CIRCULAR ADAPTABLE INDUSTRIALISED FAÇADE SYSTEM

FOR BUILDING RENOVATIONS

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Title

“Circular adaptable industrialised façade system - for building renovations”

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The topic of circularity has interested me since my bachelor studies. It has been fascinating to observe how rapidly the building industry is adapting to this new way of construction and I truly enjoyed immersing myself in the subject. While working on my thesis was not always the most enjoyable task, the end result would not have been possible without the support of many people around me.

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Abstract

The built environment is undergoing a critical transformation as it strives to meet ambitious climate targets, including the goal of carbon neutrality by 2050. One key area of focus is the renovation of the existing building stock, where envelope upgrades can drastically improve energy efficiency and reduce carbon emissions. However, current renovation methods often follow a linear approach, neglecting circular principles. This project explores the development of a circular, adaptable and industrialised façade system as a scalable solution for sustainable renovation. Using a research-through-design methodology, the study analyses design criteria for a façade system that enables disassembly, reuse and adaptability to various façade layouts.

A design framework was created that ranks materials and connections by embodied carbon, end-of-life, service life, disassembly ease, cost, adaptability and reuse potential. Two case study row houses were used to test the designs: one using a traditional prefabricated timber structure and the other using a new, modular design approach. Evaluation combined Life Cycle Assessment (LCA), the Material Circularity Indicator (MCI), and the 3DR method (disassemblability, deconstructability, resilience) to quantify environmental impact and circular performance.

The results showed that each façade configuration suits a different need, such as cost, ease of disassembly, use of regenerative or less materials and so on. However, one overall best option stood out: a timber-frame structure combined with ClickBrick cladding. This solution achieved the highest cumulative score in circularity, adaptability and long-term reusability.

The report concludes that circularity must be built into the design process from the start. Key strategies include breaking façades into layers, reducing material use, choosing recycled or bio-based materials and using dry, reversible connections. Following these steps will help design a façade system that is reusable, adaptable and maintainable over multiple cycles of use, thereby supporting a more sustainable and circular building sector

Keywords: Circular Façade, Renovation, Design for Disassembly, Industrialised Construction, Timber, Life Cycle Assessment, Material Circularity indicator

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1 INTRODUCTION

This chapter outlines the research context and problem statement, followed by the objectives, research question with sub questions and methodology. It concludes with an exploration of the study's societal and scientific relevance.

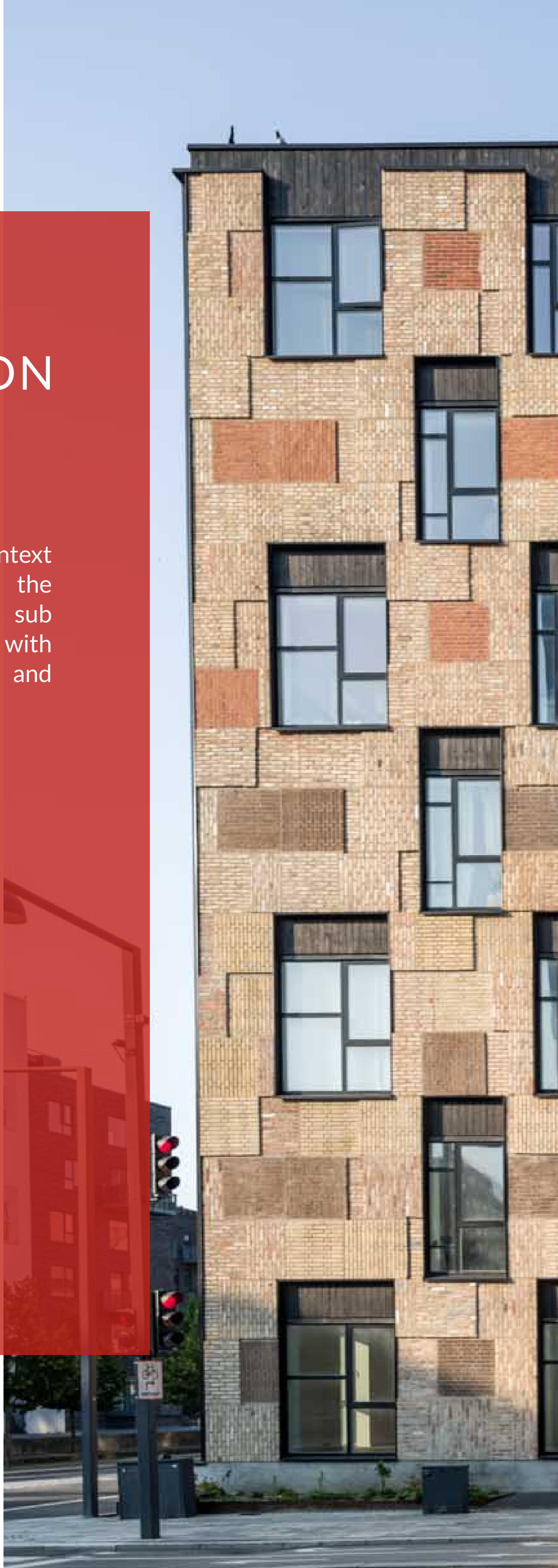


Fig. 1 - Resource Rows (Lendager, 2019)

1.1 Context

The housing demand is substantial: the government aims to build 900,000 new homes by 2030. At the same time, there is a significant sustainability challenge. To meet the Paris Agreement targets, CO_2 emissions must be reduced by 55% by 2030 and brought to zero by 2050. Additionally, the Netherlands is aiming for a fully circular construction economy by 2050. This means that a transition is needed to a different way of designing within 25 years. The goal of the Circular Construction Economy is to reduce the environmental impact of construction by minimizing the use of primary raw materials, scaling up the use of high-quality secondary materials, and utilizing renewable and Bio-based materials (Nunen, 2022). With the construction sector accounting for around 11% of CO_2 emissions and 50% of primary material consumption, it plays a crucial role in achieving these objectives.

To reduce the construction sector's impact on the climate, the government recommends using a combination of different strategies. The objective of reducing carbon emissions before 2030 can only be achieved with a combined effort of all strategies. These are grouped across three categories (Bosch et al, 2023):

1. Material strategies: building with Bio-based materials and using reused components and recycled materials.
2. Housing stock strategies: optimising the use of existing homes, adding floors to buildings, transforming spaces and building smaller to create an optimal housing stock.
3. Strategies for the construction and materials industry: further industrialisation of the construction process and the sustainability of the building materials industry.

The various sub sectors in Dutch construction contribute differently to CO_2 emissions. Between now and 2030, residential renovations will account for the largest share of emissions: 33% of the construction sector's total emissions. Preserving existing buildings and infrastructure is the best way to prevent CO_2 intensive new construction in the future (De circulaire bouweconomie, 2024).

When renovating, common measures like window replacement and façade insulation have substantial environmental costs. A balanced approach is advised, considering both energy savings and material impact. This can for instance be done by implementing a bio-based and/or circular design approach (Nunen, 2022). Building connections that are completely demountable without damaging building components are important because they allow easy, direct reuse. To enable future reuse of components, connections should be designed for easy disassembly with as little wet connections as possible. This will help to create a future without waste. At this point, designing buildings and components is more expensive because it is not yet widely used and takes more time to design. However, as it becomes more common, it will take less time and thus become less expensive (Klein et al. n.d.).

An increasing number of stakeholders are focusing on the industrial production of homes and housing components. Since the modules are pre-fabricated, they only need to be assembled on-site. This reduces construction time, minimises logistical movements, decreases construction waste, and makes the building process less prone to errors. Prefabrication and Modular Construction can also be combined with circularity. This will hit 3 birds with one stone. It helps accelerate addressing the housing shortage, achieve climate goals, and advance the circular economy. (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2021)

1.2 Problem statement

The construction sector faces significant sustainability challenges due to its substantial environmental impact. It accounts for 11% of national CO_2 emissions and 50% of primary material consumption. To meet climate goals, this impact must be drastically reduced. Because of this, the Netherlands is aiming for a fully circular construction economy by 2050.

As mentioned earlier, 33% of the construction sector's total emissions come from residential renovations between now and 2030. Renovations in the construction sector mainly focus on improving a building's energy performance through measures like insulation and technical adjustments to reduce energy costs and CO_2 emissions during use. However, there is less focus on reducing material-related CO_2 emissions, which have a significant impact during renovations. The environmental impact can be reduced by 37% by using reused, recycled or bio-based materials (De circulaire bouweconomie, 2024).

A circular economy is inseparable from reuse and recycling, but both subjects still face significant challenges, starting with the issue of availability. Components often become available at times that do not align with when they are needed. For these materials to be effectively reused, they must be considered early in the design process. However, this also requires that they are accessible at that stage, requiring temporary storage. Unfortunately, the physical infrastructure to support this process is often lacking. Reusable products and components need to be stored between their removal and eventual application and this must be done without long-distance logistical movements, which could potentially cancelling out the environmental benefits. The digital infrastructure for reuse is similarly underdeveloped. Data and information about products and materials are frequently unavailable, insufficiently detailed, unreliable, or difficult to exchange due to the lack of standardised systems. Additionally, quality risks and changing regulations present further challenges. Reused components often need to meet the same quality standards as new products. They need to be cleaned and strength tested. Because of this, contractors are reluctant to use these materials due to their limited familiarity and extra costs. New materials are often cheaper than reused or recycled ones, largely due to the high costs associated with labour, logistics, and organizing reuse and recycling processes (Bosch et al, 2023). When we look at modern façade systems, we see that they are often multi-material and feature non-reversible adhesive connections. These designs prioritize operational efficiency but make disassembly, reuse, and recycling highly challenging. Lack of standardization in component sizes, materials, and connections further complicates recovery efforts (Hartwell et al, 2021).

Industrialised renovation is a solution to scale up renovations efficiently while significantly reducing costs and on-site construction time. However, the building stock is not homogeneous, so industrialised renovation requires customised solutions. By combining standardization with digital tools and modular adaptability, industrialised solutions can be scaled up while addressing the unique characteristics of individual buildings. Technologies like laser scanning, Building Information Modelling (BIM), and parametric design are used to accurately assess existing buildings. Standardised elements are designed with a baseline concept that can be adapted to the specific requirements of different buildings during the design phase. This allows small but significant adjustments to accommodate unique building geometries, typologies, and energy performance goals (Konstantinou, 2022).

1.3 Objectives

The objective of this research is to find an industrialised façade renovation system that integrates component reuse while being adaptable to different façade layouts. However, a few boundary conditions apply. The research will focus exclusively on façade renovation. The new façade will meet the current building regulations and achieve an R-value of 4.7 m^2 K/W.

Given the goal of achieving a fully circular construction economy by 2050, the study will focus on reuse. Nevertheless, as the current market for used materials is quite limited, new materials with a promising End-of-life potential will be prioritised. These materials will form components that can be easily reused or remanufactured after deconstruction, either as whole units or as separate parts. This approach aims to enhance the lifespan of the façade and make material recovery from deconstructed buildings more attractive in the future, contributing to the circular economy (CE).

Cost is another critical factor, as contractors and clients are often concerned about expenses. Efforts will therefore be made to keep costs as low as possible to demonstrate that circularity can be not only environmentally friendly but also be cost-efficient and easy to build.

The research will use row houses as case studies, as these dwelling types accounted for 42% of homes in the Netherlands in 2023 (Wobma, 2023). Due to this large number, the renovation approach will involve standardised prefabricated components, as this method will address the demand for circular renovation more quickly. Industrialised renovation is also more feasible and profitable for these types of dwellings since they differ less than individual detached homes. However, because not all row houses are homogeneous, an adaptable method will be employed. The renovation level will be refurbishment. This means modernise and update old products, often by replacing parts. In this case that means that the old façade of the case study dwelling will be removed and the load bearing construction will remain in place. The openings for the windows and doors will also stay unchanged.

Finally, achieving CO_2 neutrality during construction is also a key objective. Therefore, Bio-based materials will be explored, with biodegradability and reusability serving as central criteria.

1.4 Research question

How can an industrialised façade renovation system incorporate future component reuse while being adaptable to different façade layouts?

Sub-questions

Which materials and connection systems are most suitable for reuse in façade renovation, based on evaluation through a circularity assessment method?

How can an industrialised façade renovation system be standardised while maintaining adaptability for diverse row house home designs?

How can an industrialised façade renovation system be designed to accommodate the varying service lives of its components while ensuring reusablity for future buildings?

How can a circular façade system be developed based on specific project requirements?

1.5 Approach and methodology

The research project adopts a mixed-methodology approach, combining a literature review with research-through-design. The research will be divided into the following 5 phases:

Phase 1 – Literature Review
During this phase, extensive research will be conducted on specific topics to establish a solid foundation for the report. Key questions will address façade renovation and circular design, such as: What sustainable building materials and cutting-edge technologies are currently preferred for reducing CO_2 emissions in renovation projects? The literature review will explore academic papers, graduation theses, and relevant reports.

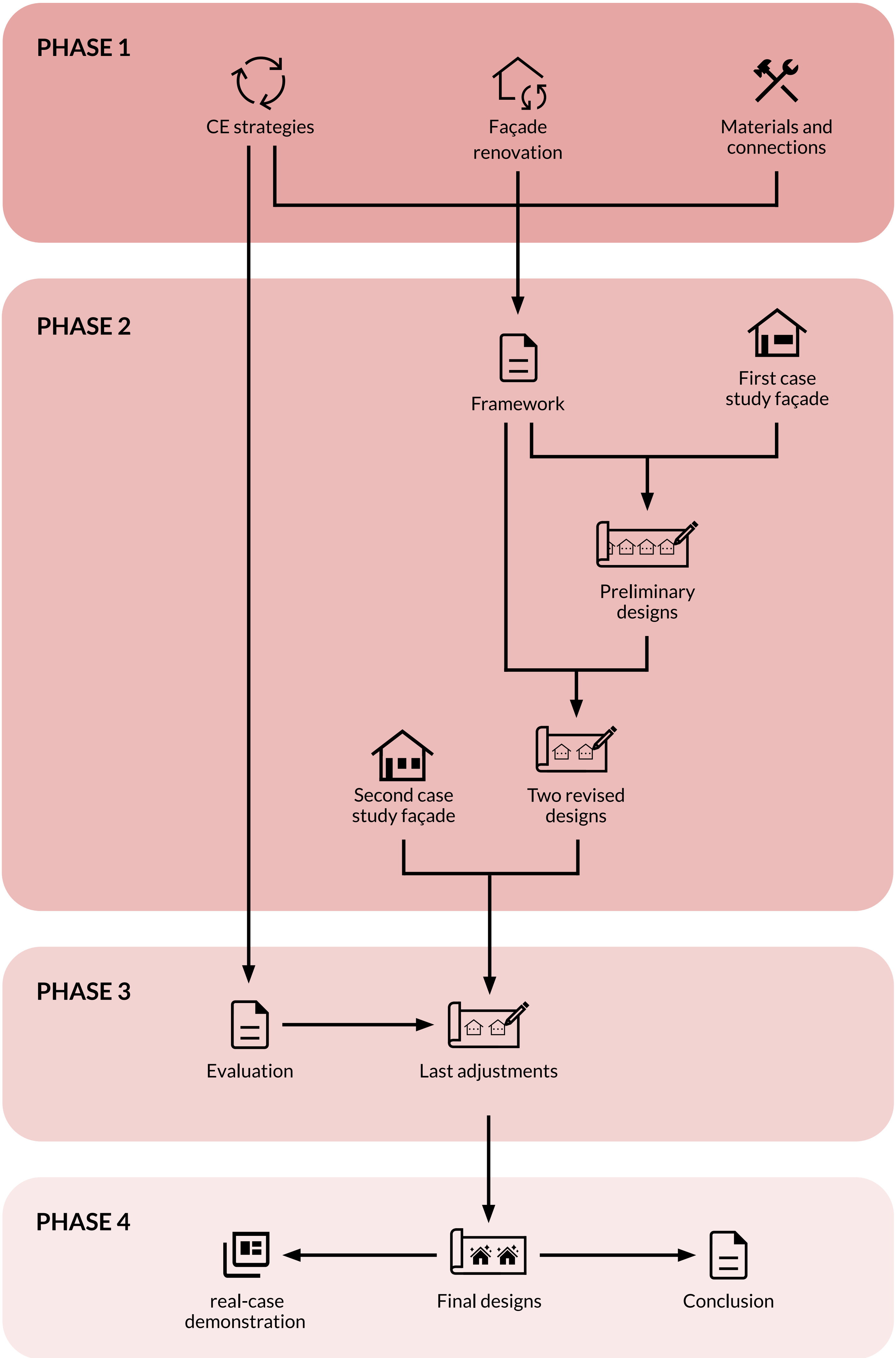
Phase 2 – Framework, Case study and Preliminary design
In this phase, a design framework will be created to outline the guidelines that the materials of an adaptable and circular façade system must fulfil. The framework will be used to guide the design process in the right direction and will also be used once the initial preliminary designs are completed. The materials that have been used will be placed within the framework to show how they perform across various aspects.

Two different row house dwellings will be selected for the case study. The designs of the façade system will be tested on these two dwellings. Data on the dwellings will be collected from existing architectural reports, archival drawings and site visits. The renovation approach will follow a refurbishment method, in which the existing façade cladding is removed and replaced with a prefabricated façade system.

The initial preliminary designs will be analysed, resulting in two designs that will be compared from this point onward. One design will resemble a more conventional prefabricated façade system, while the other will be a newly developed prefabricated façade system. Both façade systems will be tested on the second case study façade. This will reveal how the systems perform in terms of future reusability and adaptability.

Phase 3 – Evaluation
In this phase, the two façade systems will be evaluated with the help of three different methods: life cycle assessment, material circularity indicator and the 3DR method. This approach will clarify how the different structures, insulation materials and cladding types perform in terms of circularity and emissions. The last adjustments to the materials and design in general will be made at this stage, if necessary.

Phase 4 – Final Design and Conclusion
During this phase, the two façade systems will be further developed into final designs, incorporating all the knowledge gained in the previous chapters. After this, a real-case demonstration will follow, showing how a design team can utilise the knowledge from this report to design a circular façade system for a renovation project. This demonstration will include the program of requirements, how these requirements can be met and finally technical drawings of the design that best fit the specific scenario. The report will end with a conclusion and a discussion of the final designs and its outcomes. A separate section in the conclusion will include a guide explaining all the steps taken to integrate future component reuse into a façade system while being adaptable to different façade layouts.


PHASE 1
CE strategies
Façade renovation
Materials and connections
PHASE 2
Framework
First case study façade
Preliminary designs
Second case study façade
Two revised designs
PHASE 3
Evaluation
Last adjustments
PHASE 4
real-case demonstration
Final designs
Conclusion

1.6 Relevance

Societal Relevance

In today's construction landscape, the construction sector faces growing demands to decrease its environmental impact and resolve the housing shortage. The dominant take-make-dispose model in building practices contributes heavily to material waste, particularly in the renovation of outdated residential buildings. A large portion of the existing housing stock, especially post-war row houses, fails to meet current standards in energy efficiency, comfort and environmental impact, leading to frequent demolition and replacement instead of reuse.

As populations grows and the pressure on the housing demand rises, especially in crowded countries like the Netherlands, there is a clear need to renovate existing homes in a way that is both efficient and environmentally friendly. However, current façade systems often lack adaptability and are not designed for reuse or easy disassembly. This results in high volumes of waste and missed opportunities to retain material value. By introducing a prefabricated, adaptable and circular façade renovation system, this research supports the broader transition toward a circular economy. When façade systems are designed with future reuse in mind and can adapt to different dwelling types, the renovation process becomes less wasteful, more efficient and better aligned with long-term climate goals.

Scientific Relevance

This research contributes to the expanding body of knowledge on circular construction by focusing on the integration of reuse principles into industrialised renovation processes. While much of the current research in circularity targets new construction, fewer studies explore how circular economy strategies can be applied to the refurbishment of existing buildings.

By combining modular prefabrication with adaptability and circular design, this thesis addresses the scientific gap between theory and implementation in the circular refurbishment of façades. The study not only evaluates materials and connection techniques through methods like LCA, MCI and the 3DR method, but also translates these findings into a practical design solution. The outcomes of this research offer a replicable method for evaluating and improving façade circularity, which can aid architects, engineers and policymakers working on sustainable renovation strategies.

