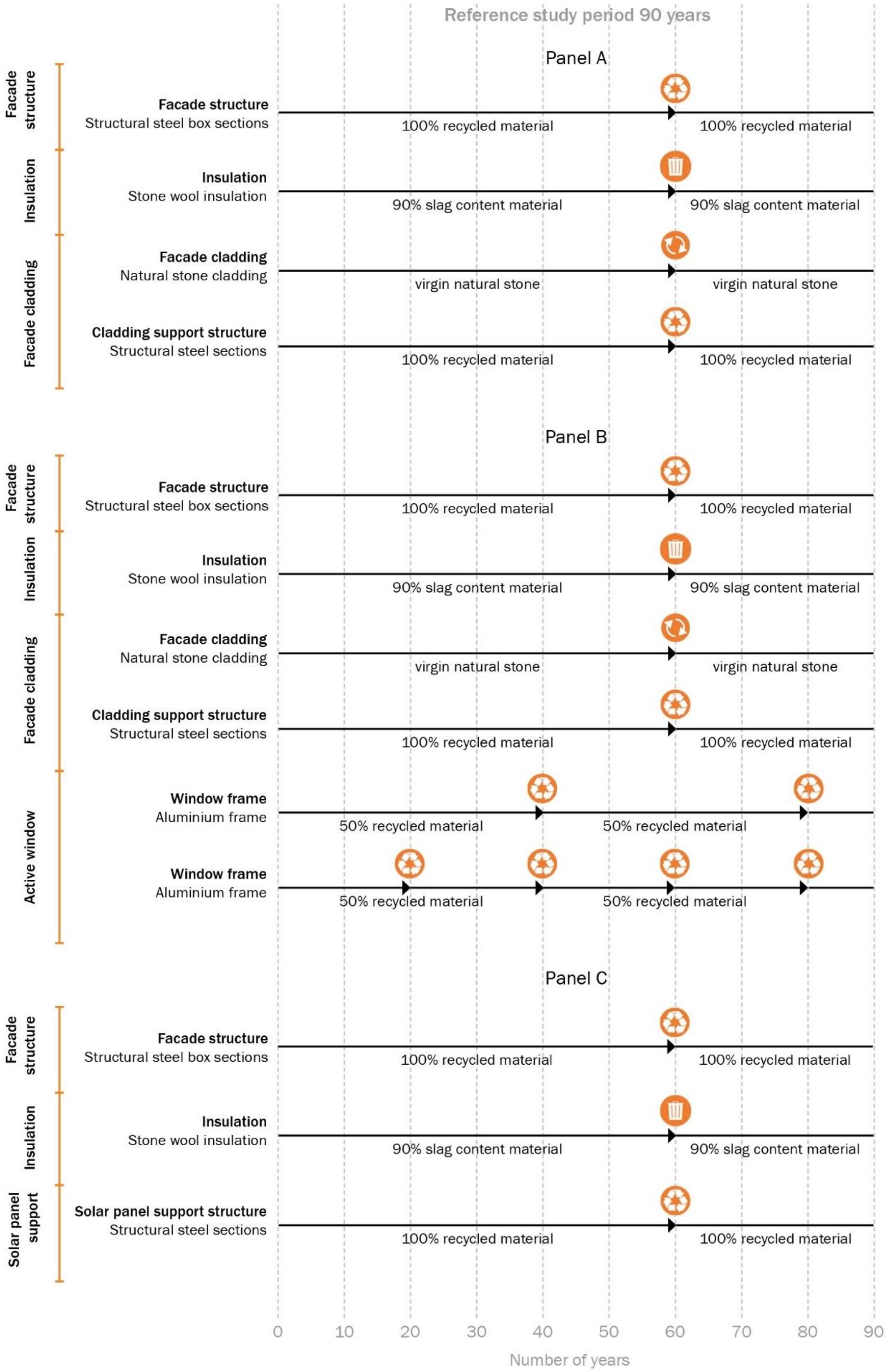


Figure 56 Recommended circular EoL scenarios for the final variant by author

8. Conclusions

This section elaborates the answers of the main research question by answering the sub-questions. The section further states the limitations of the research and discusses the trade-offs between several factors considered in the project and then ends with the idea of the broader picture.

8 Conclusions

The main research question is answered by the following sub-questions –
What design guidelines can help the façade designers integrate the considerations for a circular End-of-Life (EoL) of a façade system during the design phase and what is the information that needs to considered while following these design guidelines?

8.1 Sub-question 1: What are the different assessment methods for circularity?

Different methods can be used to access the environmental impacts of the materials used in a system. The MCI takes into account the material inputs and outputs in a system but does not calculate the environmental impacts. The MFA requires an extensive database and thus is a complex and time-consuming method. BCI takes into account a cradle-to-grave approach and not a cradle-to-cradle approach which also takes into account the benefits and loads beyond the system boundary. The LCA is a time-consuming method but takes into account the benefits and loads beyond the system boundaries for calculating the environmental impacts and also considers the environmental impacts at the EoL stage. It also takes into account different impact indicators and includes the assessment of the entire life cycle of a building. LCA can be used as a method to access the environmental impacts of the materials, the EoL processing impacts and the impacts of the materials beyond EoL stage. Thus, the method proves to be a wholesome method to reduce the impacts caused for closing the loop.

8.2 Sub-question 2: What are the design guidelines to integrate a circular EoL during the design stage?

Design guidelines help the façade designers to design a circular façade system. The guidelines are based on the materials that are selected in the system and the guidelines for multiple lifecycle planning. The use of locally sourced materials reduces the environmental impacts. The amount of reused and recycled content in the system should be maximised while designing a façade system. The design should have a low value of GWP of EoL processing. The biodegradability and recyclability of the materials in the façade system should high, the materials chosen in the system should be majorly biodegradable or recyclable. The lifecycle planning includes the guidelines regarding considering the possible EoL scenarios in a system and identifying the circular EoL scenarios. Considering the use of long lifespan materials. This enables multiple reuse cycles of the system components. The impacts should be evaluated for multiple lifecycles instead of one lifecycle.

8.3 Sub-question 3: What information impacts the circularity of the EoL stage based on the derived design guidelines?

The generative aids of circular design strategies which are applicable on a product level along with the evaluative design aids acts as a starting point for the process of research through design. Further and evaluation of different materials lifespans for each component along with the possible EoL scenarios and the circular EoL scenarios help in establishing the design variants that can be evaluated. The information that impacts the circularity of the EoL stage includes the lifespans of the standardised materials, multiple lifecycle planning, available circular EoL Scenarios, recycled material in the system, reused material in the system, recyclability of the system, biodegradability of the system and the GWP of the EoL processing.

8.4 Limitations

The project does not take into consideration the different aspects related to the EoL conditions of the façade system such as the connections and the disassembly potential of the system. A detailed study on the connections between the standardised materials and the components needs to be carried out to access the disassembly potential. The project does not take into account the costs for the processing of the materials at the EoL stage and does not consider the labour costs for deconstruction stage. It only takes into account the initial market-based costs of the standardised materials.

8.5 Discussions

There are certain trade-offs between the costs and the environmental impacts of the façade systems. Manufacturing and construction GWP impact for long and short lifespan standardised materials are more compared to the biobased standardised materials. But the EoL GWP impacts are more for the biobased standardised materials. The other environmental impact indicators, the EoL impacts are less for bio-based standardised materials. The circularity for the bio-based variants is not high since the materials are not returned back to the system. The applicable EoL scenarios for the bio-based standardised materials are at the bottom of the circularity ladder. The bio-based standardised materials have a less material recovery value. The percentage of virgin standardised materials is high in the bio-based variants.

The short lifespan variants are more circular than the long lifespan variants since they can be recycled multiple times and thus close the circularity loop. The long lifespan variants have a EoL scenario considered as a downcycle after multiple reuse cycles are less circular than those have a greater percentage of recyclability at the EoL.

Over multiple life-cycles, the impacts of the materials are less compared to the impact of only the first lifecycle. The bio-based materials have a better environmental performance, but their market-based costs are high making it a difficult choice to consider. On the other hand, these materials are also considered less circular at the EoL. The long lifespan materials have a better result in terms of the initial costs since they are durable and more circular because of the high percentage of recyclability of the materials used in the system. The low lifespan, more circular variants are more circular, their cost is less but it creates a greater environmental impact. Thus, the choice of materials in a façade system is a trade-off between the market-based material costs, environmental impacts and the materials recovered in the system.

8.6 Broader picture & integration of business model

Walter Stahel's inertia principle states that, "*Do not repair what is not broken, do not remanufacture something that can be repaired, do not recycle a product that can be remanufactured*". To bring this into action, it is important to have business model which works in the favour of circularity.

The product as a service business model can be applied at a broader scale to implement this project. As discussed by Illankoon & Vithanage (Illankoon & Vithanage, 2023), product as a service is one of the business models which aims at closing the circularity loop. Guide and Van Wassenhove (2009) stated that when it comes to circularity, a closed loop supply chain (CLSC) is the key.