2 LITERATURE REVIEW

The transition to a circular economy in the construction sector presents both challenges and opportunities. A shift from traditional linear building methods to circular strategies is necessary to reduce CO_2 emissions, material waste, and environmental impact. This chapter explores the fundamental principles of circular construction, with a focus on façade renovation. It examines key circularity strategies, including reuse, bio-based materials, and industrialised renovation methods. Additionally, different assessment methods for evaluating circularity and sustainability in façade design are reviewed. These insights will form the foundation for the development of a circular and adaptable prefabricated façade system.

Fig. 2 - Disassembly of Circl-pavilion Zuidas (Steinbach, 2024)

2.1 Circular economy

As the global population grows, so does the demand for products, leading to excessive resource consumption. This impacts the climate, biodiversity, and pollution levels. Meanwhile, supplies of essential resources are dwindling. To address this, the Dutch government collaborates with businesses and societal partners to transition the economy by 2050 to rely entirely on reusable resources, eliminating waste. In a circular economy, waste and inefficiency are minimised by using products and resources smart and sparingly. Products are repaired when broken, or turned into new ones if repair isn't possible. The traditional "produce-consume-dispose" model is replaced by a continuous cycle (Rijksoverheid, n.d.). Also known as the Cradle-to-Cradle concept. The biological and technical cycles, illustrated in the figure below, serve different purposes. The biological cycle focuses on returning products to the environment, while the technical cycle ensures that products or materials are reintegrated into the system at various stages of their life cycle (Ellen MacArthur Foundation, 2021).

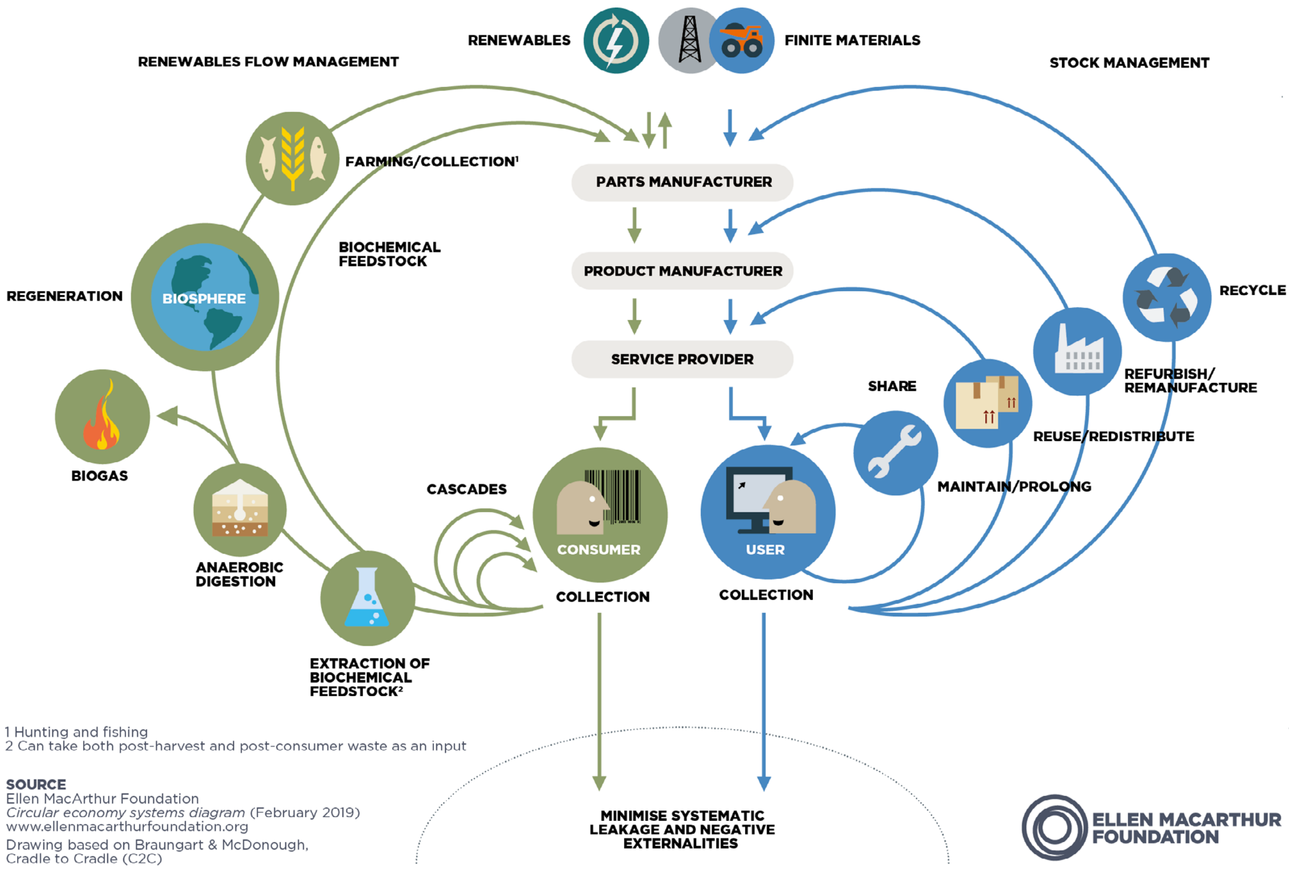


Fig. 3 - Butterfly diagram of the circular economy (Ellen macarthur foundation, 2021)

Circular economy in the Built Environment

The construction sector faces significant sustainability challenges due to its substantial environmental impact. It accounts for 11% of national CO_2 emissions and 50% of primary material consumption. To meet climate goals, this impact must be drastically reduced. Because of this , the Netherlands is aiming for a fully circular construction economy by 2050. (De circulaire bouweconomie, 2024).

A building can be viewed as a material bank, as it is expected that the materials or building products will later be reclaimed. This means that components and connections need to be designed for disassembly to enable reuse. For example, dry connections, such as screws or bolts, should always be used instead of wet connections like concrete. They should also be easily accessible to enable disassembly.
Understanding the life cycle of building products and their environmental impact at each stage is essential for creating a circular built environment. A building product typically goes through four key phases: production, construction, usage, and end-of-service. Unfortunately, the end-of-service stage is often overlooked, with used construction materials frequently ending up in landfills, which contradicts the principles of a Circular Economy. However, more sustainable alternatives such as recycling or reuse are available. To achieve this, it is crucial to be pro-active and consider End-of-life scenarios during the design phase. (Klein et al., n.d.).

2.2 Strategies

The R-strategies

The 2017 PBL Netherlands Environmental Agency Report outlines ten strategies, known as the R-strategies, aimed at reducing raw material consumption and minimising waste production. They are grouped into three categories based on their approach:

End-of-life Strategies

1. Recover: Incinerate waste to retrieve energy, though this destroys materials permanently and competes with higher-order strategies.
2. Recycle: Process discarded materials into new raw materials, which can be upcycled (higher quality) or downcycled (lower quality).

Prolonging Materials' Service-Life

3. Repurpose: Use discarded products in new functions (e.g., timber pallets turned into benches).
4. Remanufacture: Reuse parts of discarded products to create new products with the same function.
5. Refurbish: Modernise and update old products, often by replacing parts.
6. Repair: Fix broken or malfunctioning products to extend their life.
7. Reuse: Use discarded yet functional products for the same purpose, often by a new user.

Smart Manufacturing Strategies

8. Reduce: Use fewer resources during the manufacturing or usage phase.
9. Rethink: Intensify product use, reuse a building instead of demolishing it.
10. Refuse: Avoid a product by finding another way to meet its function or making it unnecessary.

The higher the number the higher the level of circularity. The R-strategies require not only technological innovation but also other changes involving collaboration among stakeholders. For example, remanufacturing demands take-back systems, storage, skilled personnel, and regulatory clarity about market re-entry and certifications.
Success also depends on a shift in mindset and values, such as caring for materials and products, as seen in remanufacturing and repair. Higher levels of circularity, like "Refuse," demand even greater changes in mentality, such as refusing to build with concrete connection and replacing them with demountable bolted connections (Ioannou, 2023).

Bio-based

Bio-based materials, derived from renewable biological sources such as wood, hemp, straw, and bamboo, offer a sustainable alternative to traditional construction materials. These materials not only store carbon but can often be recycled or composted at the end of their life cycle, significantly reducing environmental impact. These materials fit into both the technical cycle and the biological cycle.

Bio-based materials are versatile and offer many benefits. They are renewable, widely available, biodegradable, recyclable, and easy to source. They can adapt to various needs and return safely to nature without releasing toxins when disposed of properly. While some natural properties, like sensibility to decay, might seem like drawbacks, proper use and detailing can manage these challenges effectively. Additionally, they regulate indoor temperature and humidity, have a low thermal expansion, low embodied energy, and have excellent performance-to-weight ratios (Jones, 2017).

Design for Disassembly (DFD)

The theory of Design for Disassembly (DfD) is closely related to the key principles of that of the circular economy. It refers to the practice of designing products, systems, or structures in a way that facilitates their easy disassembly for repair, reuse, recycling, or proper disposal. It emphasises the intentional planning and design of components, materials, and connections to ensure efficient deconstruction and minimise waste.

The 5 key principles include: thorough documentation of materials and methods to guide future deconstruction (1). Connections are designed for easy separation, using screws, bolts, or modular structures instead of adhesives or welding (2). Non-recyclable and non-reusable components, like mechanical, electrical, and plumbing (MEP) systems, are separated to streamline the process (3). Simplicity is key, with standardised components and forms reducing complexity and enabling reuse (4). Lastly, DfD incorporates safety, productivity, and practical labour practices to ensure dismantling is efficient and worker-friendly (5).

DfD offers numerous benefits that make construction more sustainable and efficient. Environmentally, it reduces waste by enabling materials to be reused or recycled, conserving resources and lowering carbon emissions. By keeping waste away from landfills, it helps protect the environment while supporting a circular economy. Socially, DfD creates jobs by relying on labour-intensive deconstruction processes. It also improves worker safety through simplified dismantling methods. Economically, DfD saves costs by reducing disposal fees and generating value from salvaged materials. It creates new markets for reused components and increases the value of buildings designed for adaptability.

The biggest challenge of Design for Disassembly (DfD) is turning its potential into practical use. Designers often don't consider the End-of-life stage during planning, leading to buildings with complex materials and connections that hinder disassembly. Additionally, the lack of established markets for reused materials and consumer scepticism about their quality make it difficult to promote reuse and recycling. Practical barriers also arise, such as higher labour costs, longer deconstruction time lines compared to demolition and the logistical challenges of storing and transporting salvaged materials (Rios et al., 2015). However, this is slowly changing as more alternative markets for second-hand building materials are starting to appear, and designers are increasingly considering the End-of-life stage when designing buildings (RVB, 2022).

Example (Cepezed, kit of parts buildings)
Cepezed has been a pioneer since 1974 in using the kit of parts, a modular building system with prefabricated elements, which has evolved into demountable and remountable construction, contributing to the circular economy. The firm emphasizes flexibility and adaptability in its designs, featuring open floor plans and sustainable material combinations like reused wood, steel, and recycled concrete. Projects such as the temporary courthouse in Amsterdam and 'Bouwdeel (D) emontabel' demonstrate how prefabricated elements can be efficiently assembled, disassembled, and reused in new locations. Cepezed embraces uncertainty as a design principle, referencing Stewart Brand's view that buildings must be adaptable to last longer and retain their value. (Cepezed, 2024).

Fig. 4 - The temporary courthouse of Amsterdam was fully deconstructed and rebuilt at a different location (Cepezed)

Industrialised renovation
Industrialised renovation is a strategy to enhance the renovation process of existing buildings using industrial techniques like prefabrication, mechanization and automation. It is crucial for improving energy efficiency, minimizing waste, and accelerating the reduction of CO_2 of the building sector, especially given that a significant percentage of buildings today will still stand by 2050 and are responsible for nearly 40% of EU energy consumption. By employing industrialised approaches, renovation can scale up, improve quality and reduce on-site construction time and costs.

The degrees of industrialised renovation include prefabrication, mechanisation, automation, robotics, and reproduction. Prefabrication involves off-site assembly of building components, such as façade units or sandwich panels, which are then transported and installed. Mechanisation uses machines, like cranes or CAD software, to aid human labour. Automation involves tooling that performs repetitive tasks without human adjustment. Robotics introduces flexibility, allowing diversified tasks, such as robotic bricklaying. Lastly, reproduction emphasises scaling and replicating designs to standardise components while customising them for specific projects (Konstantinou & Heesbeen, 2022).

Modular construction is a subset of industrialised construction, sharing many of its principles, like controlled environments and repeatability. Modular construction focuses on assembling pre-fabricated modules or components. One significant advantage is its efficiency in terms of time and cost. Modular construction can accelerate project time lines by 20–50% due to off-site manufacturing, which takes place concurrently with on-site foundation work. This controlled environment also minimises delays caused by weather or other site-specific disruptions. Additionally, modular methods can reduce construction costs by up to 20% when optimised, largely through reduced labour needs and improved productivity. The approach also offers improved quality, as factory conditions allow for greater precision and fewer defects, which enhances the building's durability and performance, such as energy efficiency. This method is most advantageous in projects with high repeatability, such as affordable housing and hotels, but less effective in complex, bespoke developments (Bertram et al, 2019).

Life cycle assessment (LCA)

LCA is a method used to evaluate the environmental impacts of a product, process or system throughout its entire life cycle. LCA doesn't just look at CO_2 emissions during production, it also considers emissions from material transport, installation, use, maintenance and End-of-life disposal or recycling. Companies like 'One Click LCA' focus on the construction and building industry, offering tools to calculate and manage the environmental impacts of buildings, materials and infrastructure. It enables architects, engineers, and sustainability professionals to measure embodied carbon, optimise materials, and comply with green building certifications like LEED, BREEAM and others (Ramachandran, 2024).

Material Circularity Indicator (MCI)

The Material Circularity Indicator (MCI) is a metric designed to assess the circularity of a product by evaluating how effectively it minimises the consumption of non-renewable materials and reduces waste. This metric also includes all of the other ways of achieving circularity (avoiding consumption, enhancing durability, reuse, remanufacturing, bio-based materials, composting etc.) The Material Circularity Indicator evaluates both the inputs and outputs of a product's life cycle. On the input side, it considers what the product is made of and the sources of its components. On the output side, it examines what happens to the product at the end of its life. The Ellen MacArthur Foundation developed an Excel-based calculation tool to measure circularity, providing a clear indication of how circular a product is. The calculation will result in a value between 0 and 1, where 0 indicates a "take-make-dispose" product, and 1 represents a fully circular product (ellen macarthur foundation, 2024).

3DR method to quantify the circularity of buildings

The 3DR method is a way to measure how well buildings follow circular principles. It focuses on how they are designed, how easy they are to take apart (disassemblability), how they can be carefully dismantled (deconstructability), and how strong and reusable their materials and components are (resilience). This method only looks at circularity and does not consider environmental impacts. The 3DR method calculates a building's circularity using the 3DR index, which combines the building's disassemblability (DI), deconstructability (DE), and resilience (R). The formula for the index is:

$$3DR = DI \times a + DE \times b + R \times c$$

The value of the 3RD ranges from 0 to 1. A higher 3DR value, closer to 1, means the building is easy to take apart, reuse, and made with strong, reusable materials, allowing it to go through many cycles of reuse. A lower 3DR value means the building is designed in a way that makes it hard or impossible to take apart, reuse, or recycle, with a value of 0 meaning none of these is possible.

The 3RD method can be applied in two main situations:

1. In the End-of-life scenario, the building is completely disassembled, so *b* = 0, and the remaining influencers (*a* + *c*) add up to 1.
2. In the Moving or Repurposing scenario, the building is carefully deconstructed instead, so *a* = 0, and the influencers (*b* + *c*) also add up to 1.

The index influencers can be adjusted to focus on what is most important. For example, in the End-of-life scenario, increasing *a* and decreasing *c* would make disassembly a bigger priority than resilience.

The following formulas can be used to find the disassemblability (DI), deconstructability (DE) and resilience index (R). The formulas can be completed using the variables in the tables below. The disassemblability and deconstructability formula depend on variables related to how easily a building or component can be disassembled. To be specific, the type of tools required and the number of people needed. The resilience index considers how many times a component or material can be reused, or whether it can only be recycled, downcycled or is disposable (O'Grady et al, 2021).

$$DI = \sum_{i=1}^{n} (DIt_i \times DIm_i \times w_i) \Big/ w_T$$

$$DE = \sum_{j=1}^{m} (DEt_j \times DEm_j \times w_j) \Big/ w_T$$

$$R = \sum_{k=1}^{t} (Re_k \times w_k) \Big/ w_T$$

Symbol	Definition
DI_{ti} and DE_{tj}	Tools required
DIm_i and DEm_j	Equipment or people required
w_i and w_j and w_k	weight of component
Re_k	Resilience of component k
w_T	Total weight of the building

Variable	*Description*	*Operation and tools required*	*Value*
DIt, DEt	Availability, dimensions, and types of tools required to disassemble components (DIt) or deconstruct a building (DEt)	No tool	1
		Hand tool	0.9
		Power tool	0.8
		Gas/pneumatic tool	0.5
		Hydraulic equipment	0.2
DIm, DEm	People or equipment required to move components to another building (DIm) or move components following deconstruction (DEm)	One person: < 20 kg	1
		Two people: < 42 kg	0.9
		Hand trolley: < 50 kg	0.7
		Forklift: < 2,000 kg	0.4
		Crane: > 2,000 kg	0.1

Description	*Re value*
Reusable an infinite number of times	1
Reusable up to three times	0.9
Reusable only once	0.7
Recyclable	0.6
Downcyclable	0.2
Disposable	0

Fig. 5 - Calculations and tables used for the 3DR method (O'Grady et al, 2021)

Conclusion

This section explored the concept of the Circular Economy and its significance in the built environment. The transition from a linear to a circular economy aims to reduce resource depletion, minimise waste and extend material lifespans through reuse and recycling. The construction industry plays a critical role in this shift, as it accounts for a large share of material consumption and CO_2 emissions.

A Cradle-to-Cradle approach ensures that materials are continuously cycled within biological or technical loops, preventing waste generation. Additionally, Design for Disassembly (DfD) and modular construction methods enable future reuse of building components. However, implementing DfD in the construction sector faces barriers such as lack of standardization, infrastructure for reused materials and economic challenges.

The next part introduced strategies for implementing circularity in the construction sector. The R-strategies, offer a series of 10 strategies for minimising resource consumption and maximizing reuse potential. Additionally, Bio-based materials and Design for Disassembly (DfD) were discussed as key enablers of circularity. Bio-based materials provide renewable and biodegradable alternatives to conventional materials, while DfD ensures that components can be easily separated for reuse. Despite their potential, challenges such as logistics, cost, and regulatory barriers must be addressed to scale these strategies effectively.

Industrialised renovation was highlighted as a key enabler of large-scale circular renovation. Modular and prefabricated façade systems can be designed with disassembly in mind, allowing components to be reused or repurposed at the end of their life cycle. However, customization remains a challenge, as building stock varies in design and dimensions, requiring adaptable solutions.

To quantify circularity, different assessment methods were explored. The Life Cycle Assessment (LCA) evaluates the environmental impact of materials and processes across their entire life cycle. However, it only takes the environmental impact into account and not the circularity. The Material Circularity Indicator (MCI) measures the degree to which materials are sourced from circular streams and retained in the system after use, providing a numeric score to assess sustainability. Additionally, the 3DR method offers a calculation method for assessing the simplicity of a building's circularity. The calculation takes into account how easy components are to take apart and how strong and reusable their materials and components are.

A combination of these strategies and calculation methods will later be used to form a framework to assess the preliminary designs. They will help outline the requirements that a circular component must fulfil.

2.3 Façade renovation

The existing housing stock in the Netherlands consists of 7,966,331 homes, with 2,295,522 (28.8%) classified as social housing. Housing corporations manage these properties, ensuring their maintenance and improvement to meet quality standards. This requires restoring and renovating their properties to make them more sustainable, energy-efficient, and future-proof. This contributes to reducing environmental impact, increasing living comfort, extending the lifespan of buildings and lower energy costs for tenants. In the circular economy, housing corporations strive to use materials more efficiently and make optimal use of existing buildings before considering new construction. Façade renovation plays a crucial role in sustainability and circularity. The façade largely determines a building's energy efficiency. Insulating façades and replacing window frames and glazing contribute to energy savings, especially for homes aiming for a energy-neutral status (Nunen, 2022).

Industrialised façade renovation methods

Konstantinou & Heesbeen conducted a study in 2022 that explored the design and construction principles for industrialised renovation. It contains various prefabrication techniques aimed at improving energy efficiency, reducing construction time and maintaining high-quality results.

1. Prefabricated Sandwich Panels

Prefabricated sandwich panels, also known as structural insulating panels, are construction components commonly used in both new construction and renovation projects. They consist of two rigid panels, typically made of materials like oriented strand board (OSB), particleboard, or metal sheets, bonded to a lightweight core. These panels can include prefitted features such as windows, doors, services, and finishes, thanks to manufacturing techniques like automation and prefabrication. In renovation, they are often used to improve the thermal performance of walls and roofs. A notable example is the 2ndSkin renovation concept, which uses prefabricated sandwich façade panels to achieve zero-energy dwellings by integrating new windows and service installations. These panels are preassembled in factories and transported as complete units to minimise connections and improve installation efficiency.

2. Timber-Frame Panels

Timber-frame panels share similarities with sandwich panels but differ in that their strength derives from a framework of timber beams enclosing an insulated core. Windows are incorporated into the framework to ensure structural stability, and additional layers like moisture and waterproofing foils are included before external finishing. These panels are increasingly used in renovation projects, where they can replace existing walls.

3. Modular Façades

The concept of modular façades involves prefabricated units designed for repetitive assembly, either on-site or off-site. These unitised façades provide multi functionality by integrating both passive and active systems, such as building-integrated solar thermal collectors, within standardised panels.

4. Prefabricated Rain screen Façades

Prefabricated rain screen façades, another type of modular façade, are ventilated systems designed to upgrade thermal resistance, improve moisture management, and enhance the appearance of building envelopes. The outer skin or panel is called the 'rain screen', as it forms the primary rain barrier.

5. Pre assembled Configurations

Pre assembled configurations further streamline renovation processes by integrating various components into prefabricated units, which are then installed on-site. Factory Zero, for example, has developed a Climate Energy Module that incorporates building services within an insulated roof panel. This approach reduces installation time, space requirements, and occupant disruption while enhancing the efficiency of building envelope renovations (Konstantinou & Heesbeen, 2022).

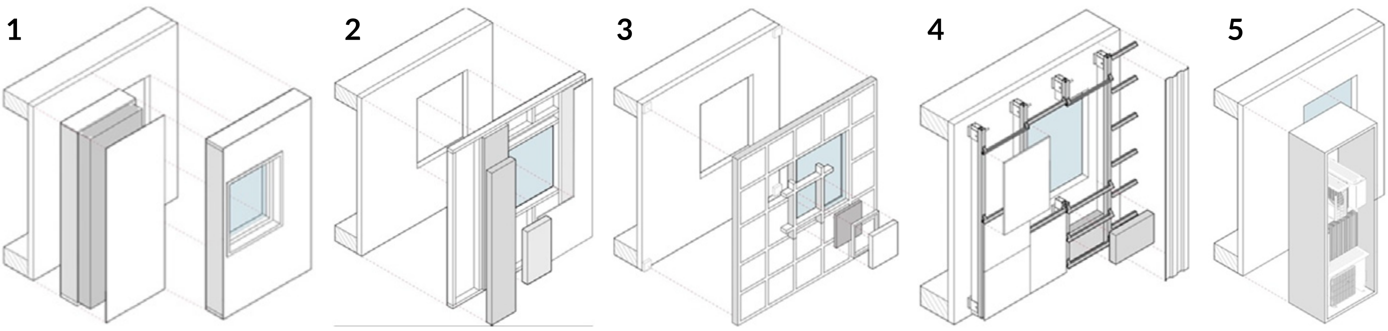


Fig. 6 - Five industrialised facade renovation methods (source: Konstantinou & Heesbeen, 2022)

Stakeholders

The façade supply chain involves clients, architects, main contractors, façade contractors, material processors, and demolition contractors, each contributing to the design, construction, and End-of-life recovery of façades. How these stakeholders communicate and transfer knowledge and/or products can be seen in the map down below. Clients set project goals, emphasizing aesthetics, performance, and cost, which guide architects in designing façades. Main contractors manage construction logistics, while façade contractors handle assembly and technical feasibility. Material processors supply raw or recycled materials, constrained by market demand and recycling technologies. Demolition contractors recover materials at the end of a building's life, often focusing on cost and landfill avoidance.

Collaboration among these stakeholders is limited by differing priorities, weak recovery infrastructure and poor communication. Improved coordination, better design for disassembly, and knowledge sharing are key to enabling circular economy practices in façade design (Hartwell, 2021).

Storing detailed information about a building, such as floor plans, technical details, and materials used, is an effective way to equip future demolition companies with the tools and knowledge needed for efficient, circular dismantling. This can be achieved with the help of a construction archive or a digital building passport, such as the online platform Madaster (Honic et al, 2021).

Additionally, there are resellers and platforms actively involved in purchasing, collecting, and renewing construction materials and products. These sources offer both larger quantities of materials and materials of high quality. In doing so, they promote circularity in the construction sector. Examples of websites to find these resellers are: opalis.eu, insert.nl, and oogstkaart.nl (Koster et al, 2020).

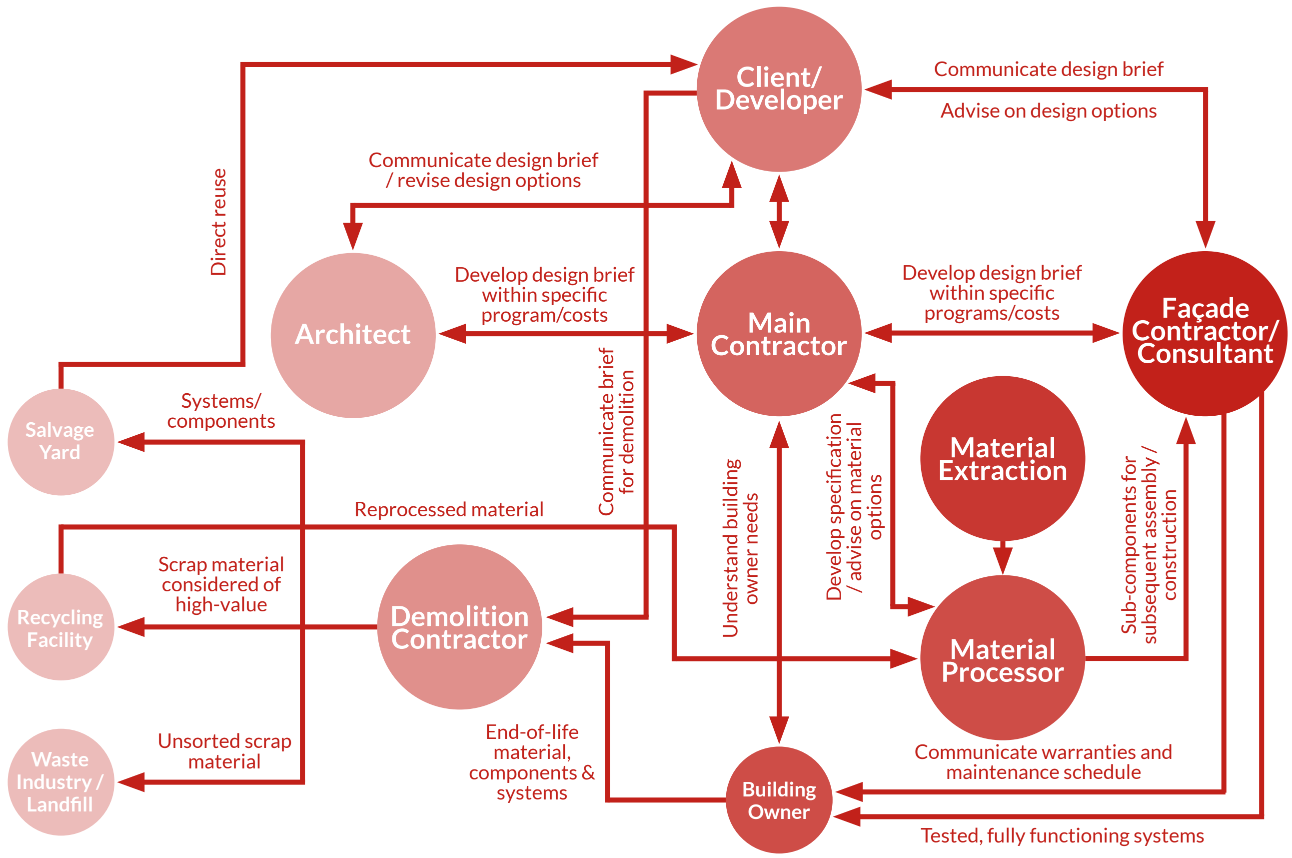


Fig. 7 - Stakeholder map showing stakeholders involved in the façade supply-chain and existing flows of knowledge and products/services (source: Hartwell, 2021)

Conclusion

This section examined how circularity principles can be integrated into façade design and refurbishment. Various industrialised façade renovation examples, such as prefabricated panels, modular façades, and preassembled configurations, enable efficient reuse and reduce material waste. These approaches improve energy efficiency, reducing construction time and create high-quality results.

Stakeholders such as architects, contractors, material processors and demolition companies play a vital role in ensuring that façade systems are designed for circularity. Collaboration between those stakeholders in combination with digital tools, such as material passports, can enhance traceability and improve material recovery at the end of a building's life cycle.

2.4 Materials and connections

In 2021, a study was conducted using an online survey completed by 69 stakeholders from across the façade knowledge and supply chain. Participants were asked to assess the reuse potential of different façade components. Overall, framework components, typically constructed from steel and aluminium, were perceived as having relatively high reuse potential. In contrast, insulation products, glazing, and connection elements were considered to have lower reuse potential (Hartwell, 2021).

Fig. 8 - Material pyramid shown in kg CO2 per m3 (Royal Danish Academy, 2019)

Also, resell platforms show that framework components are offered more frequently than insulation materials, likely because insulation is more vulnerable to environmental factors, while columns and beams are better protected. To reduce CO_2 emissions and enable component reuse, materials that withstand weather conditions or bio-based materials that can be composted may be more effective to use. However, weather-resistant insulation materials like EPS are recycled in limited numbers due to high costs and low profitability (Xu, 2024).

Steel, on the other hand, is recycled on a much larger scale and is fully recyclable, allowing for repeated reuse without quality loss (worldsteel, 2024). While steel has a higher CO2-to-volume ratio, it is more circular than EPS.

This chapter will explore materials and connections that support component reuse and CO_2 reduction, focusing not only on framework components but also on less commonly considered materials, such as insulation.

Connections designed for disassembly

Steel-steel

1. Bolted Connections

Bolts are ideal for DfD as they are easier to disassemble compared to welds. Standard bolts connect elements through pre-drilled holes, and their removal leaves the members intact for reuse. They can be installed by aligning holes in members and tightening bolts, ensuring alignment with design specifications.

2. Flexible end-plates

These plates are bolted to the column and welded to the beam, allowing the connection to carry shear forces while still being relatively easy to take apart. During disassembly, the bolts can be removed to separate the beam from the column, and the welding affects only the end plate, not the main structural members. This minimises damage and keeps the beam reusable.

3. Clamped Friction Connections

These connections use clamping forces rather than penetration to hold elements together. They are right for DfD because they leave no damage to the connected elements, preserving them for reuse. Installation involves positioning clamped components and securing with tensioned bolts. An example of this system can be seen below on the right side by Lindapter (Silverstein, 2009).

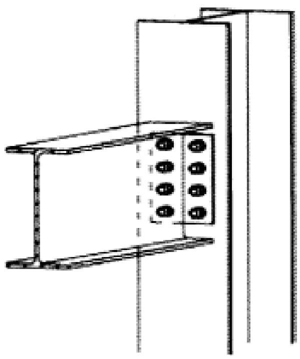


Fig. 9 **-** Bolted connection
(source: Silverstein, 2009)

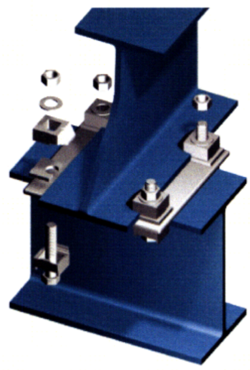


Fig. 10 **-** Clamped connection
(source: Silverstein, 2009)

Timber-timber

1. Metallic hanger

External and internal metallic hangers are widely used connectors in timber frame structures. These connections link beams to beams or beams to columns. The primary components of this connection include metallic plates, dowels, screws, and bolts. Both external and internal hangers are considered easy to assemble and require minimal labour time. Additionally, the cost of assembly and deconstruction is low, thanks to the simplicity and efficiency of these systems.

2. Hook connector

The hook connector is used to join beams to beams or beams to columns. The thin parts create a strong connection. This type of connection is particularly well-suited for DFD because it is an indirect connection and offers good accessibility. The potential for wood reuse is high, as all components can be reused without needing to be separated from the connected elements.

3. X-RAD system

X-RAD timber systems are ideal for DFD because they use modular components that can be easily deconstructed, reused, or recycled at the end of their life-cycle. The system uses mechanical fasteners, such as bolts and screws, rather than adhesives or nails, which allows for easy separation of materials. Assembly involves connecting prefabricated timber panels and steel elements in the corners. The components can be disassembled without damage.

4. Post connector

The Cross and Circular Post connectors are methods used to join columns in timber structures, transferring vertical loads between components in the system. These connections consist of a metal connector, metal dowels, and bolts. The metal connector is attached to the timber elements with screws or bolts, while the dowels increase the connection's load-bearing capacity.

The Circular Post connector is particularly well-suited for Design for Disassembly (DFD), as its connector configuration requires minimal work instructions for disassembly. Also, the potential for reusing both the wood members and connectors is high, as all parts can be reused multiple times without needing to separate the components. The Cross Post connector also provides a reasonable degree of disassembly, offering similar benefits to the Circular Post. However, the hidden connectors reduce visibility and limit accessibility, making it less favourable for disassembly. The reuse potential for this connection is lower since some fasteners need to be removed in the dismantling process (Abdulrahman, 2021).

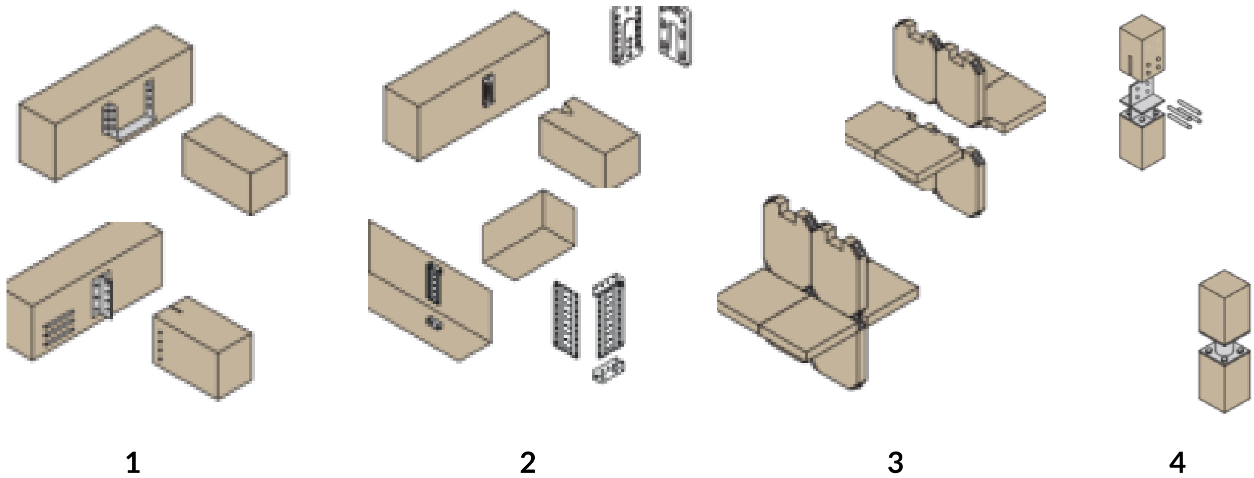


Fig. 11 - (Abdulrahman, 2021)

Timber-concrete

The deconstructable connector using self-tapping screws is ideal for disassembly because it allows separation of timber, concrete, and connectors at the end of the structure's life. The protective heat-shrink tubing prevents the screws from bonding with concrete, facilitating removal. For a wet-dry construction, drive the screw into pre-drilled holes in the timber and then pour concrete over the screw. For dry-dry connections, pre-cast the concrete, then attach it to timber using the screws through prepared holes. Ensure the rubber lid protects the screw head during concrete curing for easy disassembly. Angles like 30° or 45° provide better shear strength and stiffness compared to vertical screws (Derikvand, 2021).

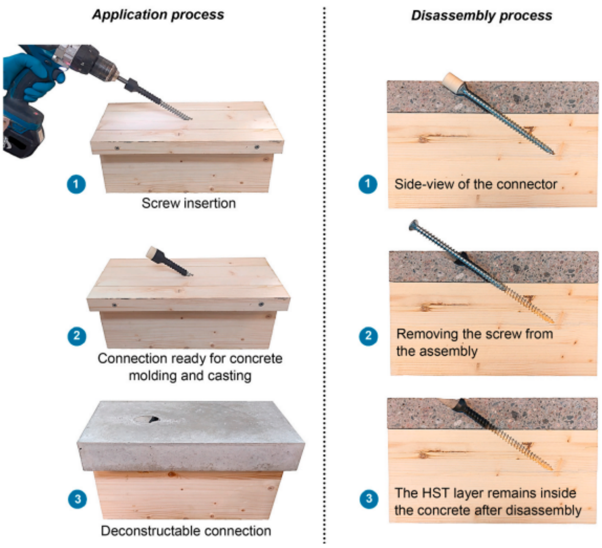


Fig. 14 - Wet to dry connection (Derikvand, 2021)

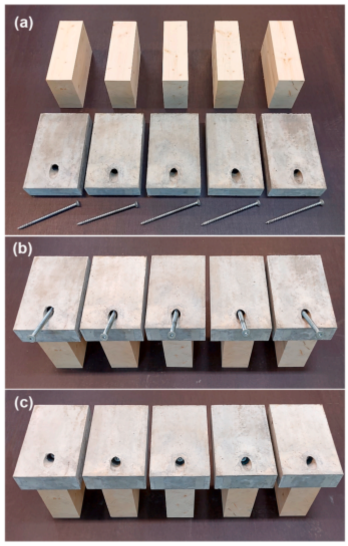


Fig. 15 - Dry to dry connection (Derikvand, 2021)

Concrete-concrete

Dry connections are ideal for DfD because they enable disassembly without damage, promoting the reuse of structural elements. In beam/column connections, steel end plates, embedded threaded rods and bolts can be used to establish the connection. For disassembly, the bolts are removed, allowing the beams and columns to separate. Wall-to-wall connections use an H-shaped steel connector and pre-tensioned bolts, secured through the walls. Disassembly simply involves unscrewing the bolts, after which the walls can be disconnected (Figueira, 2021).

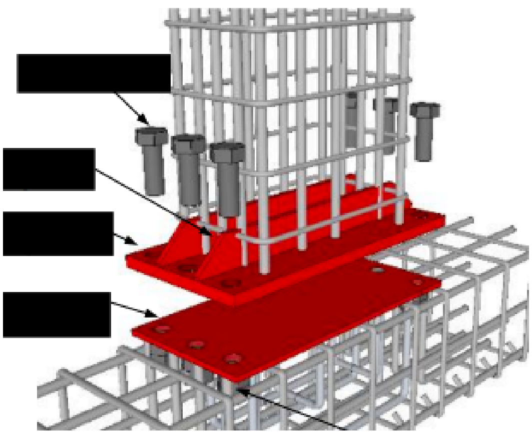


Fig. 12 - Beam to column connection (Figueira, 2021)

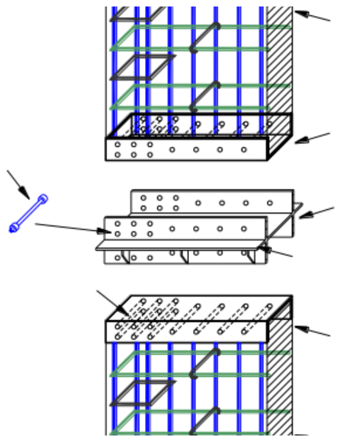


Fig. 13 - Wall to wall connection (Figueira, 2021)

Reusing wood and steel

Steel and wood are well-suited for reuse after their first service life. However, there are some factors to consider when reusing construction elements. First, the types and dimensions of the elements should be specified to include a wide range of acceptable profiles and lengths during the design phase, as this increases the likelihood of availability from suppliers. The condition of reused elements may differ from new materials, often featuring holes, paint, welds, or surface rust, which are usually acceptable. However, restrictions can be applied to the location or size of new holes if necessary. The finish is another important factor, as original coatings on steel should not be relied upon, and new coatings are often required for specific applications. At this moment the market is still scarce so supplementing reused beams with new ones in critical areas can help address this challenge.