The façade builder is not involved in the EoL stage and the scope of the façade builder is limited till the assembly stage and repair stage (Klein, 2013). But, the façade leasing model by Azcarate (2017) takes into consideration the façade builders at the EoL stage.

The façade system consisting of various combinations of long lifespan materials can be offered as a service to the clients. Since, the cost of the long lifespan materials is high for LC1, the clients might prefer the short lifespan materials. To address this, the façade service provider can offer a scheme where the clients can pay the yearly fee for the façade as a product and when the functional life of the façade ends, the clients can give back the façade to the façade company. The façade can then be inspected and reused based on the remaining technical lifespan of the components. After necessary repairs, the same façade system or its components can be redeployed in a different system. The façade company can offer multiple options tailored to different materials used in the system. Although, the initial cost of the façade system is high, the long-term investment in long lifespan materials will pay off over the years. The façade as a service model works as a system where clients can choose from the different available design alternatives which offer some level of customisation and the designers use the previously used or recycled components and standardised materials to develop the designs according to the client's needs. This system offers a transparency in the components and standardised materials available and establishes a network of systems.

9. Reflections

This section of the report focuses on the graduation process and the societal impacts of the project. It elaborates on the position of the project in the studio, the approach that was followed to achieve the results, establishes a relation between design and research. It explains the application of the reusults into practice, the degree of project innovation that is achieved and the socio-cultural and ethical impacts of the project on the people. The section elaborates on the aspects of sustainability achieved in the project and its relation to the built environment.

9 Reflections

The chosen graduation topic is revolving around the topics of circularity and facades and attempts to find different design strategies for a circular façade design. The topic focuses on technical end-of-life life scenarios of a façade system and aims to have a circular end-of-life for a façade system. Thus, the topic is a blend of two building technology themes namely façade and circularity.

9.1 Research and Design

The research methodology followed was a mixed method which consisted of literature review to find the research gap in the domain of circularity towards the end of technical life of a system. The literature review revealed a research gap in the domain of circularity, specifically related to the end of technical life of a system. The thesis then derived inspiration from AEGiR façade renovation project that aims to achieve façade circularity while reaching its goal of net-zero buildings. The components of the façade system that are considered in the thesis are inspired from the project and the thesis is based on the aim of the AEGiR project. A study of existing buildings was done from literatures to find the values of the constants for the buildings need to be renovated in the context of the Netherlands. Then a methodology of research through design was followed wherein different circular façade design variants were developed. These variants changed in the materiality and were constant in dimensions. The variants were evaluated and the method used was the assessment of environmental impacts at the material stage, EoL stage and the benefits beyond the EoL stage. The results of the research through design process consisted of some results that were predictable but the other results helped to understand that the impacts of EoL are highly governed by the choice of materials and the technical end-of-life for that material. The method was successful in establishing which materials create more impacts, which ones less and the impacts that are created by opting various EoL scenarios. These form the two most important design guidelines. The study found that materials with higher impacts during manufacturing could potentially have lower overall impacts if alternative EoL strategies are adopted compared to the current market-based scenarios. The methodology successfully determined the materials with the least environmental impacts. The results that were derived helped to establish design guidelines. The stablished guidelines were further validated by generating a design with the help of the guidelines.

The project follows a multi-lifespan approach to evaluate the variants through the LCA method. For different lifespan materials and biobased materials, the most circular EoL scenarios were chosen and compared using an evaluative approach to derive generative design aids in the form of guidelines. Along with the guidelines, the project provides the necessary information that needs to be considered to follow these guidelines.

9.2 Societal impacts

The project contributes to the society by providing design guidelines for the façade designers which take into account the different materials for the components, their circular EoL scenarios and multi-lifespan approach to evaluate the environmental impacts. The project helps in reducing the waste since it focuses on circular EoL scenarios. The project takes into account sustainability since the area of focus of the project is reduction of the environmental impacts. It guides the façade designers in closing and narrowing the loop in a circular system. The project has environmental benefits since it focuses on the reduction of carbon footprints and helps in conserving the resources. It also has economic benefits since a circular EoL may lead to cost benefits when the materials are reused instead of manufacturing new materials. A circular façade design aligns with the goal of façade renovation by reducing the energy required for the manufacturing of the façade system. While a façade renovation helps in reducing the operational energy of the houses, a circular façade renovation helps in the reduction of the embodied energy.

A circular façade has a positive impact on the environment and people since it avoids the use of toxic substances. It creates jobs in the new sectors of deconstruction, reuse and recycling.

It explores into various aesthetics for the façade design since it explores different ways to deal with circularity of the different materials. Along with providing alternatives for materials, it provides transparency in terms of material sourcing and supply chains, thus reducing the exploitation of materials. The project explores the idea of long-term thinking in a circular economy which guides the stakeholders to consider long term impacts of introducing the materials in a system. However, while thermal comfort conditions were considered in the façade design, some intangible aspects like the colour and texture of the materials used were not taken into consideration in this research. Along with these aspects, further research can be carried out with respect to the life cycle costs which will also impact the material choices.

9.3 Broader picture

With the current wave of renovation, it has become important to consider the circularity of the systems that are introduced in the existing buildings. It has become vital to take into account the embodied energy of the façade systems for a façade renovation project. This project can be used to understand the design process for circular façade renovations. The derived guidelines in the project help in reducing the embodied energy of the materials that are used in the system and help to achieve a circular EoL. The guidelines can be applied for any renovation project in the context of the Netherlands and a similar approach can be followed to observe the environmental impacts of the materials in other countries. The results may vary in the other countries depending on the availability of the materials in the country. The process that is used to derive the guidelines can be applied universally by the façade designers. The information considerations that were outlined act as guide to establish the guidelines.

	Helpful	Harmful
	Strengths	**Weaknesses**
Internal Origin	1. Enhances efficiency by reducing time in the decision-making process for designing circular facade systems. 2. Provides a straightforward method for facade designers to follow. 3. Serves as a generative design tool to develop various circular design options along multiple lifespans.	1. Only considers environmental impacts and cost for making decisions for a circular EoL. 2. Does not take into account the disassembly potential of the system or the type of connections. 3. It does not consider the operational energy for different variants and assumes it to be constant.
	Opportunities	**Threats**
External Origin	1. Since the field of circularity is growing in the facade industry, similar guidelines can be derived for taking decisions regarding EoL scenarios of a system. 2. More aspects like connections and disassembly potential can also be included in the EoL decision making. 3. Designing facades taking into account the circular EoL conditions and information considerations for multiple lifecycles ensures the circularity at the EoL stage.	1. The data taken into consideration for evaluation should not be outdated. 2. The results of the design can vary depending on the impacts of each stage depending on the location of the project. 3. The projects considers end-of-technical service life and not the end-of functional service life because of the uncertainties in the functional service life.