Testing the material properties and strength is crucial. Steel for instance, generally has a long lifespan and experiences minimal degradation under normal conditions. However, testing may be required to confirm its mechanical and chemical properties, especially for structural applications. Information about the material properties, such as yield strength, tensile strength, and toughness, may be available from original technical documents, but if such information is lacking, testing becomes necessary. Testing methods, including visual inspections, mechanical tests, and laboratory analysis.

Economic and practical factors also play a significant role when considering element reuse. Extensive testing can impact project costs and feasibility, making careful planning and cost assessments essential. Over-dimensioning structures or adopting conservative assumptions about material properties can reduce the need for testing while maintaining safety.

When not to reuse steel

Beams exposed to extreme point loads, heavy shocks, or fire are subject to conditions that can compromise their structural integrity. Similarly, beams showing signs of fatigue, such as weak points caused by excessive forces that have altered the internal structure of the metal, are at risk. This phenomenon, often identified by the appearance of cracks prior to failure, can result from repeated cycles of shocks or vibrations and is occasionally encountered in environments like elevator shafts, overhead cranes, traffic bridges, or railway tracks. Beams originating from extreme applications, such as those exposed to radioactivity, or beams with significant cross-section reductions due to corrosion may also present concerns. Visible or suspected signs of plastic deformation further indicate potential issues, as do beams manufactured before 1970, which may not adhere to modern steel standards, though their suitability can sometimes be verified through specialised testing and inspections.

When not to reuse wood

Wood should not be reused if it has significant damage or defects that compromise its structural integrity or suitability for the intended application. During preliminary inspection, issues such as cracks, rot, insect damage, or deformation can make both solid wood and glued laminated timber (GLT) unsuitable for reuse, particularly in structural applications. If dismantling causes excessive breakage, torsion, or deformation, or if GLT loses its bond quality due to poor adhesive performance, the wood's reuse potential reduces. Additionally, wood stored improperly, exposed to weather elements, or warped due to inadequate ventilation and support may no longer meet the necessary standards for reuse (Rotor vzw/asbl, 2021).

Wood types for recycling

Wood waste consists of different types of wood, divided into 3 classes. Class A wood is untreated or unprocessed wood. High-quality A-wood is shredded and then reused in the wood fibre industry. Class B wood includes hardboard, particle board, fibreboard, pressed wood, furniture, painted wood, doors, frames, and non-impregnated wood. Class C wood is impregnated wood, such as fences (pressure-treated) or railway ties (tar-treated). Classes B and C wood are of lower quality and cannot be reused. After shredding, they are used to generate renewable energy (Nijssen, 2022).

Acetylated wood

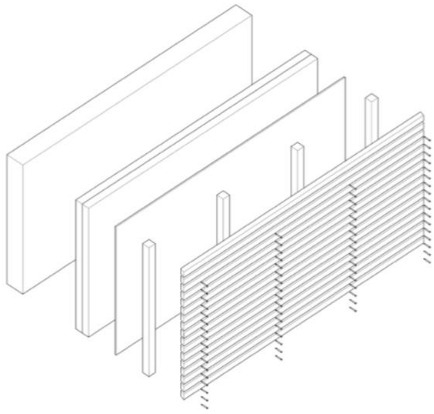
Chemically treated wood, obtained through acetylation. During this process, it is chemically preserved with acetic anhydride under high temperature and pressure. This changes the properties of the wood; it no longer absorbs moisture, making it much more stable and significantly more durable. It is 100% recyclable because it does not contain toxic chemicals and can be disposed in exactly the same way as unmodified wood (Accoya, 2019).

Façade cladding

Wooden façade systems

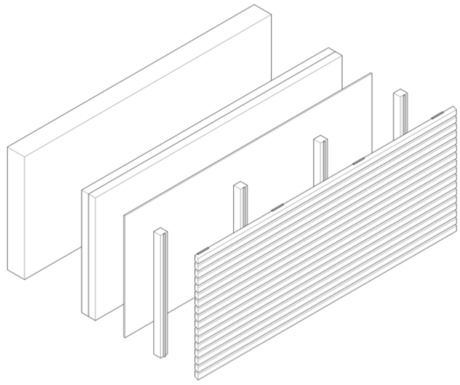
1. Open and visible fastening

Here, horizontal wooden planks are fixed to vertical frames using visible screws. While individual boards can be removed, the process leaves screw holes in the underlying frame. To ensure the same level of fastening when reattaching the boards, larger screws may be required. Alternatively, a nail gun can be used instead of screws. Nails create smaller holes in both the wood and the underlying structure, making it easier to reuse the materials if desired.



2. Hidden fastening system

This system uses horizontal planks fastened with hidden clips attached to a timber or aluminium frame. Hidden fasteners eliminate the need for visible screws, preserving the boards' integrity and enabling partial reuse after disassembly. The system scores highly for reparability, allowing quick and easy replacement of individual boards. Despite these advantages, the increased complexity of the hidden fastening system raises the cost. One other disadvantage of a click system is that it often requires a significant number of aluminium rails and plastic clips to securely install the façade panels.



3. Steel profile anchoring

In this façade system called Xilomoenia, slats are mounted using vertical steel profiles with pre-formed holes. This eliminates the need to pierce the slats, ensuring full board reusability. Disassembly and reparability are also optimal, thanks to the secure yet removable anchoring mechanism. However, the precision and material costs associated with steel profiles push the price, making it an expensive option. This system is ideal for projects prioritizing durability, flexibility, and sustainability (Paoloni et al., 2018).

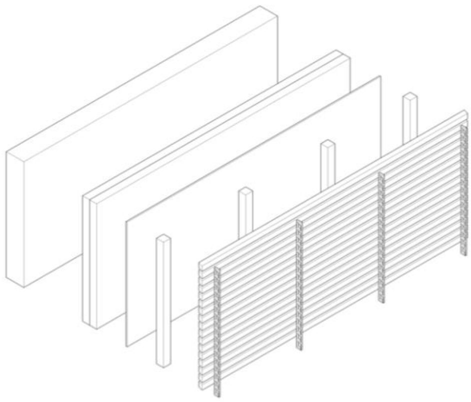


Fig. 16 - (Paoloni et al., 2018)

Metal façade systems

In 2020 the steel industry was responsible for between 7% and 9% of global CO_2 emissions (worldsteel, 2024), while the aluminium industry accounts for around 3% (IEA, 2023). To reduce these numbers metals should be recycled and ideally reused, as this would further decrease CO_2 emissions.

Researches of the technical university of Denmark did a case-study about steel reuse, focussing on a 2020 demolition in Denmark, involving a school built in 1967 with steel cladding. While most of the building was conventionally demolished for recycling, the steel façade cladding was removed for reuse. Panels were unscrewed, with damaged screws cut using angle grinders when necessary, though this increased the risk of damaging panels. Once dismantled, the panels were sorted to separate reusable ones from damaged units and transported for refurbishment. Preparation included sandblasting to remove old coatings, followed by the application of a fresh zinc layer and paint to restore durability and aesthetics. Finally, the panels were repacked and made ready for reuse. The process was labour-intensive and the use of angle grinders increased the risk of damaging panels, resulting in an 18% material loss in this case.

However, the advantages of reusing steel façade panels are significant. There is a notable environmental benefit to reusing steel façade panels compared to using new panels. The life-cycle assessment (LCA) results demonstrated that selective demolition and reuse reduced environmental impacts across all assessed categories by an average of 40% compared to the conventional demolition and production of new panels. It also minimises waste by diverting materials from landfills and reduces the demand for virgin raw materials (Andersen et al., 2022).

Fig. 17 - Dismantling of metal façade panels (Andersen et al., 2022)

Fig. 18 - Recycled Plastic façade (Pretty Plastic, 2024)

Pretty Plastic

Pretty Plastic is a sustainable cladding material made entirely from recycled PVC, such as old window frames and rain gutters. Each tile is secured with screws to an underlying wooden or aluminium structure made out of slats. Like roof tiles, they overlap each other. Installation begins at the bottom and progresses upwards. For dismantling, the process is reversed, starting from the top, with the tiles easily removed by unscrewing them. The tiles are available in three shapes: First One, Second High and Basic Third. Each shape offers a different aesthetic to suit various design preferences (Pretty Plastic, 2024).

Old brick reuse

Reusing bricks and other building materials has been practiced for centuries. However, the development of harder, cement-based mortar in the 1970s made brick reuse less efficient than before. Brick reuse is common in non-load-bearing decorative masonry, such as façades, but some bricks are also suitable for structural applications. The reclamation process involves dismantling, cleaning, sorting, and storing bricks, with careful handling to minimise breakage. Factors such as mortar type, exposure history, and contamination affect the feasibility of reuse. Bricks are assessed for structural integrity, porosity, frost resistance, and fire resistance, with standardized tests available for quality control. Market availability varies by region, with stronger handmade bricks generally being more expensive than weaker, mechanically produced ones. Reclaimed bricks significantly reduce environmental impact, lowering carbon emissions compared to new brick production.

Fig. 19 - Reusing entire slaps of reused bricks (Lendager, 2019)

Fig. 20 - Reusing separated bricks (Rotor vzw/asbl, 2021)

Reclaimed handmade bricks typically cost between €0,30 and €1,10 per piece, while extruded bricks range from €0.25 to €0.70 per piece. In comparison, new bricks cost an average of €0.30 to €0.70 per piece. While prices can be similar, used bricks often retain traces of mortar and are usually available in smaller batches. To address supply limitations, designers can mix formats or patterns to achieve the desired aesthetic and quantity (Rotor vzw/asbl, 2021). Lendager Group's Resource Rows project even repurposed entire brick façades from abandoned buildings, preserving them as whole elements and integrating them into the new construction.

Reusable brick system

ClickBrick Pure is a fully circular and dry-stackable brick façade system designed for easy assembly, dismantling, and reuse. It eliminates the need for mortar or glue by using a system that includes wall ties and stainless steel clips for secure installation and while also ensuring reusability. Wienerberger ensures that ClickBrick remains a truly circular solution by offering a return guarantee with remaining value. This means that after several years, the bricks can be dismantled without damage and returned to Wienerberger for reuse in new projects. (Wienerberger, 2025)

Fig. 21 - ClickBrick system (Wienerberger, 2025)

Façade fabric

Façade fabric is often made from PVC-treated polyester and is secured using a aluminium clamping system. The polyester mesh cloth is easy to clean and its smooth surface prevents contamination from moss, algae or bird droppings, allowing the façade to last for decades. While the façade cladding can be applied permanently, it is also easy to disassemble and reinstall at a different location (Buitink-Technology, n.d.).

Fig. 22 - Recovered stone wool (Acar, 2024)

Fig. 23 - Façade fabric on temporary courthouse of Amsterdam (Buitink-technology, n.d.)

Insulation

Stone wool insulation

The thermal conductivity of mineral wool typically ranges from 0.030 to 0.040 W/m·K depending on the specific type and density of the material. Stone wool panels generally stay in good condition after being removed and can still provide the same thermal performance as new panels even after 28 years, as long as they remain dry. However, as stone wool ages, it absorbs more water, with nearly half of the tested samples failing modern water absorption standards due to the breakdown of their water-repellent coating. Mechanical performance also declines with age, load exposure, and post-dismantling damage, with many samples not meeting current compression and puncture resistance standards. High-density panels in protected environments, such as those with vapour barriers, perform best and offer the most reuse potential (Acar, 2024).

Glass wool

Glass wool consists out of more recycled content and has lower CO_2 emissions than stone wool. While both materials are made from mineral fibres and can technically be recycled, glass wool is often made from a higher percentage of recycled materials, glass wool integrates waste materials more effectively, making it the more sustainable option (Streimikiene et al., 2020).

Bio-based insulation

Insulation materials improve buildings' thermal performance, reducing energy demand and carbon emissions, but many produce significant carbon emissions during production, whereas bio-based options offer lower environmental impact. The following Bio-based materials have the highest thermal conductivity (Cosentino, Fernandes & Mateus, 2023)

Name	Description	Thermal conductivity
Straw	A widely studied bio-based material, its insulation performance improves when fibres are aligned perpendicular to heat flow.	0.046 W/mK
Sheep wool	A natural material with excellent insulation properties, also used to enhance the performance of other materials.	0.0318 W/mK
Reed	Historically used in vernacular construction, it provides effective insulation and vapour permeability.	0.056 W/mK
Cork	A sustainable material often used in agglomerated panels for its good insulation and environmental benefits.	0.044 W/mK
Wood fibre / flax	Often combined with binders, it is a versatile insulation option with moderate thermal performance.	0.035–0.046 W/mK
Hemp	Valued for its sustainability and moderate insulation capabilities, though it requires protection from moisture.	0.35 W/mK
Banana fibre	A highly efficient insulation material developed from agricultural waste.	0.045 W/mK

Conclusion

This section explored the role of materials and connection systems in enabling reuse within façade construction. The choice of materials significantly impacts the reuse potential, durability, and environmental footprint of a building. When designing reusable façade components, it is important to carefully consider which materials and connections can be used to ensure reusability. While this itself may not be a major challenge, integrating all elements into a single component can be difficult, as façade details often contain adhesives and foils that are hard to reuse and disassemble.
While materials such as steel and timber offer high recyclability and reuse potential, challenges remain in their dismantling, storage, and economic feasibility. However, when done carefully, these challenges can be minimized. Additionally, more resale platforms continue to emerge each year so sourcing old materials will be more profitable.

Connections are equally critical in circular design. Dry construction methods, such as bolted, clamped, and mechanical fastening systems enable easy disassembly and reuse, while traditional welded and adhesive-based connections hinder material recovery and shorten the lifespan of building components.

Circular insulation can be achieved in two ways: by keeping it in the technical cycle or the biological cycle. Although it is possible to keep stone wool or synthetic insulation in the technical cycle, it can be challenging. When reusing these types of insulation, they gradually lose their mechanical performance over time and may no longer meet current standards. Bio-based insulation materials provide an alternative with a lower environmental impact, though they require careful moisture protection to maintain performance. After their service life, they can be composted or burned, closing the biological loop, unlike artificial insulators, which often end up in landfills.

3 DESIGN PROCESS

Developing a circular and adaptable prefabricated façade system requires a structured design approach that integrates circularity principles, modular construction techniques and adaptability to different facade layouts. This chapter outlines the design framework, case study selection and the iterative design process. Using insights from the literature review, preliminary designs will be developed and evaluated based on their adaptability, disassemblability and environmental impact. The goal is to create a façade system that not only meets modern energy and sustainability requirements but also facilitates future reuse and refurbishment.

Fig. 24 - Fuutstraat Nijmegen (Own image, 2025)

3.1 Framework

The framework evaluates materials for various circular façade designs based on fixed and variable factors. Fixed criteria that are based on regulations and architectural style cannot be chosen. While variable factors that derived from CE, DfD, and sustainability can. The options are ranked from 0 to 4, with the most sustainable choice scoring 0 points. A material scoring high in one category must score lower in others to remain viable. The ranking is shown in the framework diagram. Each material is individually assessed, and total scores reveal which systems are more suitable for DfD and are more sustainable.

Fixed criteria

Renovation level

The renovation level will be refurbishment. This means modernise and update old products, often by replacing parts. In this case that means that the old façade of the case study dwelling will be removed and the load bearing construction will remain in place. The cladding, insulation and windows will be part of the new system. The new façade will be a single component that has been prefabricated in a factory. The design will follow the DfD principles and connections should be easy to find. Additionally, he façade elements must be prefabricated so they can be applied on a large scale on different projects.

Regulations

The thermal performance of the façade will meet the standard for newly built houses in the Netherlands. This means the R-value of the façade system will be 4,7 m2 K/W. The windows will have an average U-value of 1,65 W/m² K (Besluit bouwwerken leefomgeving, 2021). The façade system must be designed to ensure structural stability and durability. It should withstand wind loads, moisture exposure and thermal expansion without compromising performance. The new prefabricated façade components will be securely attached to the existing load-bearing structure, ensuring a safe and reliable renovation solution. The case study houses also relate to the regulation that buildings lower than 13 meters must have a façade that meets at least fire class D according to NEN-EN 13501-1 (Overheid.nl, 2025).

Variable criteria

Cycle

When discussing circularity, there are two cycles: the technical cycle and the biological cycle. The biological cycle focuses on returning products to the environment, while the technical cycle ensures that products or materials are reintegrated into the system at various stages of their life cycle (Ellen MacArthur Foundation, 2021). Materials within the technical cycle receive 1 point because their production emits CO2, whereas biological materials withdraw CO_2 as they grow.

CO_2 emissions

The material pyramid in Chapter 2.4 indicates the CO_2 emissions. A higher position on the pyramid means that it has a greater environmental impact. The materials are divided into four sections: CO_2-absorbing materials, then materials that produce between 0-100 kg CO2, 100-1000 kg CO2 and more than 1000 kg CO2 per m3. The top scores 3 points and the bottom 0.

End-of-life

At the end of a material's life-cycle, it can follow one of five disposal routes, each with a different environmental impact. The least sustainable option is land filling, which receives 4 points. Burning the material for energy recovery is slightly better but still results in CO_2 emissions, earning 3 points. Recycling the material allows it to be repurposed, reducing waste and saving resources, which is why it receives 2 points. Using the material as compost ranks even better at 1 point. The most sustainable option is reusing the material in another building, which preserves its value and eliminates waste, earning 0 points.

Service life

The service life of a material plays a crucial role in sustainability. If a material lasts less than 50 years, it receives 2 points, as frequent replacement increases resource consumption. A lifespan between 50 and 75 years is moderately sustainable and is assigned 1 point. Materials that last more than 75 years are the most environmentally friendly, reducing the need for replacements and resource extraction, and therefore receive 0 points.

Connections

The way materials are connected affects their reusability and ease of disassembly. Connections that can be done by hand allow for complete reuse without damage, earning 0 points. Bolted connections receive 1 point because they can be reused in the same way but require tools for disassembly. Screwed connections leave holes in the material, which can limit reusability and result in a loss of quality, leading to a score of 2 points. Wet or solid connections, such as glued or cemented joints, are the least favourable, as they make reuse complicated and labour-intensive, with a high chance of material loss. Therefore, these types of connections receive 3 points.

Price

The cost of materials can vary significantly and influences the feasibility of sustainable choices. Materials can be categorized into three price levels: cheap, regular, and expensive. While cost is not directly linked to sustainability in the same way as other criteria, it remains an important factor in decision-making.

Adaptability

The ease with which a material can adapt to different façade layouts plays a crucial role in its ability to be produced on a large scale while still fitting various types of houses. For instance, soft insulation is more adaptable than rigid insulation as it can form around shapes. Similarly, small cladding panels are preferable to large sheets, which require more modifications to fit specific layouts. The adaptability is categorized into three levels. Materials that can be easily adapted to any layout receive 0 points, as they offer the highest flexibility. Those with medium adaptability are assigned 1 point. Materials that only fit a single setup, such as large plates with a specific shape, receive 2 points due to their limited adaptability.

Reusability

When materials have not reached their end of service yet and can be reused more than 3 times they will not receive any points. Materials that can be reused between 1 and 3 times receive 1 point. If a material cannot be reused at all, it is assigned 2 points.