Figure 57 SWOT analysis by author

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11. Appendix

11 Appendix

No.	Strategy	Action	Sub-Actions leading to information	Description	Key stakeholder	Key Design Phase
A	Refuse unnecessary new construction	Reuse, renovate or repurpose an existing asset	Carryout a feasibility study between renovation/ new construction options, adding embodied carbon, virgin material use and LCC as assessment criteria.	Effective use of energy and materials, reusing materials. While reusing materials, the residual service life needs to be assessed.	Architect	Strategic definition
B	Increase facade utilisation	Increase the multi-use potential of building spaces.	Design the skin layer such that it is adaptable to different use of the space layer.	When the skin is designed for a single use, it reults in a limited use of space during a day/ month/ year.	Architect	Preparation and B riefing
C	Design for longevity	Design for future climate adaptability/ resilience	Consider incremental adaptability rather than designing for the worst case distant future. Carry out climate risk assessment of the project	Think beyond the current technical standards like temperature, precipitation, seismic intensity, wind loads etc.	Facades Eng.	
		Prioritize standarised, modular elements over bespoke/tailor-made solutions, and avoid complex building geometries	Avoid complex geometrical forms, design for floor-to-floor heights, engage with local manufacturer and include disassembly potential while doing so.	Non-standard bespoke elements reduce the chances of being reclaimed and reused	Architect	Technical Design
		Investigate Product-as-a-Service schemes for components expected to have a short or medium service life in the project	Propose such business models for the skin.	Façade elemets are offten replaced before they reach the end of their first functional life. Product-as-a-service leasing scheme promotes a payment for the actual use of a certain element than an entire acquisition of the product.	Architect	Concept Architect ural Design
		Ensure the individual service life of envelope systems, components, products and materials align with the minimum service life of the building.	Before choosing the materials, the service life of each component should be considered . Create a maintenance plan/ diagram for replacing the elements in the system.	There might be contractions in the different service lives of the components of the façade system, thus provisions should be made such that it is easy to replace the elements with a lower service life.	Facades Eng.	Spatial Coordinati on - Concept Technical Design
		Make use of Whole Life-Cycle Cost assessment (WLCC) as design assessment tool	Carry out WLCC assessment for the façade system.	While estimating the real project costs, along with focusing on capital costs, operational cost and maintenance cost, the End-of-service life costs should be taken into account.	Architect	Spatial Coordinati on - Concept Technical Design
		Issue a Building Materials Passport	Create a framework of information which needs to be transferred from the façade designer to the deconstruction contractor.	Effective recovery abd reuse is not possible if detailed informationis not gathered and easily accessible in the future.	Architect	Technical Design
D	Design for Adaptability	Increase convertibility: Allow for changes in building use by designing the building envelope to allow for more than one use, or to allow modifications in window size and spacing.	Scenario planning should be done, draw one alternative façade showing would could work for one other use type, avoid load bearing facades to allow for future changes to be made easily in the system.	Increase convertibility: Allow for changes in building use by designing the building envelope to allow for more than one use, or to allow modifications in window size and spacing.	Architect	Spatial Coordinati on - Concept Technical Design
		Develop and issue an Adaptability Manual document	Providing a adaptability manual document including clear instructions and diagrams on how the façade will adapt to different scenarios, include information about materials and connection types.	A building can be designed to be highly adaptable over time	Architect	Technical Design
E	Design for Disassembly	Develop and issue a disassembly manual for the façade system	Develop a Disassembly manual document including clear instructions and diagrams on how to disassembly different componenets and for different scenarios.	This strategy aims to enabling disassembly potential at the end of service life.	Architect	Technical Design
F	Design for a low waste	Design taking into consideration the amount of waste that can be created at the End-of-Life or end of first service life. Generetae information that helps the deconstructiuon contractors take decisions.	Prepare an approximate Bill of Materials, Use the levels template for entering the data - inert, non-hazardous or hazardous, decide upon different end market destinations. Thus, this should provide a detailed information upon how the materials should be collected, stored, treated and transported.	It helps in determining how much of the total material that is used is recycled, which elements and materials are reused.	Architect	Technical Design
G	Design with products for a low GWP	Design the system with low GWP by comparing different options of materials and components.	Choose materials with lower embodies carbon, design for energy efficiency to minimize operational energy, explore the carbon sequencing techniques within the building envelop	Meaures the amount of gas that is emitted in the atmosphere over a specific amount period, using CO2 as a reference.	Façade Designer	Technical Design
H	Hazardous substances	Design with materials that have low acidification potential at the End of service life stage.	Ensuring biological materials remain uncontaminated.		Façade Design	Technical Design

Circular Design Strategies

Resource	Quantity			CO₂e	Comment	Building Parts	Transport, kilometers		Transport, leg 2, kilometers	Service life	Localisation	Repair/year (B3)	Wastage	EOL Process	Reused material	Locally reused
Structural steel profiles, generic,	550.7	kg		1,9t - 52%	LC1 Facade structure	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
EPS insulation panels, graphite, L=	11.16	m	x 100 mm	81kg - 2%	LC1 Insulation	1.2.3 External walls	430	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	4 %	Reuse as material	☐	☐
Fibre cement boards, 1300 kg/m3 (81	11.16	m	x 9 mm	0,12t - 3%	LC1 Facade cladding	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	5 %	Reuse as material	☐	☐
Clay brick (One Click LCA)	810	kg		0,2t - 5%	LC1 Facade cladding	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	5 %	Reuse as material	☐	☐
Structural steel profiles, generic,	16.15	kg		55kg - 2%	LC1 Solar panel	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Aluminium frame window double glaze	1.44	m		0,12t - 3%	LC1 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐
Structural steel profiles, generic,	550.7	kg		30kg - 0,8%	LC2 Facade structure	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☑	☐
EPS insulation panels, graphite, L=	11.16	m	x 100 mm	47kg - 1%	LC2 Insulation	1.2.3 External walls	430	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	4 %	Plastic-based material	☑	☐
Fibre cement boards, 1300 kg/m3 (81	11.16	m	x 9 mm	0,74kg - -0%	LC2 Facade cladding	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	5 %	Concrete crushed to	☑	☐
Clay brick (One Click LCA)	810	kg		4,6kg - 0,1%	LC2 Facade cladding	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	5 %	Brick/stone crushed to	☑	☐
Structural steel profiles, generic,	16.15	kg		0,89kg - -0%	LC2 Solar panel	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☑	☐
Aluminium frame window double glaze	1.44	m		0,12t - 3%	LC2 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐
Structural steel profiles, generic,	550.7	kg		0,46t - 13%	LC3 Facade Structure	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
EPS insulation panels, graphite, L=	11.16	m	x 100 mm	81kg - 2%	LC3 EPS insulation	1.2.3 External walls	430	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	4 %	Reuse as material	☐	☐
Fibre cement boards, 1300 kg/m3 (81	11.16	m	x 9 mm	0,12t - 3%	LC3 Facade cladding	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	5 %	Reuse as material	☐	☐
Clay brick (One Click LCA)	810	kg		0,2t - 5%	LC3 Facade cladding	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	5 %	Reuse as material	☐	☐
Structural steel profiles, generic,	16.15	kg		14kg - 0,4%	LC3 Solar panel	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Aluminium frame window double glaze	1.44	m		0,12t - 3%	LC3 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐

Variant 1 software inputs

Resource	Quantity			CO₂e	Comment	Building Parts	Transport, kilometers		Transport, leg 2, kilometers	Service life	Localisation	Repair/year (B3)	Wastage	EOL Process	Reused material	Locally reused
Structural steel profiles, generic,	550.7	kg		1,9t - 58%	LC1 Facade structure	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Glass wool insulation with fibre-gl	11.16	m		30kg - 0,9%	LC1 Insulation	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	8 %	Reuse as material	☐	☐
Flat fibre cement panels for claddi	7.56	m	x 6 mm	25kg - 0,8%	LC1 Facade cladding	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	5 %	Reuse as material	☐	☐
Structural steel profiles, generic,	16.75	kg		57kg - 2%	LC1 Facade cladding	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Structural steel profiles, generic,	16.15	kg		55kg - 2%	LC1 Solar panel	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Aluminium frame window triple glaze	1.44	m		0,22t - 7%	LC1 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐
Structural steel profiles, generic,	550.7	kg		30kg - 0,9%	LC2 Facade structure	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☑	☐
Glass wool insulation with fibre-gl	11.16	m		0,13kg - -0%	LC2 Insulation	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	8 %	Landfilling (for inert	☑	☐
Flat fibre cement panels for claddi	7.56	m	x 6 mm	0,35kg - -0%	LC2 Facade cladding	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	5 %	Concrete crushed to	☑	☐
Structural steel profiles, generic,	16.15	kg		0,89kg - -0%	LC2 Facade cladding	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☑	☐
Structural steel profiles, generic,	16.15	kg		0,89kg - -0%	LC2 Solar panel	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☑	☐
Aluminium frame window triple glaze	1.44	m		0,22t - 7%	LC2 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐
Structural steel profiles, generic,	550.7	kg		0,42t - 13%	LC3 Facade structure	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Glass wool insulation with fibre-gl	11.16	m		30kg - 0,9%	LC3 Reused	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	8 %	Reuse as material	☐	☐
Flat fibre cement panels for claddi	7.56	m	x 6 mm	25kg - 0,8%	LC2 Facade cladding	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	5 %	Reuse as material	☐	☐
Structural steel profiles, generic,	16.75	kg		13kg - 0,4%	LC3 Facade cladding	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Structural steel profiles, generic,	16.15	kg		12kg - 0,4%	LC3 Solar panel	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Aluminium frame window triple glaze	1.44	m		0,22t - 7%	LC2 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐

Variant 2 software inputs

Resource	Quantity			CO_2e	Comment	Building Parts	Transport, kilometers		Transport, leg 2, kilometers	Service life	Localisation	Repair/year (B3)	Wastage	EOL Process	Reused material	Locally reused
Structural steel profiles, generic,	550.7	kg		1,9t - 50%	LC1 Facade structure	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Stone wool (mineral wool) insulatio	11.16	m	x 80 mm	79kg - 2%	LC1 Insulation	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	8 %	Reuse as material	☐	☐
Natural stone cladding, A4 = 0 - 10	7.56	m		0,36t - 10%	LC1 Facade cladding	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	4.5 %	Reuse as material	☐	☐
Structural steel profiles, generic,	16.15	kg		55kg - 1%	LC1 Facade cladding	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Structural steel profiles, generic,	16.15	kg		55kg - 1%	LC1 Solar panel frame	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Aluminium frame window triple glaze	1.44	m		0,13t - 3%	LC1 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐
Structural steel profiles, generic,	550.7	kg		30kg - 0,8%	LC2 facade structure	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☑	☐
Stone wool (mineral wool) insulatio	11.16	m	x 80 mm	0,43kg - -0%	LC2 Insulation	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	8 %	Landfilling (for inert	☑	☐
Natural stone cladding, A4 = 0 - 10	7.56	kg		0,04kg - -0%	LC2 Cladding	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	4.5 %	Brick/stone crushed to	☑	☐
Structural steel profiles, generic,	16.15	kg		0,89kg - -0%	LC2 Cladding frame	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☑	☐
Structural steel profiles, generic,	16.15	kg		0,89kg - -0%	LC2 solar panels	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☑	☐
Aluminium frame window triple glaze	1.44	m		0,13t - 3%	LC2 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐
Structural steel profiles, generic,	550.7	kg		0,42t - 11%	LC3 Facade structure	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Stone wool (mineral wool) insulatio	11.16	m	x 80 mm	79kg - 2%	LC3 Insulation	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	8 %	Reuse as material	☐	☐
Natural stone cladding, A4 = 0 - 10	7.56	m		0,36t - 10%	LC3 Facade cladding	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	4.5 %	Reuse as material	☐	☐
Structural steel profiles, generic,	16.15	kg		12kg - 0,3%	LC3 Cladding frame	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Structural steel profiles, generic,	16.15	kg		12kg - 0,3%	LC3 solar panels	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐
Aluminium frame window triple glaze	1.44	m		0,13t - 3%	LC3 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐

Variant 3 software inputs

Resource	Quantity			CO_2e	Comment	Building Parts	Transport, kilometers		Transport, leg 2, kilometers	Service life	Localisation	Repair/year (B3)	Wastage	EOL Process	Reused material	Locally reused
Extruded aluminium profiles for win	223.81	kg		3,5t - 48%	LC1 Facade structure	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling	☐	☐
XPS insulation panels, L=0.033 W/mK	11	m	x 80 mm	0,11t - 1%	LC1 Insulation	1.2.3 External walls	430	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	4 %	Plastic-based material	☐	☐
Galvanized steel façade cladding pa	51	m		1,1t - 16%	LC1 Facade cladding	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Steel recycling	☐	☐
Structural steel hollow sections	34.02	kg		90kg - 1%	LC1 Facade cladding	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Local, not needed	None	3.3 %	Steel recycling	☐	☐
Structural steel hollow sections	16.15	kg		43kg - 0,6%	LC1 Solar panel frame	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Local, not needed	None	3.3 %	Steel recycling	☐	☐
Steel frame window, 44.82kg/m2, Uw<	1.44	m		0,29t - 4%	LC1 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐
Extruded aluminium profiles for win	223.81	kg		0,38t - 5%	LC2 Facade structure	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling	☐	☐
XPS insulation panels, L=0.035 W/mK	11	m	x 100 mm	0,12t - 2%	LC2 Insulation	1.2.3 External walls	430	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	4 %	Plastic-based material	☐	☐
Galvanized steel façade cladding pa	51	kg		0,11t - 2%	LC2 Facade cladding	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Steel recycling	☐	☐
Structural hollow steel sections (H	34.02	kg		95kg - 1%	LC2 Facade cladding	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☐	☐
Structural hollow steel sections (H	16.15	kg		45kg - 0,6%	LC2 Solar panel	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☐	☐
Steel frame window, 44.82kg/m2, Uw<	1.44	m		0,29t - 4%	LC2 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐
Extruded aluminium profiles for win	223.81	kg		0,38t - 5%	LC2 Facade structure	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling	☐	☐
XPS insulation panels, L=0.035 W/mK	11	m	x 100 mm	0,12t - 2%	LC2 Insulation	1.2.3 External walls	430	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	4 %	Plastic-based material	☐	☐
Galvanized steel façade cladding pa	51	kg		0,11t - 2%	LC2 Facade cladding	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Steel recycling	☐	☐
Structural hollow steel sections (H	34.02	kg		95kg - 1%	LC2 Facade cladding	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☐	☐
Structural hollow steel sections (H	16.15	kg		45kg - 0,6%	LC2 Solar panel	1.2.3 External walls	370	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☐	☐
Steel frame window, 44.82kg/m2, Uw<	1.44	m		0,29t - 4%	LC2 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐

Variant 4 software inputs

Resource	Quantity		CO₂e	Comment	Building Parts	Transport, kilometers		Transport, leg 2, kilometers	Service life	Localisation	Repair/year (B3)	Wastage	EOL Process	Reused material	Locally reused
Extruded aluminium profiles for win ?	33.41	kg	0,52t - 8%	LC1 Facade cladding	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Extruded aluminium profiles for win ?	16.15	kg	0,25t - 4%	LC1 Solar panel frame	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Glass wool insulation panels, L = 0 ?	11.16	m x 80 mm	35kg - 0,6%	LC1 Insulation	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Local, not needed	None	8 %	Use EOL defined in EPD		
PVC facade cladding, instalation pa ?	7,5	m	0,23t - 4%	LC1 Facade cladding	1.2.3 External walls	430	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Plastic-based material		
Aluminium frame window triple glaze ?	1.44	m	0,22t - 3%	LC1 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product		
Extruded aluminium profiles for win ?	223.81	kg	3,5t - 56%	LC1 Facade structure	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Extruded aluminium profiles for win ?	223.81	kg	0,38t - 6%	LC2 Facade structure	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Extruded aluminium profiles for win ?	33.41	kg	56kg - 0,9%	LC2 Facade cladding	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Extruded aluminium profiles for win ?	16.15	kg	27kg - 0,4%	LC2 Solar panel	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
PVC facade cladding, instalation pa ?	7,5	kg	12kg - 0,2%	LC2 Facade cladding	1.2.3 External walls	430	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Plastic-based material		
Glass wool insulation panels, L = 0 ?	11.16	m x 80 mm	35kg - 0,6%	LC1 Insulation	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Local, not needed	None	8 %	Use EOL defined in EPD		
Aluminium frame window triple glaze ?	1.44	m	0,22t - 3%	LC2 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product		
Extruded aluminium profiles for win ?	223.81	kg	0,38t - 6%	LC3 Facade structure	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Extruded aluminium profiles for win ?	33.41	kg	56kg - 0,9%	LC3 Facade cladding	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Extruded aluminium profiles for win ?	16.15	kg	27kg - 0,4%	LC3 Solar panel	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
PVC facade cladding, instalation pa ?	7,5	kg	12kg - 0,2%	LC3 Facade cladding	1.2.3 External walls	430	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Plastic-based material		
Glass wool insulation panels, L = 0 ?	11.16	m x 80 mm	35kg - 0,6%	LC3 Insulation	1.2.3 External walls	60	Trailer combination, 40	Not defined	30	Local, not needed	None	8 %	Use EOL defined in EPD		
Aluminium frame window triple glaze ?	1.44	m	0,22t - 3%	LC3 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product		

Variant 5 software inputs

Resource	Quantity		CO₂e	Comment	Building Parts	Transport, kilometers		Transport, leg 2, kilometers	Service life	Localisation	Repair/year (B3)	Wastage	EOL Process	Reused material	Locally reused
Extruded aluminium profiles for win ?	223.81	kg	3,5t - 50%	LC1 Facade structure	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
PIR (polyisocyanurate foam) insulat ?	11	m x 100 mm	0,32t - 5%	LC1 Insulation	1.2.3 External walls	430	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	4 %	Plastic-based material		
Aluminium façade cladding panel, an ?	7,6	m	0,33t - 5%	LC1 Facade cladding	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Extruded aluminium profiles for win ?	33.41	kg	0,52t - 8%	LC1 Facade cladding	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Extruded aluminium profiles for win ?	16.15	kg	0,25t - 4%	LC1 Solar panel frame	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Aluminium frame window triple glaze ?	1.44	m	0,13t - 2%	LC1 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product		
Extruded aluminium profiles for win ?	223.81	kg	0,38t - 5%	LC2 Facade structure	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
PIR (polyisocyanurate foam) insulat ?	11	m x 100 mm	0,32t - 5%	LC2 Insulation	1.2.3 External walls	430	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	4 %	Plastic-based material		
Aluminium façade cladding panel, an ?	7,6	kg	44kg - 0,6%	LC2 Facade cladding	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Extruded aluminium profiles for win ?	33.41	kg	56kg - 0,8%	LC2 Facade cladding	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Extruded aluminium profiles for win ?	16.15	kg	27kg - 0,4%	LC2 Solar panel	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Aluminium frame window triple glaze ?	1.44	m	0,13t - 2%	LC2 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product		
Extruded aluminium profiles for win ?	223.81	kg	0,38t - 5%	LC3 Facade structure	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
PIR (polyisocyanurate foam) insulat ?	11	m x 100 mm	0,32t - 5%	LC3 Insulation	1.2.3 External walls	430	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	4 %	Plastic-based material		
Aluminium façade cladding panel, an ?	7,6	kg	44kg - 0,6%	LC3 Facade cladding	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Extruded aluminium profiles for win ?	33.41	kg	56kg - 0,8%	LC3 Facade cladding	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Extruded aluminium profiles for win ?	16.15	kg	27kg - 0,4%	LC3 Solar panel	1.2.3 External walls	470	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	7.5 %	Aluminium recycling		
Aluminium frame window triple glaze ?	1.44	m	0,13t - 2%	LC3 Window	1.2.3 External walls	380	Trailer combination, 40	Not defined	30	Netherlands IEA2022	None	None	Glass-containing product		