FRAMEWORK

SUBJECT	RANGE				
Cycle					
CO_2 emissions	>1k	100 - 1k	0 - 100	<0	
End-of-life					
Service life	<50	50 - 75	>75		
Connections					
Price	€€€	€€	€		
Adaptability					
Reusability	<1	1 - 3	>3		

First icon = 0 points
Each step = +1 point

3.2 Case study

The design of the renovation system will be tested on two different façade layouts. The selected buildings are row houses that no longer meet current regulations and standards. The chosen row house should also be representative of the average row house in the Netherlands, meaning it should have a masonry wall and not exceed three stories in height.

To ensure easy access to construction drawings, the municipality of Nijmegen was selected. The row houses on Fuutstraat were chosen because the façades on one side of the street differ from those on the other. If these buildings were to be renovated in the future, both sides of the street would likely be renovated simultaneously or at around the same time. This means the prefabricated façade system must be easily adaptable to different façade layouts; otherwise, manufacturing them in the same factory would be more challenging. In this sense, Fuutstraat provides a strong test case for the adaptability of the system.

Fig. 25 - Fuutstraat during construction (Commissariaat van Politie Nijmegen, Afd. Fotografie, 1949)

Fig. 26 - Fuutstraat now (Own image)

History

During the second World War, Nijmegen suffered heavy destruction, first from an allied bombing in February 1944 and later from fires set by retreating German troops. The reconstruction of the city centre was the municipality's absolute priority, resulting in less attention to addressing the severe housing shortage. The actual reconstruction, which began in 1947, initially progressed very slowly due to a lack of funds and building materials. The major construction boom only started in 1952, after the national government approved the municipal plans and additional funding became available. As a result, the architecture of early post-war housing was mostly traditional and simple. Because the municipality lacked a coherent expansion plan, new housing developments in the late 1940s and early 1950s were scattered across various open areas on the outskirts of the city, including in the Wolfskuil, the neighbourhood of the case study dwellings (Roodenburg, 2004). The post-war houses in the Wolfskuil were part of a 217-home complex between Marialaan and Oude Heselaan, designed by architect L.D. Kuipers. Projects like these marked a significant step in addressing the housing shortage following the war. In this neighbourhood, the completion of the 1,000th post-war home was celebrated as a major milestone in the city's reconstruction. (De Gelderlander, 1948).

Materials

The sloped roof consists of a tiled covering supported by wooden purlins. The second-floor structure is made up of a wooden beam layer, while the first floor features a combination of a wooden beam layer and a partially hollow brick floor. The foundation is composed of concrete strip footings on soil, while the basement itself is constructed with masonry foundation walls. The load bearing walls in the basement are made from a concrete based stone while the load bearing walls above ground are made from regular bricks. The exterior walls are made of exposed masonry.

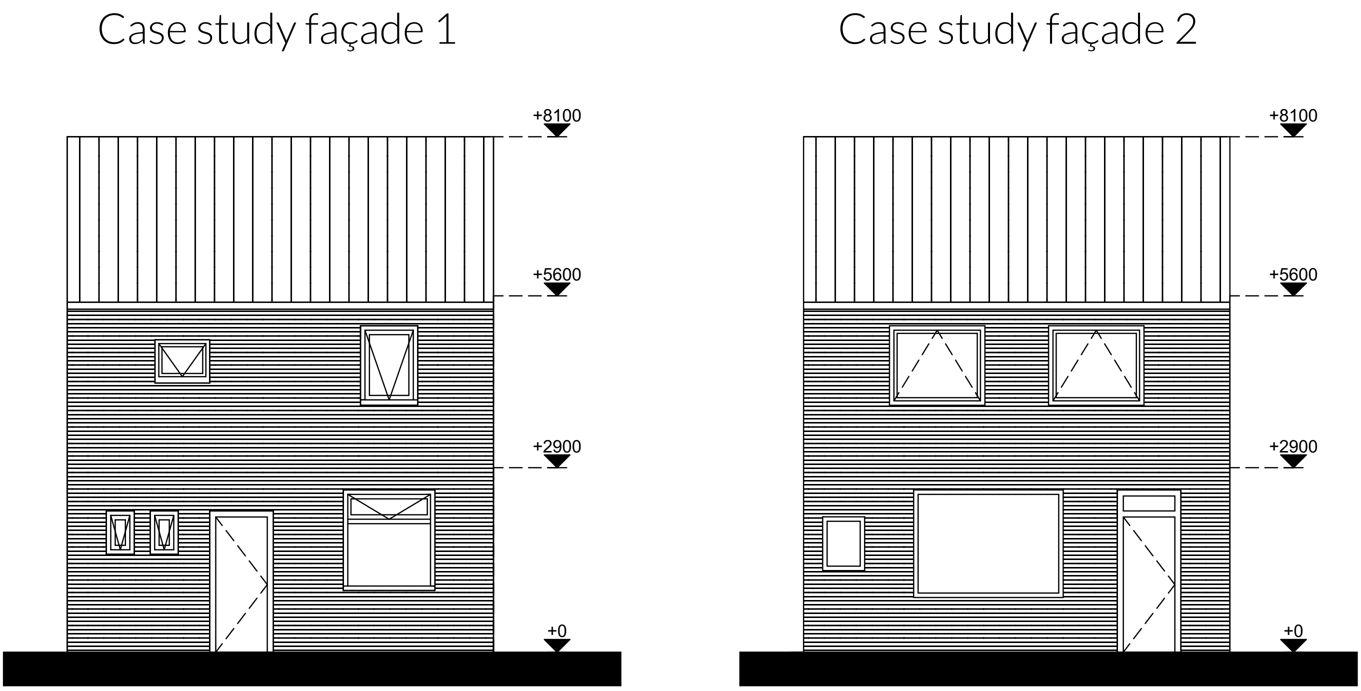


Fig. 27 - Drawings of case study facade 1 & 2 (Own drawing)

Fig. 28 - Photo's of case study façade 1 & 2 (Own image)


3.3 Preliminary designs

The goal is to create a façade system that meets modern energy and sustainability requirements while enabling future reuse and refurbishment. Multiple designs will be developed, each emphasising a different theme: bio-based materials, material reduction, and reuse. All designs will incorporate materials researched in the literature review. The framework will serve as a guiding tool throughout the design process, ensuring that less sustainable options are avoided in favour of those with lower scores. This means that non-reusable and costly materials are less likely to be included in a preliminary designs.

Once a preliminary façade design is completed, it will undergo evaluation. Each system consists of multiple layers and each layer will be assessed using the framework. This evaluation is not final but helps steer the design in the right direction. For instance, a bio-based material that absorbs CO_2 may score well in one category but, if unsuitable for reuse and performing poorly in other areas, it is unlikely to be selected for the final design.

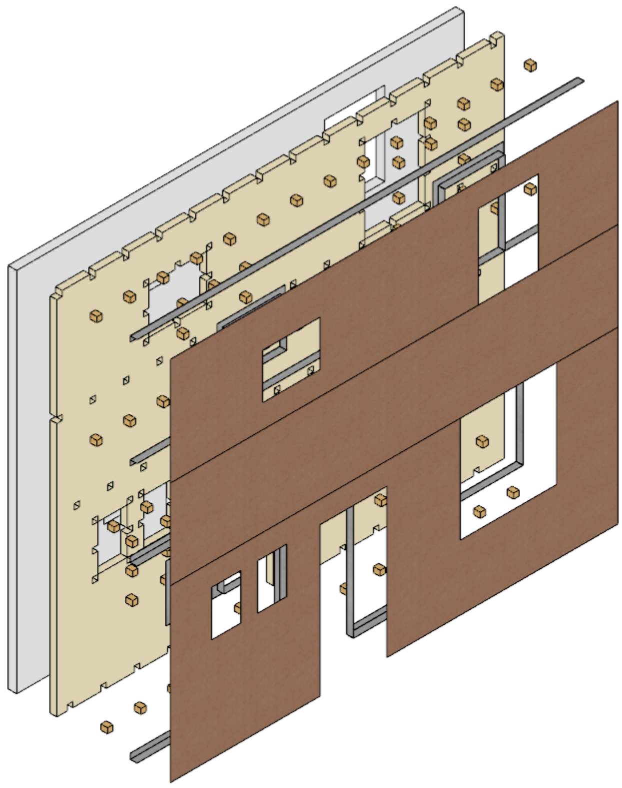
The designs will first be developed for Case Study façade 1. Basic designs consisting of the main layers will be created and assessed using the framework, after which necessary adjustments will be made. Once refined, the designs will be tested on the second case study façade as a scenario-planning exercise to evaluate their reusability. In this scenario-planning exercise, the façades will be used for 30 years on the first façade and then reused on the second façade. This will help identify the necessary changes to facilitate component and material reuse, as well as determine whether entire components can be reused or only parts.

The final design will be selected as the best option among the preliminary designs. It will then be finalised and made technically correct. Its evaluation will be conducted in the next chapter using various methods to quantify circularity, including a LCA, MCI, and the 3DR method.

Design 1 material reduction

This design has been created with the intention of saving as much material as possible, which in turn will reduce CO_2 emissions. All the layers are made from thin and lightweight materials. For instance, the cladding consists of a thin layer of façade fabric and the supporting structure is made from small timber blocks instead of beams. These timber blocks are also more adaptable to different types of façades since they do not need to be cut to size like the beams would.

Fig. 29 - Examples with facade fabric cladding (source: Buitink-Technology, n.d.)



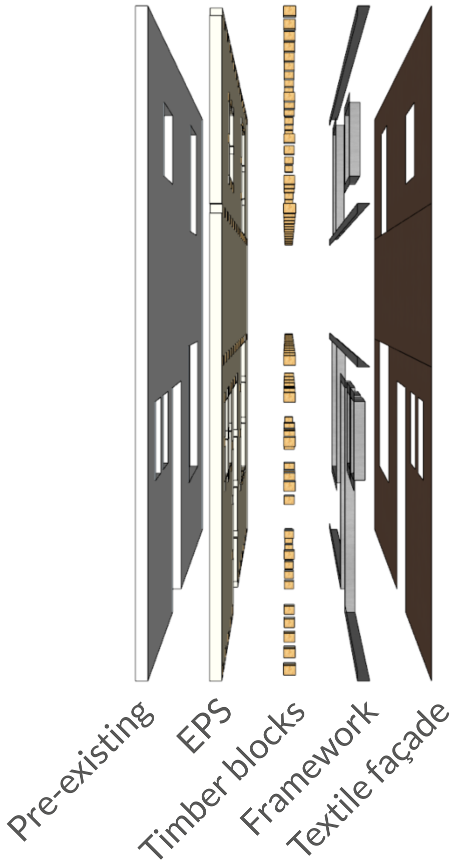


Fig. 30 - Exploded views of the reduced material design variant

Cladding

The façade fabric cladding consists out of a thin PVC-treated polyester mesh than can last for decades. It can be applied permanently, but it is also easy to disassemble and reinstall at a different location (Buitink-Technology, n.d.). However, the fabric consists of rather large panels that are cut to specific sizes, making reuse for different layouts challenging. Therefore, it is more practical to recycle the fabric after use rather than reinstall it elsewhere.

Cladding supporting structure

Aluminium clamping frames hold the textile façade in place and can be reused. However, the construction time will be extended, as the profiles need to be measured and cut to size. This process will inevitably leave small pieces that cannot be reused. When that happens, aluminium can be melted down and recycled while retaining its original properties.

Structure

The structure will consist of small timber blocks instead of beams to save material. This will also reduce thermal bridges. However, transporting the prefabricated façade system as a whole component will be more challenging.

Insulation

Expanded Polystyrene (EPS) consists out of 98% air and offers one of the best insulating properties on the market, with a thermal conductivity of 0.031 W/mK. Composed solely of polystyrene, EPS is an ideal material for recycling. Its production does not require harmful additives, making it an environmentally responsible choice. Some companies offer complete turnkey solutions, ensuring that EPS products can be taken back and recycled in a closed-loop system. Beyond its insulating performance and ability to be recycled, EPS also has other practical advantages: It can be molded into almost any shape, it does not absorb water, preventing moisture-related issues and it does not provide a breeding ground for plants, grass or moss (Kingspan, n.d.).

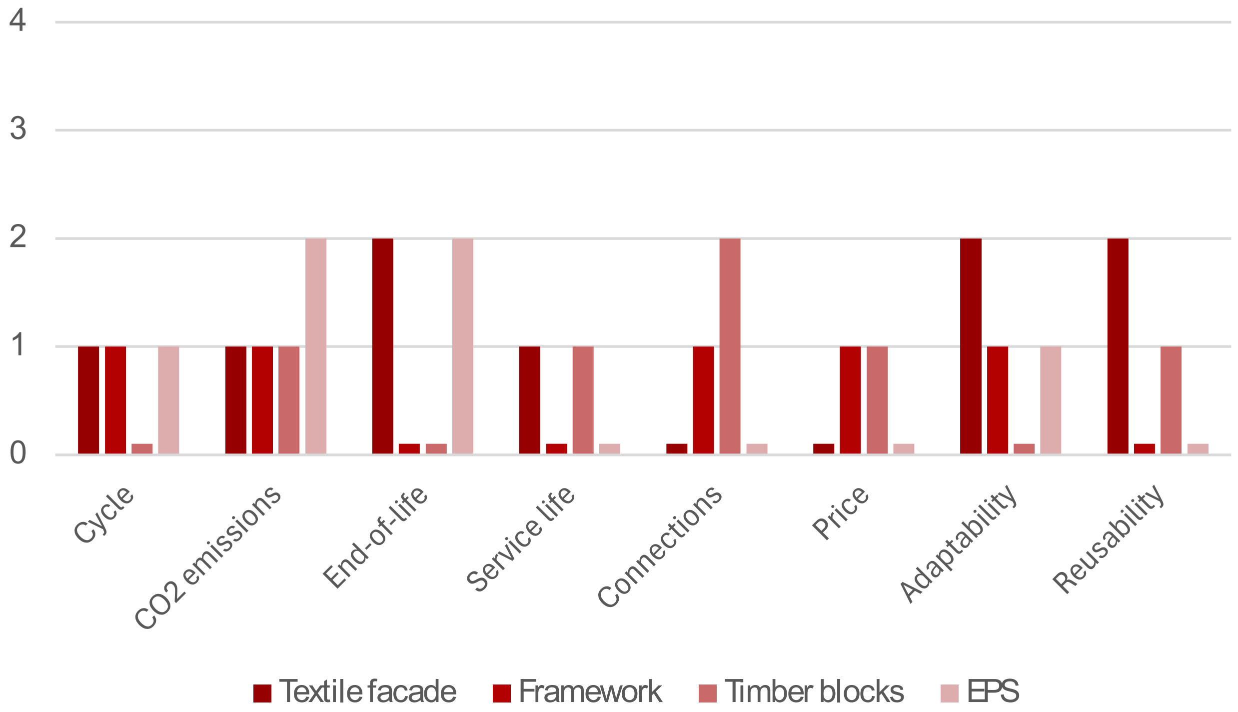


Fig. 33 - Graph that shows the points given by the framework, the higher the points the worse the material performs in terms of circularity and emissions (source: own)

Design 2 bio-based

Bio-based materials were the main focus of this design. All the materials used are sourced from renewable biological resources and are biodegradable when untreated. This means they can be used as compost at the end of their life. If not, they can be easily recycled or burned for energy.

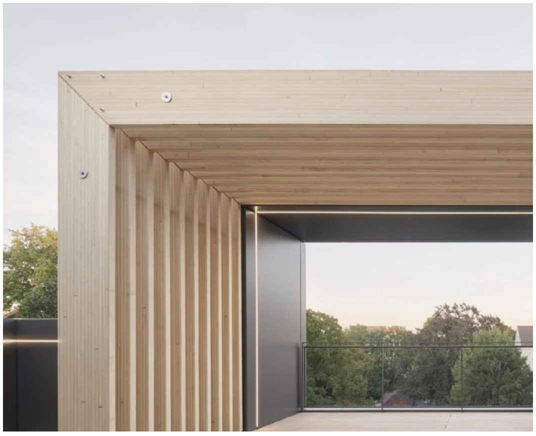
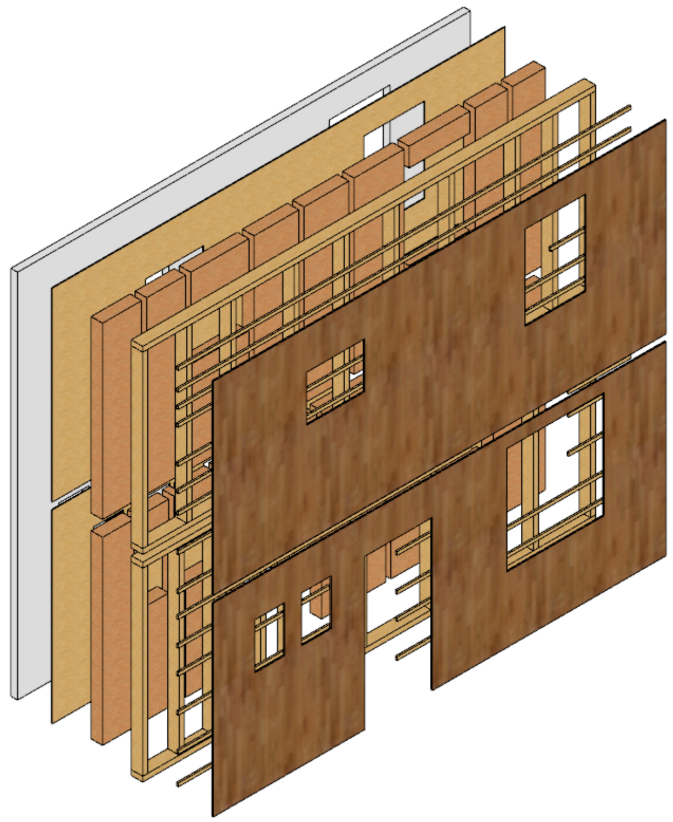


Fig. 31 - Accoya wood (source: Accoya 2023)

Fig. 32 - Flax insulation (source: Bouwmaat 2023)



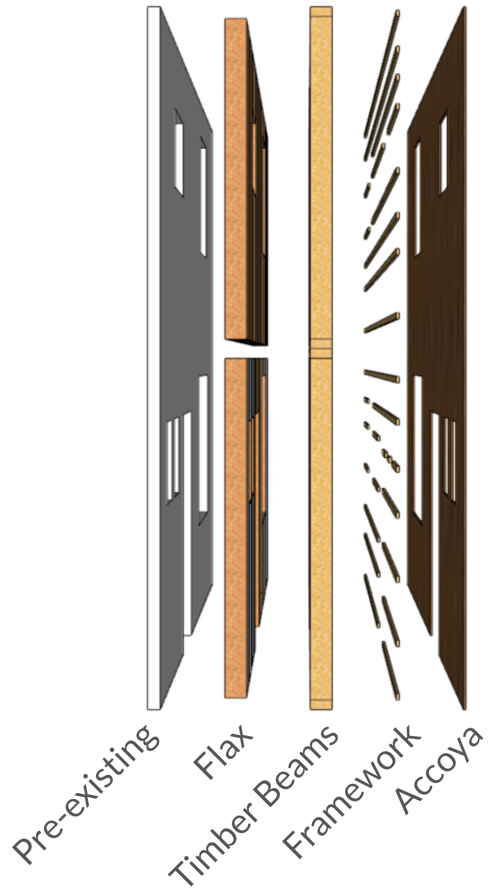


Fig. 34 - Exploded views of the bio-based design variant

Cladding

For the façade, a long-lasting bio-based material will be chosen. This is why chemically treated wood has been selected. During production, its properties are changed, preventing moisture absorption, which makes it much more stable and significantly more durable. It is 100% recyclable because it contains no toxic chemicals and can be disposed of in the same way as unmodified wood (Accoya, 2019). The cladding can be cut to size to fit different façade layouts. However, when an uninterrupted look is desired during reuse, some virgin planks are required when the cladding is adapted to a new façade.

Cladding supporting structure

The traditional way of supporting wooden cladding is by using a wooden framework that uses screws or a nail gun. Another option is the use of a hidden fasting system that uses an aluminium frame. Nails create smaller holes in both the wood and the underlying structure, making it easier to reuse the materials if desired. The hidden fastening system scores highly for reparability, allowing quick and easy replacement of individual boards. Despite these advantages, the increased complexity of the hidden fastening system raises the cost. One other disadvantage of a click system is that it often requires a significant number of aluminium rails and plastic clips to securely install the façade panels. That is why for this design nails with a wooden framework are used.