Variant 6 software inputs

Resource	Quantity		CO$_2$e	Comment	Building Parts	Transport, kilometers		Transport, leg 2, kilometers		Service life	Localisation		Repair/year (B3)	Wastage	EOL Process	Reused material	Locally reused
Softwood timber from spruce and pin ?	0.44	m	61kg - 7%	LC1 Facade structure	1.2.3 External walls	220	Trailer combination, 40		Not defined	30	Local, not needed		None	17.9 %	Wood-based material	☐	☐
Wood fibre flexible insulation for ?	0,9	m	49kg - 6%	LC1 Insulation	1.2.3 External walls	350	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	8 %	Landfilling (for inert	☐	☐
Façade wood panel, 25-50 mm, 17 kg/ ?	7,5	m	54kg - 6%	LC1 Facade cladding	1.2.3 External walls	220	Trailer combination, 40		Not defined	30	Local, not needed		None	17.9 %	Wood-based material	☐	☐
Softwood timber from spruce and pin ?	0.1856	m	26kg - 3%	LC1 Facade cladding	1.2.3 External walls	220	Trailer combination, 40		Not defined	30	Local, not needed		None	17.9 %	Wood-based material	☐	☐
Wooden frame window, triple glazed, ?	1.44	m	87kg - 10%	LC1 Window	1.2.3 External walls	380	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	None	Glass-containing product	☐	☐
Softwood timber from spruce and pin ?	0.44	m	61kg - 7%	LC2 Facade structure	1.2.3 External walls	220	Trailer combination, 40		Not defined	30	Local, not needed		None	17.9 %	Wood-based material	☐	☐
Wood fibre flexible insulation for ?	0,9	m	49kg - 6%	LC2 Insulation	1.2.3 External walls	350	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	8 %	Landfilling (for inert	☐	☐
Façade wood panel, 25-50 mm, 17 kg/ ?	7,5	m	54kg - 6%	LC2 Facade cladding	1.2.3 External walls	220	Trailer combination, 40		Not defined	30	Local, not needed		None	17.9 %	Wood-based material	☐	☐
Softwood timber from spruce and pin ?	0.1856	m	26kg - 3%	LC2 Facade cladding	1.2.3 External walls	220	Trailer combination, 40		Not defined	30	Local, not needed		None	17.9 %	Wood-based material	☐	☐
Wooden frame window, triple glazed, ?	1.44	m	87kg - 10%	LC2 Window	1.2.3 External walls	380	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	None	Glass-containing product	☐	☐
Softwood timber from spruce and pin ?	0.44	m	61kg - 7%	LC3 Facade structure	1.2.3 External walls	220	Trailer combination, 40		Not defined	30	Local, not needed		None	17.9 %	Wood-based material	☐	☐
Wood fibre flexible insulation for ?	0,9	m	49kg - 6%	LC3 Insulation	1.2.3 External walls	350	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	8 %	Landfilling (for inert	☐	☐
Façade wood panel, 25-50 mm, 17 kg/ ?	7,5	m	54kg - 6%	LC3 Facade cladding	1.2.3 External walls	220	Trailer combination, 40		Not defined	30	Local, not needed		None	17.9 %	Wood-based material	☐	☐
Softwood timber from spruce and pin ?	0.1856	m	26kg - 3%	LC3 Facade cladding	1.2.3 External walls	220	Trailer combination, 40		Not defined	30	Local, not needed		None	17.9 %	Wood-based material	☐	☐
Wooden frame window, triple glazed, ?	1.44	m	87kg - 10%	LC3 Window	1.2.3 External walls	380	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	None	Glass-containing product	☐	☐

Variant 7 software inputs

Resource	Quantity			CO$_2$e	Comment	Building Parts	Transport, kilometers		Transport, leg 2, kilometers		Service life	Localisation		Repair/year (B3)	Wastage	EOL Process	Reused material	Locally reused
Softwood timber from spruce and pin ?	310	kg		91kg - 11%	LC1 Facade structure	1.2.3 External walls	220	Trailer combination, 40		Not defined	30	Local, not needed		None	17.9 %	Wood-based material	☐	☐
Wheat straw bale insulation, L=0.04 ?	11.16	m	x 220 mm	23kg - 3%	LC1 Insulation	1.2.3 External walls	350	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	8 %	Landfilling (for inert	☐	☐
Clay plaster with flax fibre, 1300- ?	295	kg		9,8kg - 1%	LC1 Facade cladding	1.2.3 External walls	110	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	13 %	Landfilling (for inert	☐	☐
Structural hollow steel sections (H ?	14.35	kg		56kg - 7%	LC1 Solar panel frame	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	3.3 %	Steel recycling	☐	☐
Wooden frame window, triple glazed, ?	1.44	m		87kg - 11%	LC1 Window	1.2.3 External walls	380	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	None	Glass-containing product	☐	☐
Softwood timber from spruce and pin ?	310	kg		91kg - 11%	LC2 Facade structure	1.2.3 External walls	220	Trailer combination, 40		Not defined	30	Local, not needed		None	17.9 %	Wood-based material	☐	☐
Wheat straw bale insulation, L=0.04 ?	11.16	m	x 220 mm	23kg - 3%	LC2 Insulation	1.2.3 External walls	350	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	8 %	Landfilling (for inert	☐	☐
Clay plaster with flax fibre, 1300- ?	295	kg		9,8kg - 1%	LC2 Facade cladding	1.2.3 External walls	110	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	13 %	Landfilling (for inert	☐	☐
Structural hollow steel sections (H ?	14.35	kg		56kg - 7%	LC2 Solar panel	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	3.3 %	Steel recycling	☐	☐
Wooden frame window, triple glazed, ?	1.44	m		87kg - 11%	LC2 Window	1.2.3 External walls	380	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	None	Glass-containing product	☐	☐
Softwood timber from spruce and pin ?	310	kg		91kg - 11%	LC3 Facade structure	1.2.3 External walls	220	Trailer combination, 40		Not defined	30	Local, not needed		None	17.9 %	Wood-based material	☐	☐
Wheat straw bale insulation, L=0.04 ?	11.16	m	x 220 mm	23kg - 3%	LC3 Insulation	1.2.3 External walls	350	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	8 %	Landfilling (for inert	☐	☐
Clay plaster with flax fibre, 1300- ?	295	kg		9,8kg - 1%	LC3 Facade cladding	1.2.3 External walls	110	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	13 %	Landfilling (for inert	☐	☐
Structural hollow steel sections (H ?	14.35	kg		56kg - 7%	LC3 Solar panel	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	3.3 %	Steel recycling	☐	☐
Wooden frame window, triple glazed, ?	1.44	m		87kg - 11%	LC3 Window	1.2.3 External walls	380	Trailer combination, 40		Not defined	30	Netherlands	IEA2022	None	None	Glass-containing product	☐	☐

Variant 8 software inputs

Resource	Quantity		CO_2e	Comment	Building Parts	Transport, kilometers		Transport, leg 2, kilometers		Service life	Localisation	Repair/year (B3)	Wastage	EOL Process	Reused material	Locally reused
Rammed earth wall, lime stabilised, ?	1500	kg	43kg - 1%	LC1 Facade cladding	1.2.3 External walls	40	Dumper truck, 19 ton		Not defined	30	Netherlands IEA2022	None	None	Do nothing	☐	☐
Structural steel profiles, generic, ?	362	kg	1,2t - 29%	LC1 Facade structure	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☐	☐
Structural steel profiles, generic, ?	14.35	kg	49kg - 1%	LC1 Solar panel frame	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☐	☐
Wooden frame window, triple glazed, ?	1.44	m	84kg - 2%	LC1 Window	1.2.3 External walls	380	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐
Rammed earth wall, lime stabilised, ?	1500	kg	43kg - 1%	LC2 Facade cladding	1.2.3 External walls	40	Dumper truck, 19 ton		Not defined	30	Netherlands IEA2022	None	None	Do nothing	☐	☐
Structural steel profiles, generic, ?	362	kg	1,2t - 29%	LC2Facade structure	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☐	☐
Structural steel profiles, generic, ?	14.35	kg	49kg - 1%	LC2 Solar panel	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☐	☐
Wooden frame window, triple glazed, ?	1.44	m	84kg - 2%	LC2 Window	1.2.3 External walls	380	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐
Rammed earth wall, lime stabilised, ?	1500	kg	43kg - 1%	LC3 Facade cladding	1.2.3 External walls	40	Dumper truck, 19 ton		Not defined	30	Netherlands IEA2022	None	None	Do nothing	☐	☐
Structural steel profiles, generic, ?	362	kg	1,2t - 29%	LC3 Facade structure	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☐	☐
Structural steel profiles, generic, ?	14.35	kg	49kg - 1%	LC3 Solar panel	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☐	☐
Wooden frame window, triple glazed, ?	1.44	m	84kg - 2%	LC3 Window	1.2.3 External walls	380	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐

Variant 9 software inputs

Resource	Quantity			CO_2e	Comment	Building Parts	Transport, kilometers		Transport, leg 2, kilometers		Service life	Localisation	Repair/year (B3)	Wastage	EOL Process	Reused material	Locally reused	
Structural steel profiles, generic, ?	550.7	kg		0,42t - 28%	LC1 Facade structure	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐	change
Stone wool (slag wool) insulation, ?	11.16	m	x 80 mm	38kg - 3%	LC1 Insulation	1.2.3 External walls	60	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	8 %	Reuse as material	☐	☐	change
Natural stone wall cladding, 95 mm, ?	7.56	m	x 95 mm	28kg - 2%	LC1 Facade cladding	1.2.3 External walls	60	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	4.5 %	Reuse as material	☐	☐	change
Structural steel profiles, generic, ?	16.15	kg		12kg - 0,8%	LC1 Cladding frame	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐	change
Structural steel profiles, generic, ?	16.15	kg		12kg - 0,8%	LC1 Solar panel frame	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐	change
Aluminium frame window triple glaze ?	1.44	m		0,14t - 9%	LC1 Window	1.2.3 External walls	380	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐	change
Structural steel profiles, generic, ?	550.7	kg		30kg - 2%	LC2 facade structure	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☑	☐	change
Stone wool (slag wool) insulation, ?	11.16	m	x 80 mm	0,21kg - -0%	LC2 Insulation	1.2.3 External walls	60	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	8 %	Landfilling (for inert	☑	☐	change
Natural stone wall cladding, 95 mm, ?	7.56	m	x 95 mm	9,9kg - 0,7%	LC2 Facade cladding	1.2.3 External walls	60	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	4.5 %	Use EOL defined in EPD	☑	☐	change
Structural steel profiles, generic, ?	16.15	kg		0,89kg - 0,1%	LC2 Cladding frame	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☑	☐	change
Structural steel profiles, generic, ?	16.15	kg		0,89kg - 0,1%	LC2 solar panels	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Steel recycling	☑	☐	change
Aluminium frame window triple glaze ?	1.44	m		0,14t - 9%	LC2 Window	1.2.3 External walls	380	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐	change
Structural steel profiles, generic, ?	550.7	kg		0,42t - 28%	LC3 Facade structure	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐	change
Stone wool (slag wool) insulation, ?	11.16	m	x 80 mm	38kg - 3%	LC3 Insulation	1.2.3 External walls	60	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	8 %	Reuse as material	☐	☐	change
Natural stone wall cladding, 95 mm, ?	7.56	m	x 95 mm	28kg - 2%	LC3 Facade cladding	1.2.3 External walls	60	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	4.5 %	Reuse as material	☐	☐	change
Structural steel profiles, generic, ?	16.15	kg		12kg - 0,8%	LC3 Cladding frame	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐	change
Structural steel profiles, generic, ?	16.15	kg		12kg - 0,8%	LC3 solar panels	1.2.3 External walls	370	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	3.3 %	Reuse as material	☐	☐	change
Aluminium frame window triple glaze ?	1.44	m		0,14t - 9%	LC3 Window	1.2.3 External walls	380	Trailer combination, 40		Not defined	30	Netherlands IEA2022	None	None	Glass-containing product	☐	☐	change

Final variant software inputs

Resource	Quantity		Unit cost		Total cost		Financial & social cost		CO_2e	Comment	Building Parts	Transport, kilometers		Service life	Localisation		EOL Process
Structural steel profiles, generic, ?	550.7	kg	0.76	€ / kg	419	€	601.47	€	3,6t - 24%	V1	Not defined	370	Trailer combination, 40	30	Netherlands	IEA2022	Steel recycling
EPS insulation panels, graphite, L= ?	22	kg	4.79	€ / kg	105	€	117.203	€	0,21t - 1%	V1	Not defined	430	Trailer combination, 40	30	Netherlands	IEA2022	Plastic-based material
Clay brick, 126 kg/m2, Cette FDES c ?	810	kg	0.2	€ / kg	162	€	177.33	€	0,3t - 2%	V1	Not defined	60	Trailer combination, 40	30	Netherlands	IEA2022	Brick/stone crushed to
Fibre cement boards, 1300 kg/m3 (81 ?	130	kg	1.89	€ / kg	245	€	256.37	€	0,23t - 1%	V1	Not defined	60	Trailer combination, 40	30	Netherlands	IEA2022	Concrete crushed to
Aluminium frame window triple glaze ?	32	kg	8.48	€ / kg	271	€	285.73	€	0,3t - 2%	V1	Not defined	380	Trailer combination, 40	30	Netherlands	IEA2022	Glass-containing product
Glass wool insulation for pipes, un ?	16	kg	0.86	€ / kg	14	€	31.013	€	0,35t - 2%	V2	Not defined	60	Trailer combination, 40	30	Netherlands	IEA2022	Landfilling (for inert
Flat fibre cement panels for claddi ?	61	kg	1.81	€ / kg	111	€	113.38	€	47kg - 0,3%	V2	Not defined	60	Trailer combination, 40	30	Netherlands	IEA2022	Concrete crushed to
Stone wool (mineral wool) insulatio ?	23	kg	0.82	€ / kg	19	€	22.180	€	66kg - 0,4%	V3	Not defined	60	Trailer combination, 40	30	Netherlands	IEA2022	Landfilling (for inert
Natural stone cladding, A4 = 0 - 10 ?	300	kg	0.68	€ / kg	205	€	239.24	€	0,68t - 4%	V3	Not defined	60	Trailer combination, 40	30	Netherlands	IEA2022	Brick/stone crushed to
XPS insulation panels, L=0.033 W/mK ?	28	kg	7.27	€ / kg	204	€	219.971	€	0,28t - 2%	V4	Not defined	430	Trailer combination, 40	30	Netherlands	IEA2022	Plastic-based material
Extruded aluminium profiles for win ?	223.81	kg	3.3	€ / kg	739	€	1063.9	€	6,5t - 43%	V4	Not defined	470	Trailer combination, 40	30	Netherlands	IEA2022	Aluminium recycling
Glass wool insulation panels, L = 0 ?	22	kg	2.23	€ / kg	49	€	52.182	€	64kg - 0,4%	V5	Not defined	60	Trailer combination, 40	30	Local, not needed		Landfilling (for inert
PVC facade cladding, instalation pa ?	7,2	m	19.07	€ / m2	137	€	176.43	€	0,6t - 4%	V5	Not defined	430	Trailer combination, 40	30	Netherlands	IEA2022	Plastic-based material
PIR (polyisocyanurate foam) insulat ?	49	kg	4.79	€ / kg	2157	€	2525.4	€	0,7t - 5%	V6	Not defined	430	Trailer combination, 40	30	Netherlands	IEA2022	Plastic-based material
Aluminium façade cladding panel, an ?	19	kg	3.3	€ / kg	63	€	93.999	€	0,62t - 4%	V6	Not defined	470	Trailer combination, 40	30	Netherlands	IEA2022	Aluminium recycling
Softwood timber from spruce and pin ?	210	kg	1.57	€ / kg	330	€	331.41	€	26kg - 0,2%	V7	Not defined	220	Trailer combination, 40	30	Local, not needed		Wood incineration
Wood fibre flexible insulation for ?	45	kg	2.43	€ / kg	109	€	113.53	€	91kg - 0,6%	V7	Not defined	350	Trailer combination, 40	30	Netherlands	IEA2022	Landfilling (for inert
Façade wood panel, 25-50 mm, 17 kg/ ?	130	kg	27.89	€ / kg	209	€	211.321	€	44kg - 0,3%	V7	Not defined	220	Trailer combination, 40	30	Local, not needed		Wood incineration
Wooden frame window, triple glazed, ?	53	kg	8.61	€ / kg	473	€	481.68	€	0,17t - 1%	V7	Not defined	380	Trailer combination, 40	30	Netherlands	IEA2022	Glass-containing product
Wheat straw bale insulation, L=0.04 ?	260	kg	1.17	€ / kg	304	€	305.99	€	28kg - 0,2%	V8	Not defined	350	Trailer combination, 40	30	Netherlands	IEA2022	Landfilling (for inert
Clay plaster with flax fibre, 1300- ?	295	kg	0.72	€ / kg	212.4	€	213.20	€	14kg - 0,1%	V8	Not defined	110	Trailer combination, 40	30	Netherlands	IEA2022	Landfilling (for inert
Structural hollow steel sections (H ?	14.35	kg	0.76	€ / kg	11	€	16.400	€	0,11t - 0,7%	V8	Not defined	370	Trailer combination, 40	30	Netherlands	IEA2022	Steel recycling
Rammed earth wall, lime stabilised, ?	1500	kg	0.01	€ / kg	22	€	26.046	€	82kg - 0,5%	V9	Not defined	40	Dumper truck, 19 ton	30	Netherlands	IEA2022	Do nothing
Burnt wooden facade cladding withou ?	130	kg	1.73	€ / kg	225	€	225.27	€	44kg - 0,3%	V9	Not defined	220	Trailer combination, 40	30	Netherlands	IEA2022	Wood incineration