Structure

Construction timber has an excellent performance-to-weight ratio. Additionally, it can be reused structurally if it has no issues such as cracks, rot, insect damage, or deformation. If it is not treated with chemicals, it can be returned to nature as compost. Otherwise, it can be recycled into particle boards or be burned for energy. The same amount of CO_2 that wood absorbs is emitted into the air when burned (Jones, 2017).

Insulation

Wood fibre and flax insulation both have some of the best insulating properties among all bio-based insulation materials. Isovlas building insulation is treated with a natural fire retardant, making it fire-resistant. This means it has a European fire classification of C while wood firbe insulation has a E classification. It also is cradle-to-cradle recyclable and even compostable. Additionally, it is easy to adjust and fold to fit different shapes and layouts (Isovlas, 2025).

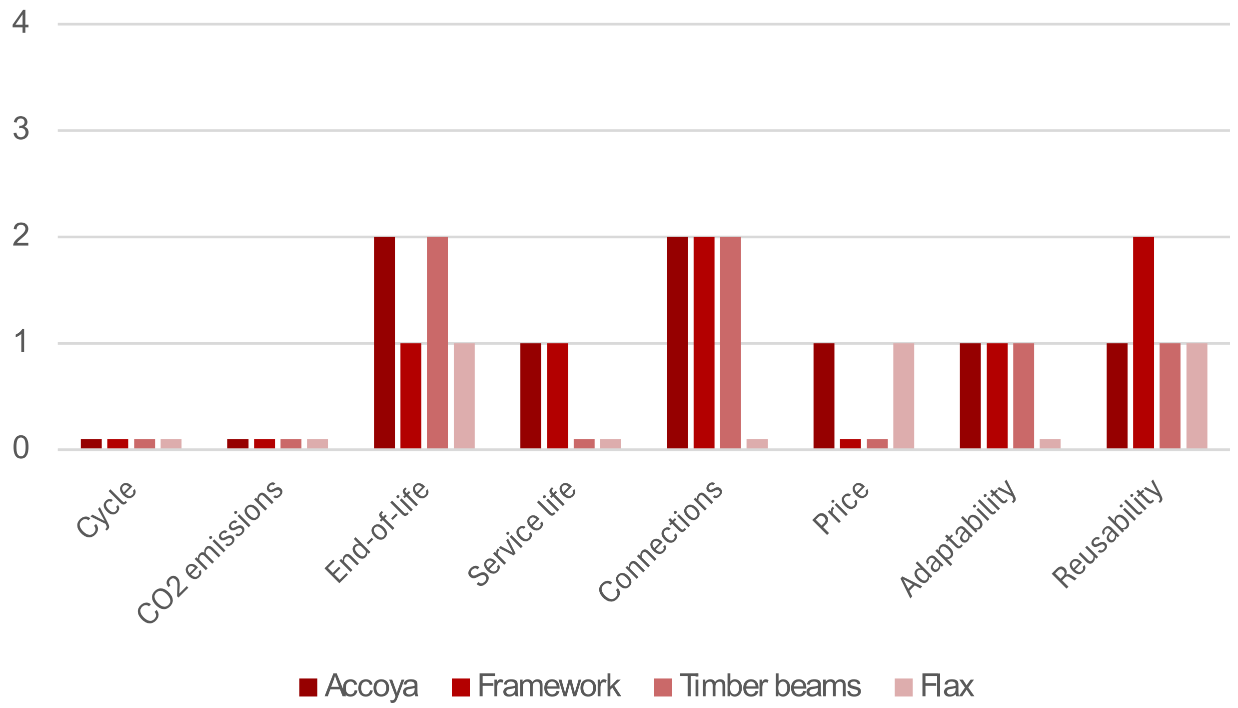


Fig. 35 - Graph that shows the points given by the framework, the higher the points the worse the material performs in terms of circularity and emissions (source: own)

Design 3 Reuse

Reusability is one of the most important aspects of this research study, which is why three designs were created with this subject. This design includes recycled PVC tiles with a aluminium structure. Similar to the design with reduced materials, the structure consists of small elements. However, this time they are made from aluminium, allowing them to be reused more often. The glass wool insulation is placed between the brackets and can easily fit into almost any shape.

Fig. 36 - Pretty Plastic facade, using the 'First one' tiles (source: Pretty Plastic, n.d.)

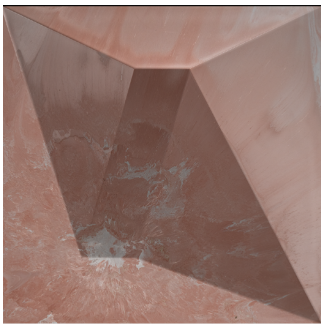
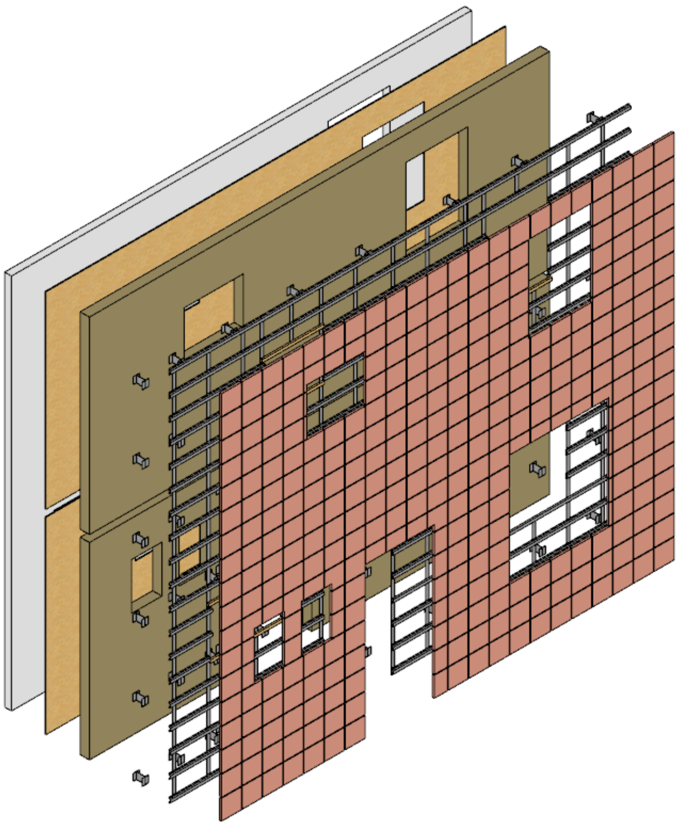


Fig. 37 - Pretty Plastic 'Second high' tile (source: Pretty Plastic, n.d.)



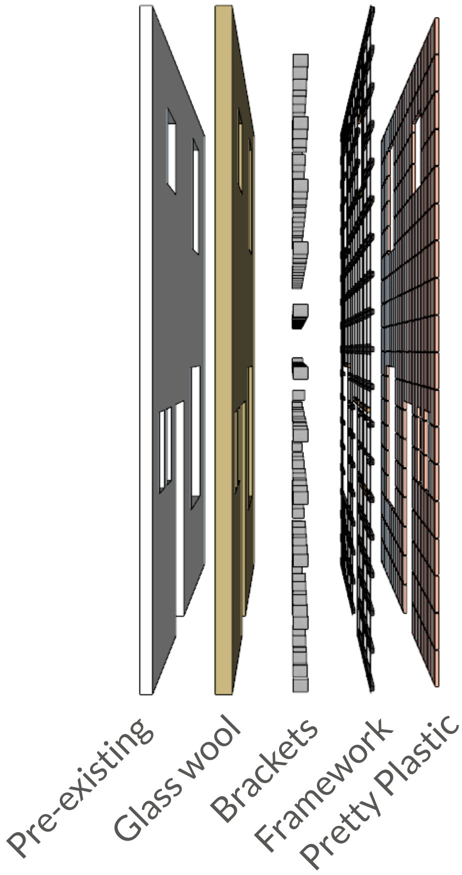


Fig. 38 - Exploded views of the first reuse design variant

Cladding

Pretty Plastic is a sustainable cladding material made entirely from recycled PVC, such as old window frames and rain gutters. Each tile is secured with screws to an underlying wooden or aluminium structure. The tiles can be easily removed and reused in a different location. Their small size makes them adaptable to almost any façade layout. There are three types of tiles. The square one used in this design is called Second High (Pretty Plastic, 2024).

Cladding supporting structure

Aluminium clamps hold the pretty plastic façade tiles in place and can be reused. The clamps are attached to aluminium frames. As stated earlier, they can be reused or recycled as well.

Structure

Aluminium brackets are designed to support the façade and its framework. It can be used with a wide range of cladding materials, including Pretty Plastic tiles, façade textiles and other façade types. To enhance thermal efficiency, thermal breaks are placed between the brackets and the bearing wall, minimizing heat transfer (LeonardoFix, 2024).

Insulation

Glass wool is a cost effective insulation material with a low thermal conductivity, ranging from 0.033 to 0.040 W/mK. Additionally, it offers excellent acoustic insulation, making it a versatile choice for both thermal and soundproofing applications. Glass wool reduces waste since it is largely made from recycled glass. Its lightweight and compressible nature simplifies handling and installation. It also emits less CO_2, is better suited for recycling and is cheaper than stone wool (Streimikiene et al., 2020).

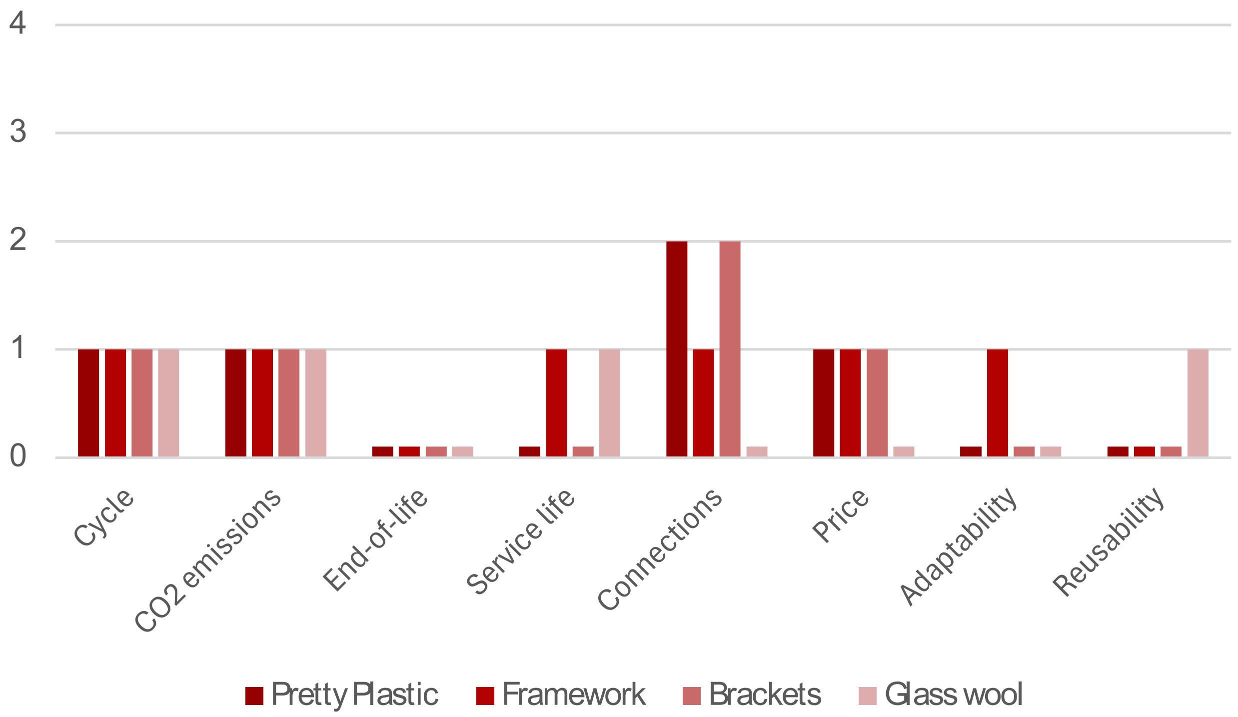


Fig. 39 - Graph that shows the points given by the framework, the higher the points the worse the material performs in terms of circularity and emissions (source: own)

Design 4 Reuse

Brick façades fit well into the Dutch street scape, where brick is widely used. They offer a viable renovation option to maintain architectural consistency, as the buildings were originally clad with bricks. This reuse design features a cavity wall façade system called ClickBricks. This system uses bricks that are connected without mortar and can be disassembled by hand when needed. One big advantage of this design is that the supporting structure of the cladding is directly connected to the bearing wall. This means the design requires one less layer, which saves materials.

Fig. 40 - Connecting ClickBricks to the bearing wall (Wienerberger, 2025)

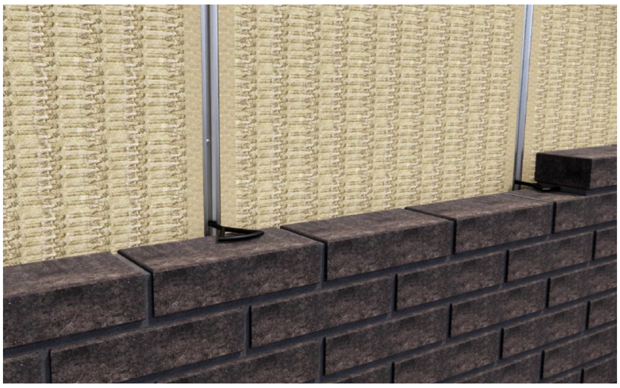


Fig. 41 - Wall ties attached to a rail (Rockwool, 2023)

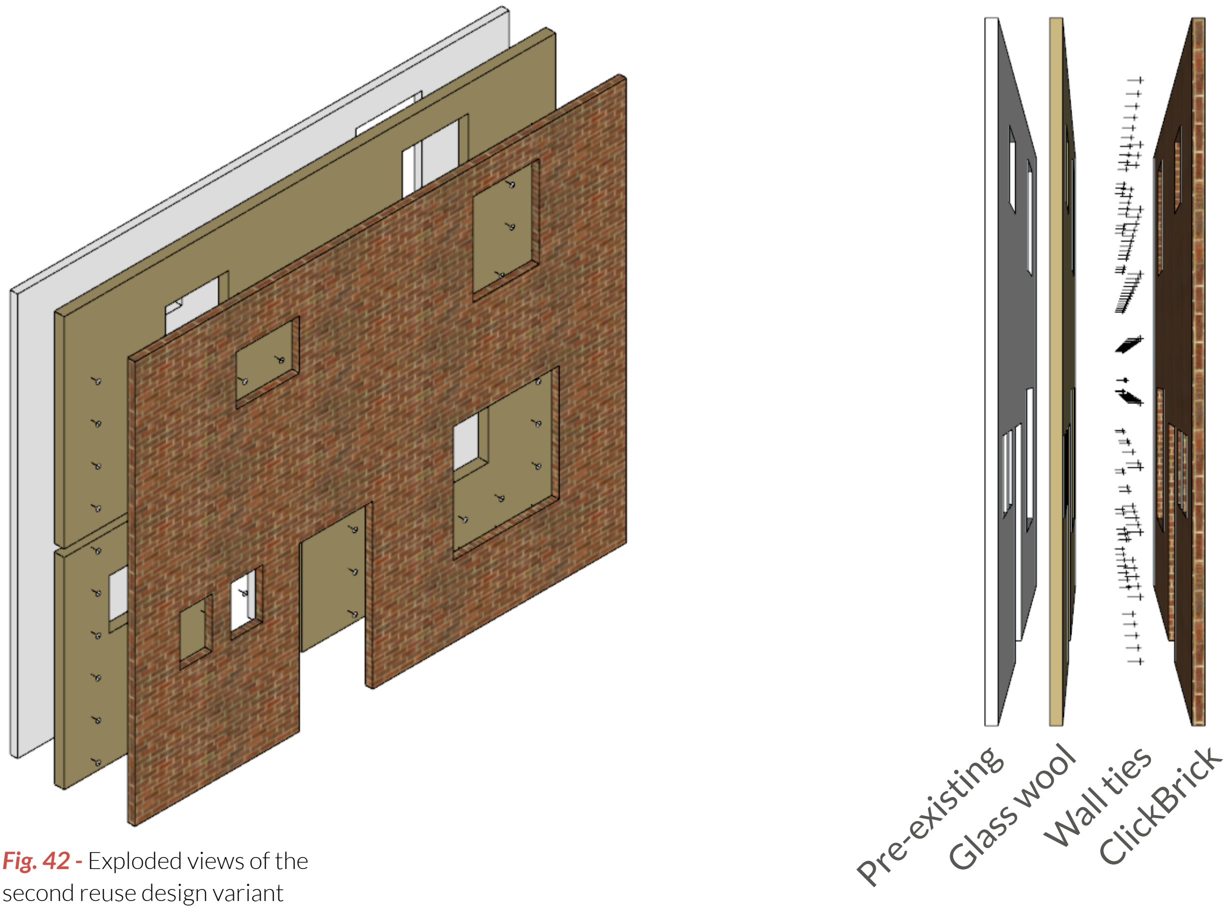


Fig. 42 - Exploded views of the second reuse design variant

Cladding

ClickBrick Pure is a fully circular and dry-stackable brick façade system designed for easy assembly, dismantling and reuse. It eliminates the need for mortar or glue by using a system that includes wall ties and stainless steel clips for secure installation and while also ensuring reusability (Wienerberger, 2025). The cladding is also highly adaptable to any façade layout since it consists of small components.

Insulation

As sated before, glass wool is a cost effective insulation material with a low thermal conductivity. It is suitable for use in a cavity wall in combination with bricks. (Streimikiene et al., 2020).

Cladding supporting structure

Wall ties are used to connect the ClickBrick façade to the load-bearing inner wall. This way, both walls are connected, but the outer wall cannot transfer moisture to the inner wall. The bricks are stacked and secured with clips in between each brick. Cavity ties must be placed in brick grooves at vertical joints, spaced at a maximum of 420 mm horizontally and every six layers vertically, ensuring alignment to prevent pressure issues. About six ties per square meter are required, with additional ties for smaller walls. The final layers of the façade must always include cavity ties. (Wienerberger, 2025). There are also systems where the wall ties are attached to a rail, eliminating the need to drill them into the load-bearing wall (Rockwool, 2023). The graph that shows the points received based on the framework uses common wall ties instead of those from Rockwool.

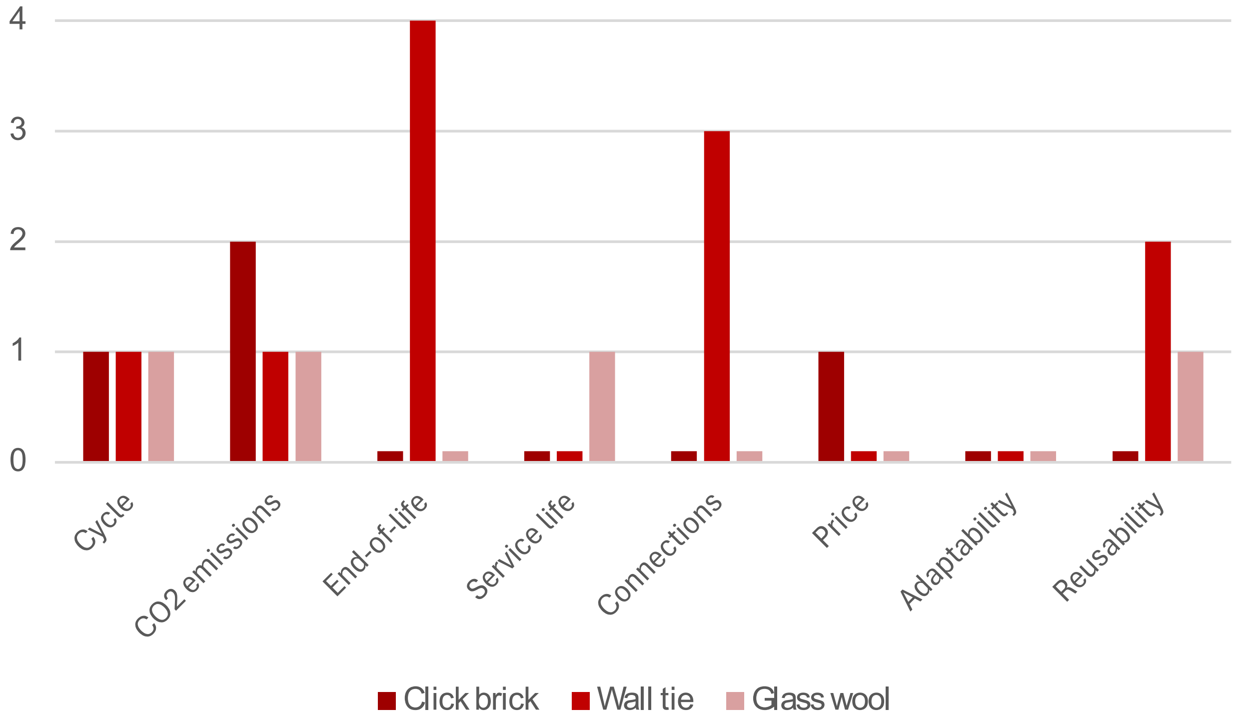


Fig. 45 - Graph that shows the points given by the framework, the higher the points the worse the material performs in terms of circularity and emissions (source: own)

Design 5 Reuse

The last design uses the original bricks for the cladding, which helps preserve existing materials and reduces construction waste during the renovation of the case houses. This approach supports sustainability by minimising the need for new resources. It also helps maintain the architectural style and visual continuity of the street, allowing the updated homes to blend naturally with their surroundings. In addition, reusing bricks can lower renovation costs and simplify the building process.

Fig. 44 - Prefabricated façade components with concrete and insulation (Lendager, 2019)

Fig. 43 - System to recover the bricks from donor building (Reconstructing The World, 2024)

Reusing bricks and other building materials has been practiced for centuries. There is a 40% reduction in CO_2 emissions compared to using new bricks. Bricks can be reused individually, but they can also be reused as entire façade elements. Lendager and Rijksvastgoedbedrijf explored this technique, where entire slabs are cut from a donor building and then strengthened with concrete on the back. This is mainly due to contractors wanting to ensure that no cracks will appear in the future. Smaller buildings do not require concrete on the back (Reconstructing The World, 2024). For the case study houses, there is no need for a donor building. The slabs can be cut on-site and reinstalled at a later stage. This can be done with wall ties on-site or as a prefabricated slab with insulation already in place.

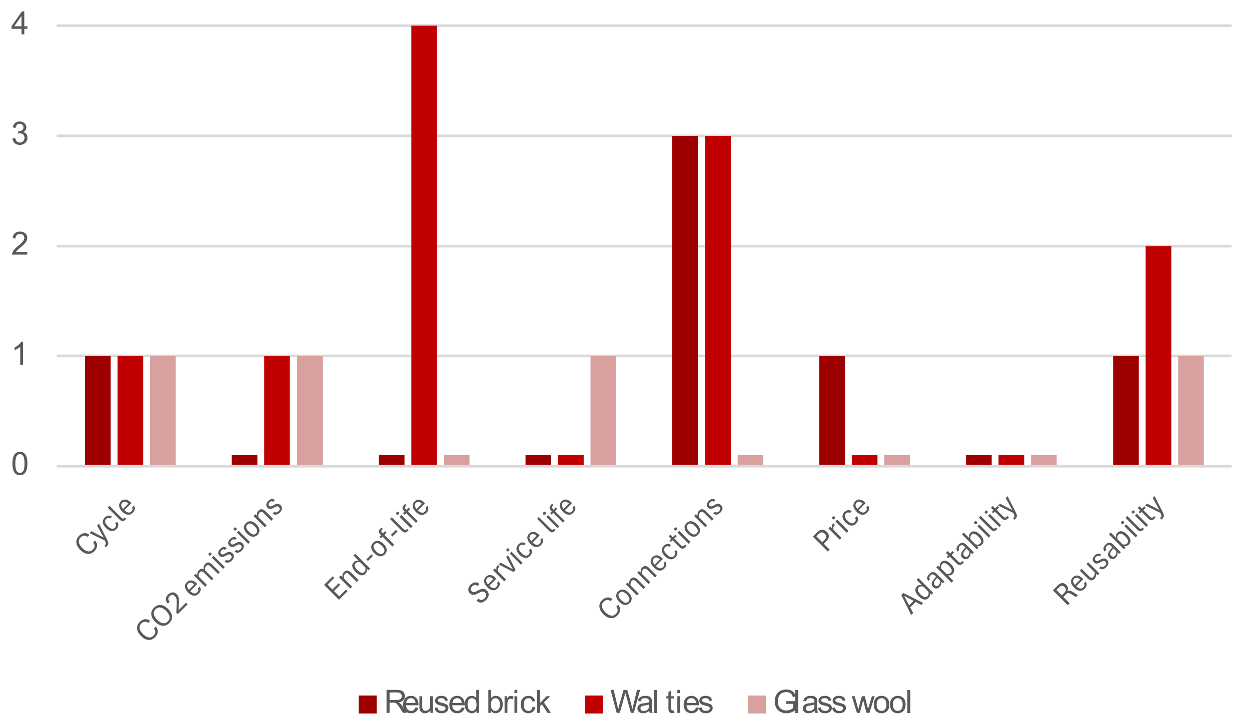


Fig. 46 - Graph that shows the points given by the framework, the higher the points the worse the material performs in terms of circularity and emissions (source: own)

Conclusion

When designing the different variants, it became clear which materials emit more CO_2 and which ones are worse for reuse. The framework output on the next page shows how all the materials perform. The more often a material appears on the left side of the framework, the less likely it will be chosen for future designs. Materials on the right side are better for the environment and more suitable for reuse.

The choice of where to place a material within the framework is mostly based on the information provided by the manufacturer. Cost considerations are based on the average cost of the material group (e.g., structure, insulation, cladding). Adaptability is assessed based on whether the material needs to be cut extensively, not at all, or if the product is not designed to be adapted to a second façade. Finally, reusability is determined by the material's resilience. Stronger materials that are resistant to rotting score higher, while materials that lack adaptability or rely on chemical bonds score lower.

Wall ties, for instance, do not perform very well in the framework. However, with a few alterations, such as using wall ties on a rail that can be reused, they may be selected for future designs. On the other hand, a textile façade is harder to modify, and such cladding is not very adaptable because it is made for a specific façade layout.

Adaptability and the potential for reuse are especially important. The materials that score the highest in these areas are ClickBrick, PrettyPlastic and aluminium brackets. This is why one version contains a main structure using aluminium brackets. Another version will contain timber beams and the two will be compared based on their reusability, CO_2 emissions and other subjects. Also in the next chapter they will be evaluated side by side.

To ensure the façade system is suitable for various contexts, three types of cladding will be used: ClickBrick, Pretty Plastic and Accoya. ClickBrick performs well in terms of adaptability and reusability while it also aligns well with the existing street appearance. Pretty Plastic is similarly adaptable and reusable due to its small panel size. However, unlike ClickBrick, it is made from 100% recycled material, whereas ClickBrick is made from virgin materials and has a relatively high CO_2 footprint during production. Accoya, on the other hand, performs strongly in terms of low CO_2 emissions, end-of-life potential and cost-effectiveness.

Rigid insulation materials made from non-natural, non-breathable substances such as EPS, PIR, PUR, rock wool and glass wool pose a risk of internal condensation, which can lead to mold formation and an unhealthy indoor climate. That is why in those constructions often vapour-proof foils are used. In contrast, natural insulation materials, such as flax, have a breathable moisture regulation due to their fibre structure. This prevents condensation by adjusting moisture absorption and release according to the surrounding environment. Additionally, it is short-cycle renewable, absorbs CO_2 when growing, contains no harmful particles, is recyclable and has a lifespan of more than 75 years thanks to self-healing fibres that do not degrade (Isovlas, 2017).

FRAMEWORK OUTPUT

SUBJECT	RANGE
Cycle	
CO2 emissions	>1k · 100 - 1k · 0 - 100 · <0
End-of-life	
Service life	<50 · 50 - 75 · >75
Connections	
Price	€€€ · €€ · €
Adaptability	
Reusability	<1 · 1 - 3 · >3

Cladding

- ClickBrick
- Pretty plastic
- Accoya
- Textile façade

Cladding structure

- Timber frame
- Aluminium frame
- Wall ties

Main structure

- Timber beams
- Timber blocks
- Aluminium brackets

Insulation

- Flax
- Glass wool
- EPS

3.4 Revised designs

In the previous chapter it became clear which materials are most suitable for the design of the façade systems. Adaptability and reuse potential are key considerations in the façade system design. The best-performing materials in these areas are ClickBrick, Pretty Plastic and aluminium brackets. The two overall best performing structural versions are a aluminium bracket variant and a timber beam variant. Three cladding types will be used: ClickBrick, Pretty Plastic and Accoya. The focus in this chapter shifts to industrialisation, transport, reusability and force calculations.

Industrialisation

The initial designs primarily focused on materials and how they connect to each other. The next step explores how the façades can be manufactured in a factory and later be transported. To simplify transport and construction, the ground-floor and first-floor façade systems are designed as separate elements. The new designs focus on the ground floor, as it is more challenging due to the door opening, making it less rigid than the first-floor façade.

The revised design of the 'bio-based' variant consists of a timber frame with flax insulation between the beams. An OSB board at the back prevents the insulation from falling out and provides stability to the façade element. The wooden cladding is attached to a timber framework, which is then connected to the timber frame beams.

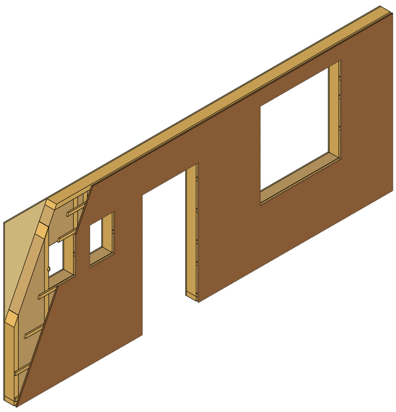


Fig. 47 - Bio-based variant

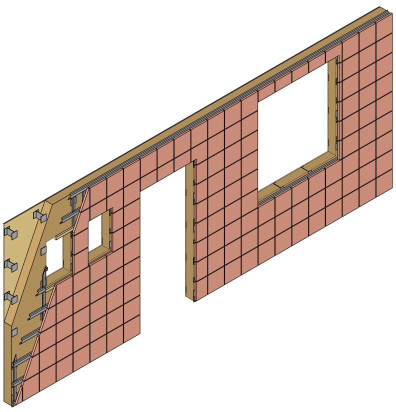


Fig. 48 - Reuse varaint with Pretty Plastic cladding

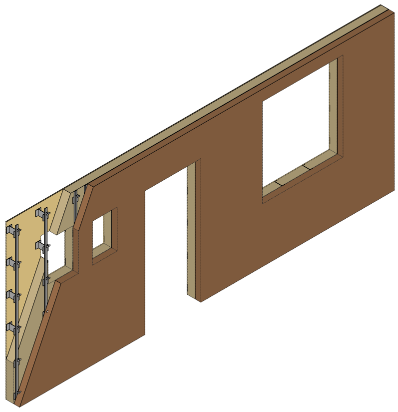


Fig. 49 - Reuse variant with ClickBrick cladding

The structure of the reusable variants consists of aluminium brackets that connect the OSB board to the cladding, forming a single rigid element. A layer of flax insulation is placed between the brackets. A significant difference between the 'bio-based' variant and the 'reusable' variants is that the stiffness of the 'reusable' façade system comes entirely from the OSB board, as there are no columns or beams but only brackets. This design minimises material use, enhances reusability, and allows adaptability to various façade layouts. Aluminium rails are attached to the aluminium brackets to hold the façade in place. The aluminium brackets are placed 600 mm apart to comply to the assembly instructions of the different cladding types. The brick façade will be constructed on-site, as its brittleness and weight make it difficult to transport.

Reusability

Another key design consideration is ensuring that the façade can be reused. The materials were selected primarily for their reusability. The next step is to determine whether the façade can be reused as a whole or in large sections rather than just at the material level.

Standardised elements

The first alternative design consisted of standardised plywood panels with aluminium brackets to support the cladding. However, this approach presented challenges, as not all houses are identical. As a result, in addition to standardised elements, custom components are also required. Eventually, when reusing the façade, you are left with a collection of custom parts that are less likely to fit another building. These components then need to be recycled instead of being reused. Determining which panels are compatible and which are not can be time-consuming. Finally, rigidly connecting various elements requires additional materials and extra steps.

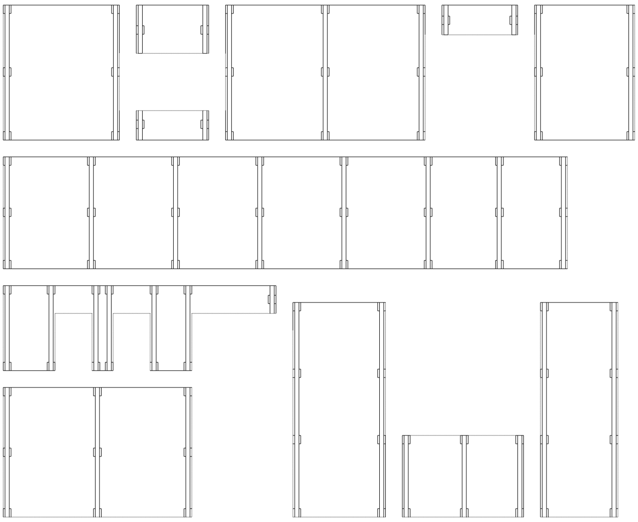


Fig. 50 - Standardised elements separated

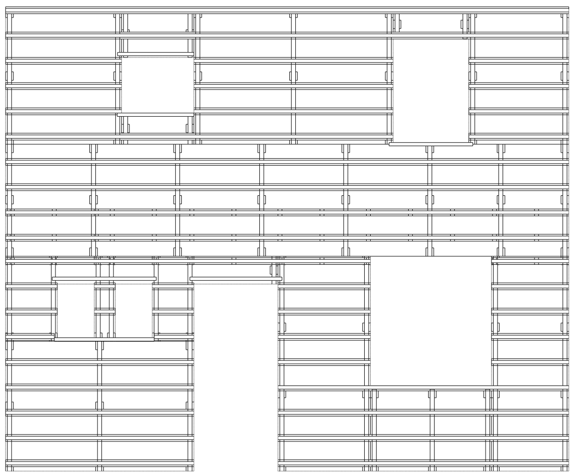


Fig. 51 - Standardised elements connected

Timber frame

The second design option is the use of a more conventional timber frame. Timber frame construction is a building method that uses wooden structural elements, they can be combined with insulation and finishing layers to create complete wall, floor, and roof sections. Parties like Friesland prefab produce theses elements in a controlled factory setting, ensuring consistent quality and efficient assembly. The different elements in this case are connected with a nail gun but they can also be attached using screws (Friesland Prefab, n.d.).

Nails do not leave large holes when removed, but they can be difficult to extract. Therefore, reversibility can be improved by using reversible connections. Woodinc, for instance, designed a system called STRUCTUREZ, which uses precise, prefabricated wooden elements connected with metal joinery designed for quick assembly and easy disassembly. These connections are both strong and reversible, by using drive pins, allowing components to be reused (Woodinc, n.d.).

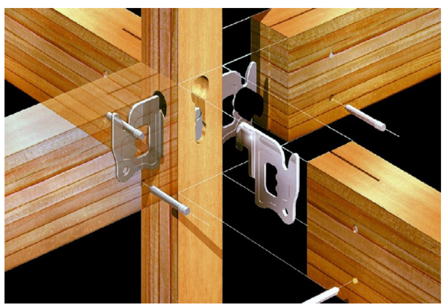


Fig. 52 - Reversable steel 'STRUCTUREZ' connections (Woodinc, n.d.)

Fig. 53 - Prefabricated timber frame structure (Friesland Prefab, n.d.)

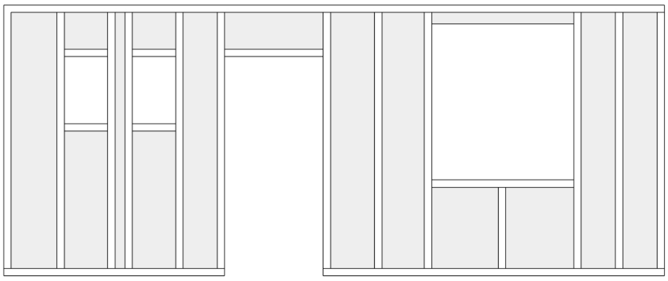


Fig. 54 - Timber frame structure layout on the first case study facade

Plywood-aluminium frame

The third design focused on a standardised frame structure with a reduced material approach. Instead of covering the entire façade with wooden boards, only small sections are covered. The frame consists of horizontal plywood planks connected to the existing load-bearing wall, with aluminium brackets attaching them to vertical plywood planks. The vertical planks hold the cladding and a timber framework can be added if necessary to accommodate vertical wooden cladding. The planks are 100 mm wide and the brackets dimensions are 100 x 100 x 135 mm. The 135 mm depends on the thickness of the insulation.

If the façade element needs to be reused on a new building, the planks can be repositioned to create new openings. The drawing on the next page shows how the planks are transferred from one façade to another. The height is the same so the vertical planks only need to be moved. Due to the size differences of the windows, some horizontal planks need to be cut to different lengths. This results in a small amount of material loss, which is still less than when using boards or standardised panels, as previously discussed. The parts highlighted in green indicate which materials are made from virgin resources. The rest can be reused from the previous façade.

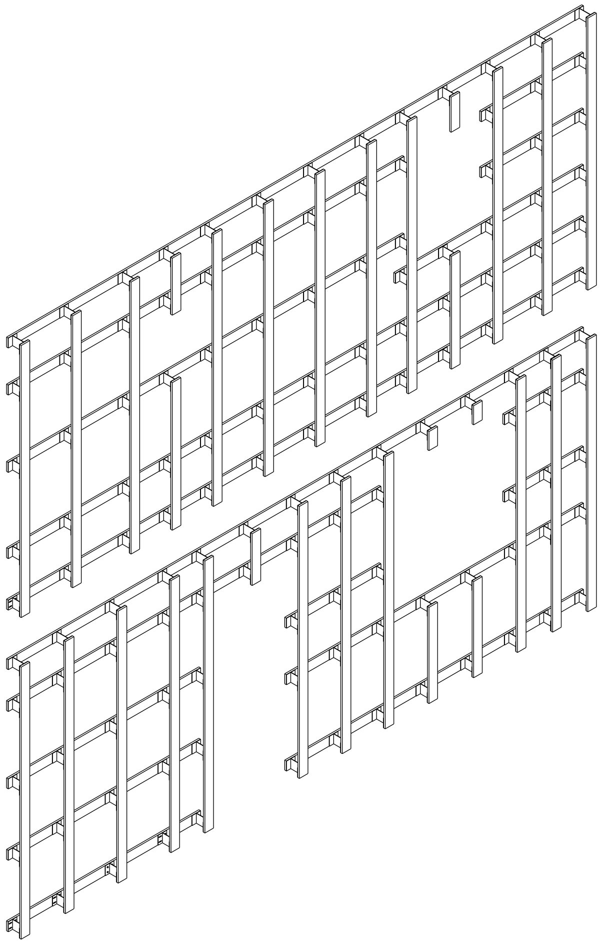


Fig. 55 - Plywood-aluminium structure layout on the first case study facade

To increase adaptability, pre-drilled holes in the plywood were considered. The holes, in combination with the slits in the brackets, would allow the brackets to be placed anywhere on the planks. Since the holes are already there, the only step required is to place the nuts and bolts to connect the planks and brackets. However, pre-drilled holes can make the timber more brittle. Additionally, this step might be somewhat redundant. Another disadvantage of using bolts and nuts is that they protrude from the wood, making the installation of frames and profiles for the cladding more difficult. They can be recessed, but this adds another step and further weakens the wood.