Cost software inputs

		Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6	Variant 7	Variant 8	Variant 9
LC1										
Section	Result category	Global warming kg CO2e								
A1-A3	Construction Materials	2341.82	2171.93	2441.77	3912.18	4418.37	4693.41	163.05	174.33	1348.28
A4	Transportation to site	11.03	9.13	9.72	6.83	7.22	6.73	4.98	8.28	10.48
A4	Transport to the building site	11.03	9.13	9.72	6.83	7.22	6.73	4.98	8.28	10.48
A5	Construction/installation process	79.52	66.63	84.35	265.71	317	336.37	81.89	59.95	41.24
A5c	Construction site - material wastage - materials	79.14	66.34	84.04	262.74	315.49	332.04	9.65	6.41	40.56
A5d	Construction site - material wastage - transport	0.388	0.283	0.314	0.396	0.491	0.428	0.688	0.909	0.176
A5e	Construction site - material wastage - waste	0	0	0	2.57	1.01	3.9	71.55	52.64	0.503
	Stage A	2522.928	2323.443	2629.91	4457.26	5066.8	5379.61	336.788	310.799	1451.72
C1-C4	End of life	1.25	1.83	1.73	18.05	15.33	17.99	27.34	24.01	17.27
C2	Waste transport	1.23	1.8	1.69	14.95	13.73	13.08	3.86	5.45	16.41
C3	Waste processing	0.00671	0.00981	0.00925	3.07	1.44	4.89	23.33	17.09	0.83
C4	Waste disposal	0.0167	0.0244	0.023	0.0336	0.155	0.023	0.146	1.46	0.0272
	Stage B	1.25	1.83	1.73	18.05	15.33	17.99	27.34	24.01	17.27
	GWP imapct	2524.178	2325.273	2631.64	4475.31	5082.13	5397.6	364.128	334.809	1468.99
D	Installed Materials - benefit	-2199.22	-1915.61	-2289.71	-2214.17	-2651.57	-2582.94	124.65	62.5	-830.27
A5-benefit	Construction site - material wastage - benefit	-78.21	-64.35	-83.2	-2063.63	-2466.61	-2401.99	22.41	15.45	-27.38
A5m-benefit	Construction site - material use - benefit				-150.54	-184.96	-180.95			
B3-benefit	Repair - benefit	0	0	0				0	0	
B4-B5-benefit	Material replacement - benefit				0	0	0			
D2	Exported energy (not included in totals)									
	Stage D	-2277.43	-1979.96	-2372.9	-4428.3	-5303.1	-5165.9	147.06	77.95	-857.65
	GWP benefit	-2277.43	-1979.96	-2372.9	-4428.3	-5303.1	-5165.9	147.06	77.95	-857.65
LC2										
A1-A3	Construction Materials	114.16	213.92	122.98	886.6	668.26	881.22	163.05	174.33	1348.28
A4	Transportation to site	11.03	9.13	9.04	6.48	5.78	6.53	4.98	8.28	10.48
A4	Transport to the building site	11.03	9.13	9.04	6.48	5.78	6.53	4.98	8.28	10.48
A5	Construction/installation process	0.388	0.283	0.283	38.86	35.5	50.41	81.89	59.95	41.24
A5c	Construction site - material wastage - materials	0	0	0	35.19	34.24	46.13	9.65	6.41	40.56
A5d	Construction site - material wastage - transport	0.388	0.283	0.283	0.362	0.382	0.412	0.688	0.909	0.176
A5e	Construction site - material wastage - waste	0	0	0.803	3.31	0.882	3.86	71.55	52.64	0.503
	Stage A	136.996	232.746	142.429	977.282	750.824	995.092	336.788	310.799	1451.72
C1-C4	End of life	73.45	25.54	25.64	17.66	13.55	17.53	27.34	24.01	17.27
C2	Waste transport	25.77	24.19	24.2	13.41	12.73	12.64	3.86	5.45	16.41
C3	Waste processing	47.66	1.28	1.28	4.21	0.672	4.87	23.33	17.09	0.83
C4	Waste disposal	0.0167	0.0655	0.162	0.0336	0.155	0.023	0.146	1.46	0.0272
	Stage B	73.45	25.54	25.64	17.66	13.55	17.53	27.34	24.01	17.27
	GWP impact	210.446	258.286	168.069	994.942	764.374	1012.62	364.128	334.809	1468.99
D	Installed Materials - benefit	-1256.2	-1313.35	-1285.8	-73.48	-18.08	4.07	124.65	62.5	-830.27
A5-benefit	Construction site - material wastage - benefit	0	0	0	-71.03	-16.85	4.53	22.41	15.45	-27.38
A5m-benefit	Construction site - material use - benefit				-2.45	-1.23	-0.459			
B3-benefit	Repair - benefit	0	0	0				0	0	
B4-B5-benefit	Material replacement - benefit				0	0	0			
D2	Exported energy (not included in totals)									
	Stage C	-1256.2	-1313.35	-1285.8	-146.96	-36.16	8.141	147.06	77.95	-857.65
	GWP benefit	-1256.2	-1313.35	-1285.8	-220.44	-54.24	12.212	169.47	93.4	-885.03
LC3										
A1-A3	Construction Materials	941.17	690.05	961.42	886.6	668.26	881.22	163.05	174.33	1348.28
A4	Transportation to site	11.03	9.13	9.72	6.48	5.78	6.53	4.98	8.28	10.48
A4	Transport to the building site	11.03	9.13	9.72	6.48	5.78	6.53	4.98	8.28	10.48
A5	Construction/installation process	33.32	17.72	35.5	38.86	35.5	50.41	81.89	59.95	41.24
A5c	Construction site - material wastage - materials	32.91	17.44	35.19	35.19	34.24	46.13	9.65	6.41	40.56
A5d	Construction site - material wastage - transport	0.388	0.283	0.314	0.362	0.382	0.412	0.688	0.909	0.176
A5e	Construction site - material wastage - waste	0.0216	0	0	3.31	0.882	3.86	71.55	52.64	0.503
	Stage A	1029.8696	743.753	1051.86	977.282	750.824	995.092	336.788	310.799	1451.72
C1-C4	End of life	1.9	1.83	1.73	17.66	13.55	17.53	27.34	24.01	17.27
C2	Waste transport	1.85	1.8	1.69	13.41	12.73	12.64	3.86	5.45	16.41
C3	Waste processing	0.0418	0.00981	0.00925	4.21	0.672	4.87	23.33	17.09	0.83
C4	Waste disposal	0.0167	0.0244	0.023	0.0336	0.155	0.023	0.146	1.46	0.0272
	Stage B	1.9	1.83	1.73	17.66	13.55	17.53	27.34	24.01	17.27
	GWP impact	1031.7696	745.583	1053.59	994.942	764.374	1012.62	364.128	334.809	1468.99
D	Installed Materials - benefit	-790.18	-433.74	-809.35	-73.48	-18.08	4.07	124.65	62.5	-830.27
A5-benefit	Construction site - material wastage - benefit	-31.71	-15.45	-34.35	-71.03	-16.85	4.53	22.41	15.45	-27.38
A5m-benefit	Construction site - material use - benefit				-2.45	-1.23	-0.459			
B3-benefit	Repair - benefit	0	0	0				0	0	
B4-B5-benefit	Material replacement - benefit				0	0	0			
D2	Exported energy (not included in totals)									
	Stage C	-821.89	-449.19	-843.7	-146.96	-36.16	8.141	147.06	77.95	-857.65
	GWP benefit	-821.89	-449.19	-843.7	-146.96	-36.16	8.141	147.06	77.95	-857.65

LCA results GWP

LCA Stage A										
Impact	Unit	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6	Variant 7	Variant 8	Variant 9
GWP	CO2 eq	3.88E+03	3.30E+03	3.82E+03	6.41E+03	6.57E+03	7.37E+03	1.01E+03	9.32E+02	4.36E+03
Bio-CO2 storage	CO2 eq bio	0.00E+00	1.09E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.39E+03	2.80E+03	6.26E+01
ODP	kg CFC11eq	2.56E-04	2.39E-04	2.82E-04	4.36E-04	6.03E-04	7.12E-04	5.50E-05	5.63E-05	2.97E-04
AP	kg SO2eq	1.37E+01	1.25E+01	1.72E+01	2.40E+01	2.15E+01	2.51E+01	3.42E+00	3.07E+00	1.73E+01
EP	kg PO4eq	2.43E+00	2.44E+00	3.61E+00	6.17E+00	5.79E+00	7.08E+00	8.28E-01	9.76E-01	3.24E+00
POCP	kg Ethenee	1.64E+00	1.54E+00	1.88E+00	2.07E+00	2.16E+00	2.67E+00	3.08E-01	1.93E-01	2.37E+00
ADPE	kg Sbe	5.46E-01	4.35E-01	4.45E-01	1.19E+00	3.91E-01	4.65E-01	2.70E-01	4.26E-01	5.34E-01
ADPF	MJ	4.85E+04	4.48E+04	1.62E+04	8.39E+04	8.92E+04	1.03E+05	7.51E+03	8.86E+03	5.96E+04

Table 13 Results of the KPIs for LCA Stage A

LCA Stage C										
Impact	Unit	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6	Variant 7	Variant 8	Variant 9
GWP	CO2 eq	7.66E+01	2.92E+01	2.91E+01	5.34E+01	4.24E+01	5.31E+01	8.20E+01	7.20E+01	5.18E+01
Bio-CO2 storage	CO2 eq bio	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ODP	kg CFC11eq	7.34E-06	5.68E-06	5.66E-06	8.53E-06	8.26E-06	7.83E-06	2.37E-06	4.02E-06	1.01E-05
AP	kg SO2eq	1.70E-01	1.38E-01	1.38E-01	2.07E-01	2.03E-01	1.90E-01	5.67E-02	1.08E-01	2.45E-01
EP	kg PO4eq	3.44E-02	2.93E-02	2.93E-02	4.39E-02	4.26E-02	4.04E-02	1.23E-02	2.34E-02	5.19E-02
POCP	kg Ethenee	3.98E-03	2.03E-03	2.04E-03	3.03E-03	4.22E-03	2.79E-03	7.56E-04	1.88E-03	3.63E-03
ADPE	kg Sbe	2.09E-01	2.01E-01	2.00E-01	3.02E-01	2.76E-01	2.78E-01	8.40E-02	1.19E-01	3.57E-01
ADPF	MJ	9.21E+02	8.12E+02	8.07E+02	1.22E+03	1.15E+03	1.12E+03	3.37E+02	5.32E+02	1.44E+03

Table 14 Results of the KPIs for LCA Stage C

LCA Stage D										
Impact	Unit	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6	Variant 7	Variant 8	Variant 9
GWP	CO2 eq	-4.25E+03	-3.66E+03	-4.38E+03	-2.21E+03	-2.50E+03	-2.39E+03	3.74E+02	1.88E+02	-2.49E+03
Bio-CO2 storage	CO2 eq bio	0.00E+00	-1.64E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ODP	kg CFC11eq	-2.46E-04	-2.29E-04	-2.82E-04	-2.00E-04	-2.20E-04	-2.38E-04	-1.30E-07	-4.83E-06	-1.37E-04
AP	kg SO2eq	-1.62E+01	-1.48E+01	-1.98E+01	-1.23E+01	-1.37E+01	-1.42E+01	-5.19E-03	-3.63E-01	-1.04E+01
EP	kg PO4eq	-2.64E+00	-2.60E+00	-3.76E+00	-1.05E+00	-1.06E+00	-1.07E+00	-1.16E-03	-5.46E-02	-1.56E+00
POCP	kg Ethenee	-2.11E+00	-2.03E+00	-2.42E+00	-1.24E+00	-1.28E+00	-1.34E+00	-3.42E-04	-5.10E-02	-1.48E+00
ADPE	kg Sbe	-3.93E-02	-2.81E-02	-2.09E-02	-9.03E-03	-9.87E-03	-9.38E-03	-1.81E-05	-4.50E-04	-1.26E-02
ADPF	MJ	-5.58E+04	-5.11E+04	-6.00E+04	-2.58E+04	-3.06E+04	-2.73E+04	-1.62E+01	-1.19E+03	-3.42E+04

Results of the KPIs for LCA Stage D

Most impact	
Least impact	

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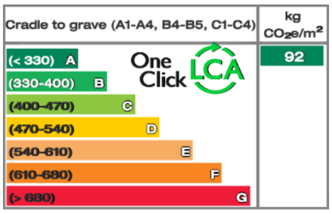
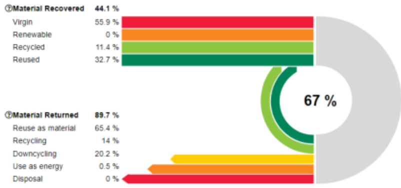
<tr><td>Variant 1</td><td>
</td><td>
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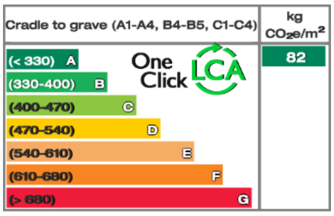
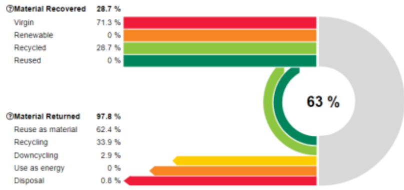
<tr><td>Variant 2</td><td>
</td><td>
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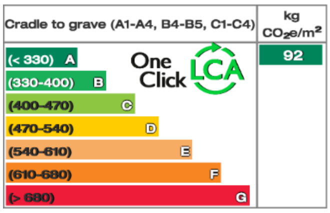
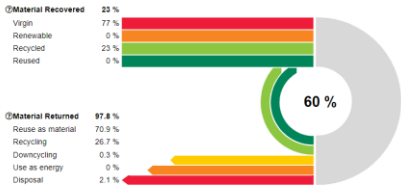
<tr><td>Variant 3</td><td>
</td><td>
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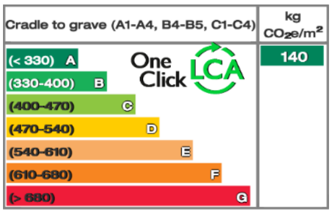
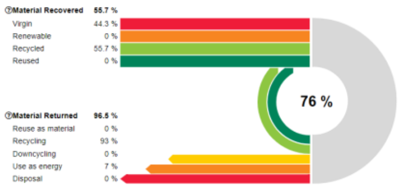
<tr><td>Variant 4</td><td>
</td><td>
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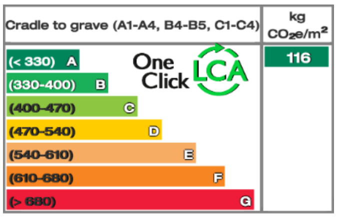
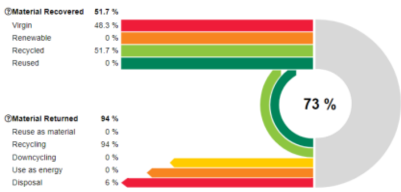
<tr><td>Variant 5</td><td>
</td><td>
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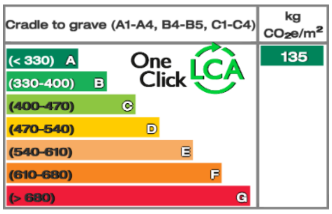
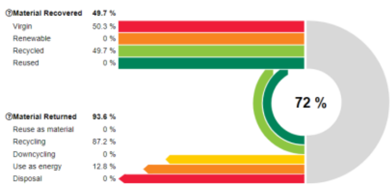
<tr><td>Variant 6</td><td>
</td><td>
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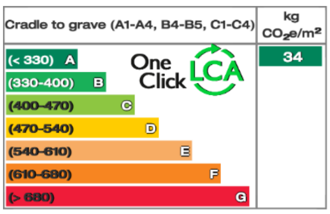
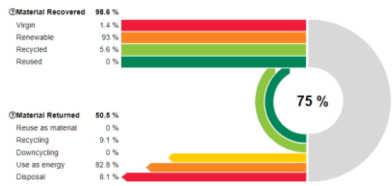
<tr><td>Variant 7</td><td>
</td><td>
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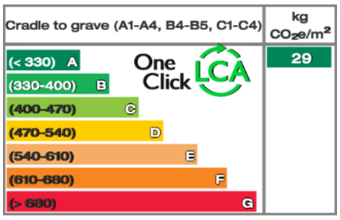
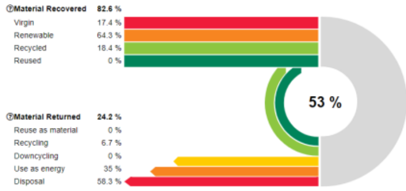
Variant 8





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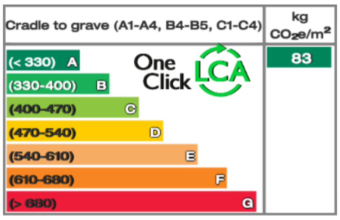
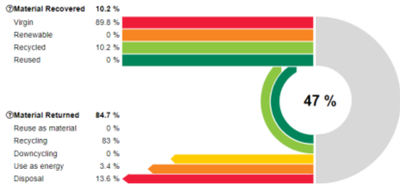
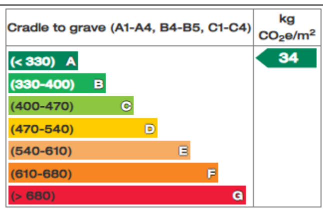
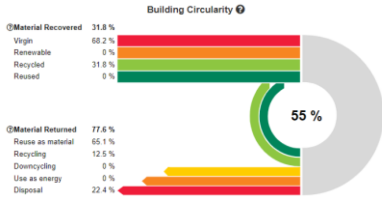




Final Design





Environmental impact and Building Circularity