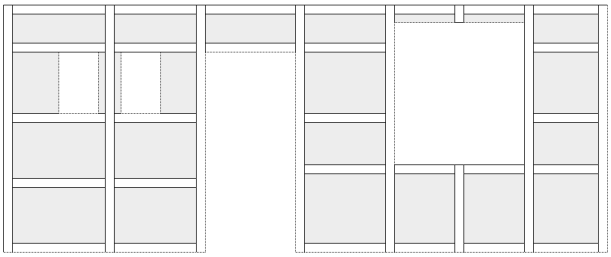


Fig. 58 - Plywood-aluminium structure layout on the first case study facade

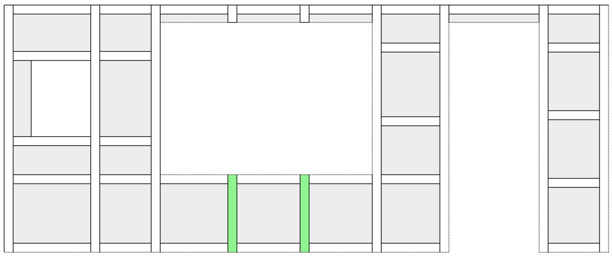


Fig. 59 - Plywood-aluminium structure layout on the second case study facade

If bolts and nuts are replaced with screws, the same hole cannot be reused, as it would be less structurally sound. However, four holes per side in the brackets allow them to be placed in the same location without needing to use the same holes in the plywood. Normally, brackets are designed with slits to allow for tolerance, but since the façade elements are manufactured in a factory, this is not necessary. At the same time, these holes provide a stronger connection, preventing the bracket from moving.

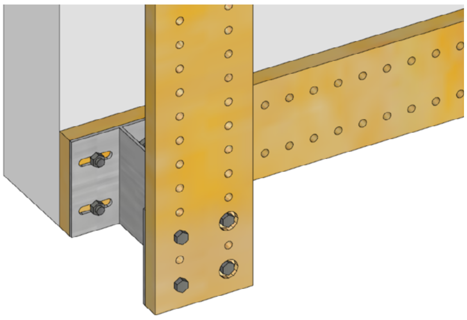


Fig. 56 - Brackets with nuts and bolts

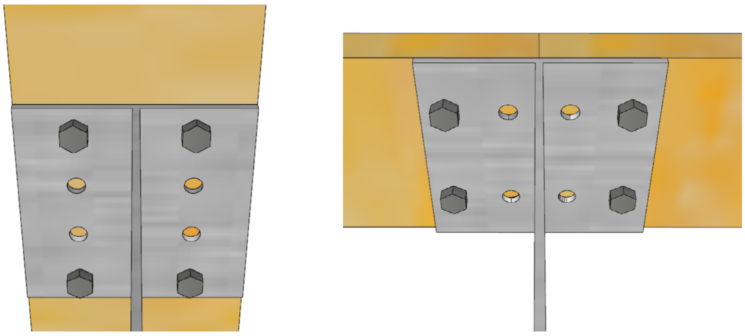


Fig. 57 - Brackets with screws

Steel or aluminium brackets

Aluminium brackets are a good choice when designing lightweight constructions because they offer a combination of low weight, ease of handling, and excellent corrosion resistance. Steel, on the other hand, is often used for heavier applications. The yield strength of steel is around 250 MPa, whereas that of aluminium is only about 40 MPa (Aluminium-online, n.d.).

When designing a bracket with a height of 100 mm, a length of 130 mm, and a thickness of 3 mm, the bracket can withstand a force of approximately 2 kN (Rjfaçades, n.d.). While steel is stronger than aluminium, if made thinner than 3 mm, it becomes more prone to buckling, harder to weld or fasten, and more susceptible to corrosion (Wang, Rashed & Murakawa, 2014).

Virgin steel production emits roughly 1.9 to 2.1 kilograms of CO_2 per kilogram, while virgin aluminium emits between 10 and 13 kilograms of CO_2 per kilogram. However, using recycled materials significantly reduces emissions: recycled steel reduces CO_2 emissions by approximately 58% compared to primary steel production, and recycled aluminium achieves a 92% reduction. As a result, recycled steel emits around 0.6 kilograms of CO_2 per kilogram, and recycled aluminium emits about 0.5 kilograms per kilogram. Making it a more environmentally friendly option (EuRIC AISBL, n.d.).

When evaluating this façade system, the following weight calculation can be made: Pretty Plastic has a maximum weight of 24.4 kg/m². Combined with approximately 10 kg/m² for insulation and the cladding structure, the total weight is around 35 kg/m². Due to the design, each bracket only needs to support a maximum area of 0.5 m². This results in a maximum load of 17.5 kg, or 0.17 kN, per bracket. This is well below the bracket's load capacity of 2 kN.

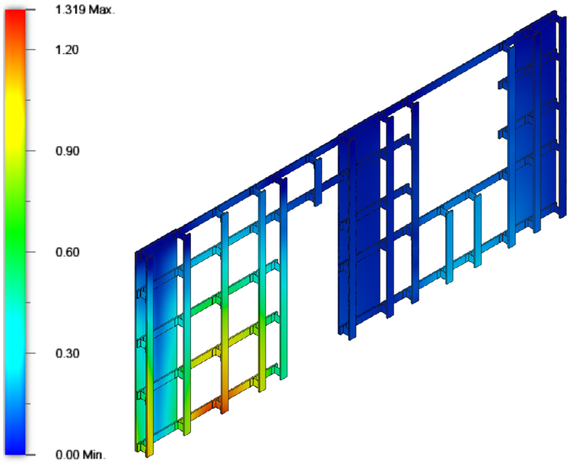


Fig. 60 - The maximum displacement is 1,32 mm

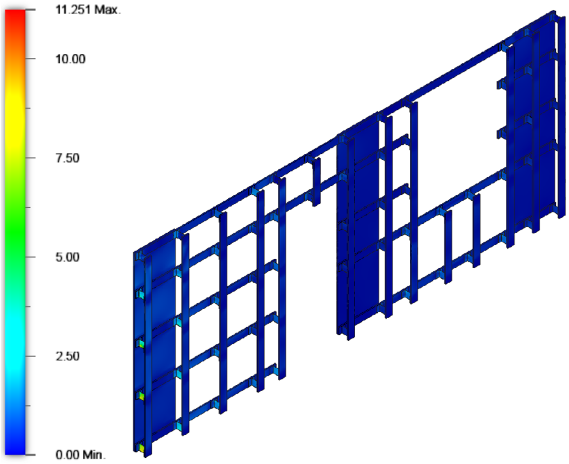


Fig. 61 - The maximum von Mises stress is 11,25 MPa

Additionally, a simulation was conducted to calculate the forces and deformation of the entire façade element when lifted by a crane. The deformation was found to be 1.32 mm and the maximum Von Mises stress was 11.25 MPa, which remains below the aluminium yield strength of 40 MPa.

Combining Findings

Cladding

The insights from the different design approaches and the reusability study were combined into new preliminary designs. Various cladding options such as ClickBricks, Pretty Plastic or wooden cladding can be fitted. For brick façades, a system with wall ties attached to a rail on the vertical plywood planks or timber beams eliminates the need for drilling into the load-bearing wall. The wooden Accoya façade is mounted on timber slats and the Pretty Plastic façade in mounted on aluminium rails. A water-repellent foil is placed between the cladding and the structure to protect the structure and insulation from moisture. All façade types can be applied to both the 'bio-based' and the 'reusable' structure. The façade systems can be made in a factory by hand and machine.

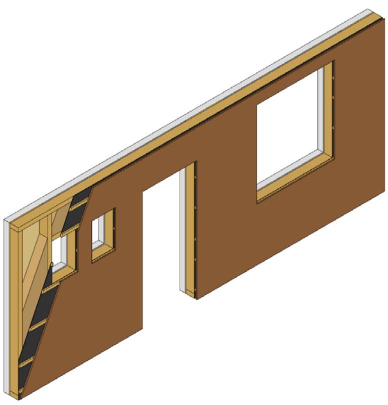


Fig. 62 - Wooden Accoya cladding

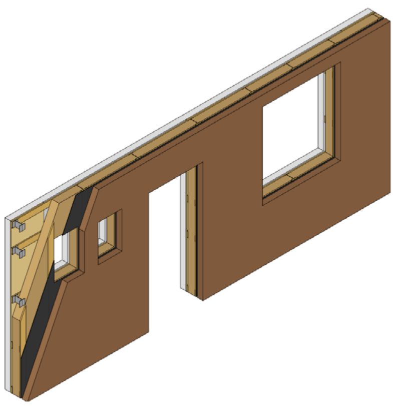


Fig. 63 - ClickBrick cladding

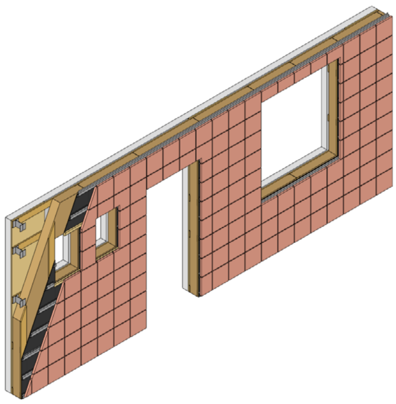


Fig. 64 - Pretty plastic cladding

Structure
The structure consists of either a plywood frame with aluminium brackets or a timber frame construction with steel connections from Woodinc. It is not necessary to cover the entire back of the structure with OSB panels. Instead, both structures are reinforced with smaller OSB panels to keep the structure rigid. The panels are 600 mm, matching the approximate 600 mm centre-to-centre distance of the vertical frame elements. This also helps keep the panel sizes standardised. If the height of the façade defers when being reused, the height of the panels can be cut and stacked on top of each other. The panels on the left side in the drawings below show this principle. Both designs feature a timber beam at the top and bottom, as this is where the connections to the existing bearing wall will clamp the façade system.

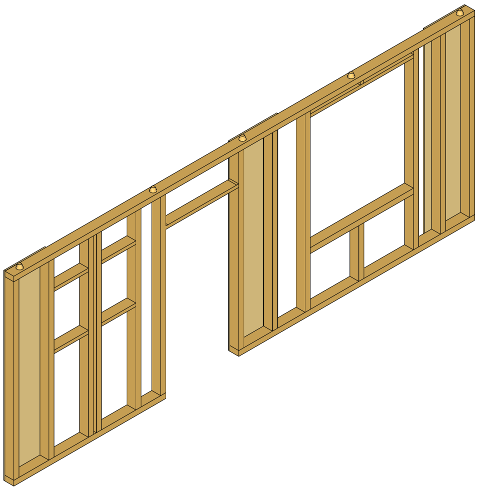


Fig. 65 - Timber frame structure

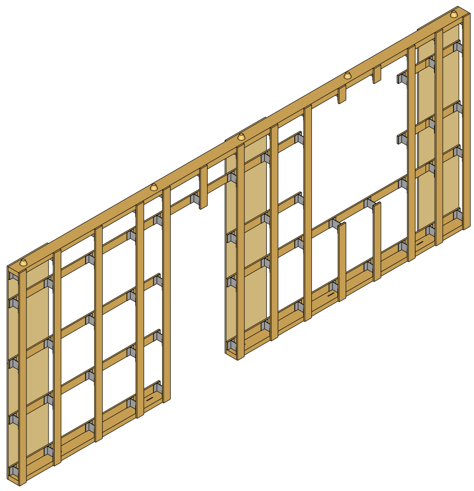


Fig. 66 - Plywood-aluminium frame structure

Insulation
Natural materials like flax offer breathable moisture regulation through their fibrous structure, preventing condensation by balancing moisture with the environment. Flax is also fast-renewable, CO_2-absorbing during growth, non-toxic, recyclable and long-lasting (75+ years) due to self-healing fibres. It also outperforms many other bio-based insulation materials in fire safety, with a European fire classification of C.

To meet the Dutch Building Decree, which requires an R-value of 4.7 m^2K/W for new construction, the insulation layer must provide a significant portion of this resistance. Isovlas flax insulation has a thermal conductivity of 0.035 W/mK (Isovlas, 2025). Using the formula R = Thickness/**thermal conductivity**, achieving an R-value of 3.7 m^2K/W requires a thickness of approximately 130 mm. Additional construction layers such as interior finishes and air cavities contribute to reaching the total R-value of 4.7. The insulation will be held into place using small aluminium hooks that are attached to the structure.

3.5 Connection to the existing wall

The next step is to design how the facade systems can be connected to the existing bearing wall. Two connection systems will be compared and their pros and cons will be listed. In the end, the most suitable option for renovation and reuse will be selected.

Steel brackets

Halfen type-W brickwork support brackets can withstand a maximum point load of 4 kN. The L-shaped brackets have a thickness of 10 mm, a height of 55 mm, a depth of 115 mm and a width of 90 mm. The total weight of the façade is 5 kN. If a safety factor of 1.5 is applied to account for wind forces and other loads, the total force on the anchors becomes 7,5 kN. When five anchors are used, each must support 1,5 kN. This is still well below the 4 kN capacity of a Halfen bracket (Halfen, 2017).

A HUS4-HR anchor with hexagonal head are made for masonry and limestone walls, the size 10 can handle a maximum shear force of 1,7 kN. The minimum depth in the wall is 75 mm. The integrated washer has a diameter of 20,5 mm and the diameter of the screw thread is 12,25 mm. After use the anchors can be removed from the wall (Hilti, 2024). Using two of these anchors per bracket is sufficient to carry the load of 0,75 kN.

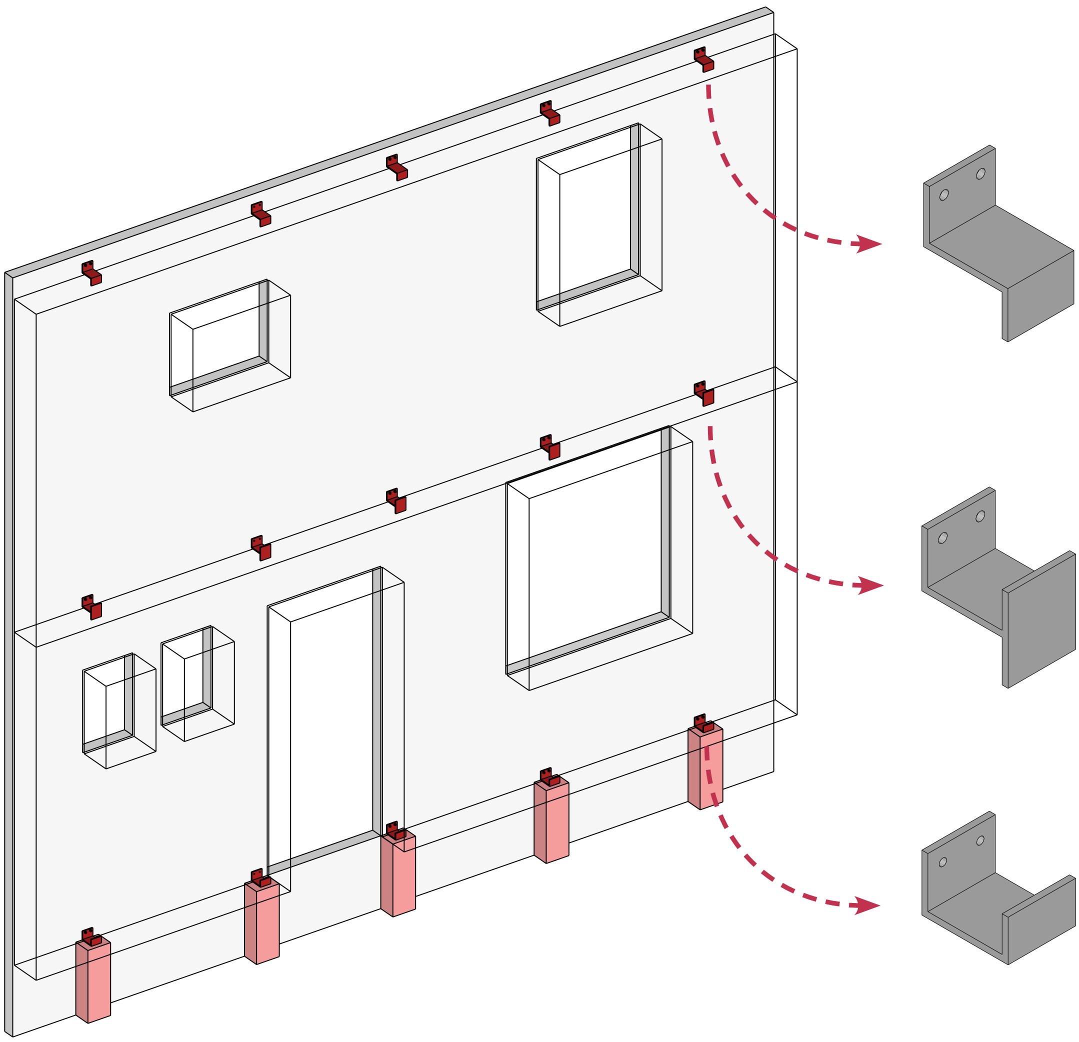


Fig. 67 - See through image of façade elements and placement of brackets (own image, 2025)

The brackets used to clamp the façade systems will have the same length (115 mm) and width (90 mm) as the ones from Halfen, but they will be 2 mm thinner, as they can carry twice the required load. Another difference is that each L-profile includes an extension at the end. This extension slides into the façade system to secure it in all directions.

There are three different types of brackets: bottom, middle and top. Thanks to the precise fit, no additional fasteners are needed; the connection brackets only need to be screwed into the wall. The brackets can be removed when the façade is reused, leaving no marks on the façade system. Besides, due to this clamping system, no brackets need to be placed on the sides or fastened through the façade system. This allows cladding and insulation to stay in place, with installation possible per dwelling. The system slides in easily, ensuring a fast and efficient assembly. There also is a 20 mm gap between the existing bearing wall and the façade system. This space allows for imperfections in the existing wall without affecting the façade system.

Although the steel brackets are structurally sufficient based on calculations, the condition and load-bearing capacity of the existing wall remain uncertain. To reduce risk, additional concrete footings will be installed on top of the existing foundation. These footings are designed to directly support the weight of the prefabricated facade system, ensuring that the load is safely transferred without stressing the existing wall structure too much.

The drawing on the previous page illustrates the placement of the various brackets. The following page presents the mounting procedure for the façade system, which is identical for both the timber and the plywood–aluminium structures. The procedure is numbered, starting at the bottom of the façade and progressing upward. The drawing below also includes these numbers to clearly indicate the location of each step in the mounting sequence.

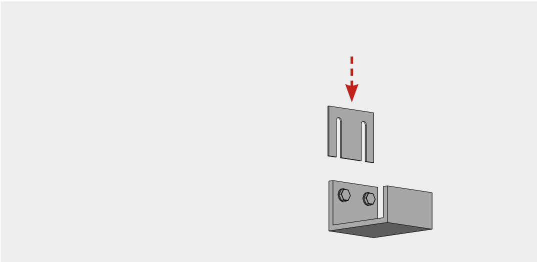
Timber cone sliding connections

The timber cone connections were designed with construction tolerances in mind, enabling a robust yet flexible connection that does not require highly precise alignment. The system is based on a simple assembly principle: the upper facade unit is lowered onto the lower one and both are anchored to the existing load-bearing wall using steel brackets. These joints are fully mechanical, requiring neither screws nor chemical anchors and they can be disassembled if needed after installation.

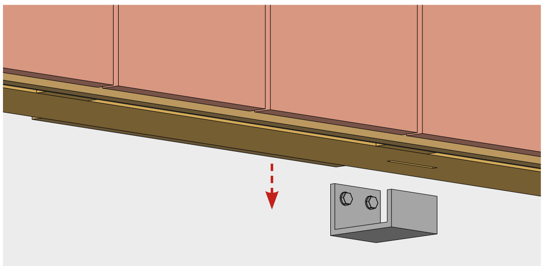
To accommodate tolerances but still keep a clamped fit, cone-shaped timber joints were implemented. The connecting opening is also cone-shaped but intentionally narrower, resulting in a 1 cm gap between the beams of the two systems. This configuration allows the two units to lock into place under its own weight, forming a secure connection without additional fastening. Steel brackets are used to anchor both facade systems to the existing wall. These brackets maintain the correct spacing from the wall and restrict horizontal movement. To ensure airtightness and reduce thermal bridging, two layers of compressible sealing tape are installed between the facade elements.

The system is placed on a timber beam that incorporates the cone-shaped joints and is anchored to the existing load-bearing wall using steel brackets. This assembly rests on prefabricated concrete footings, which are placed directly on top of the existing foundation using a bolted connection so they can later be reused. The mounting procedure is identical for both the timber and the plywood–aluminium structures.

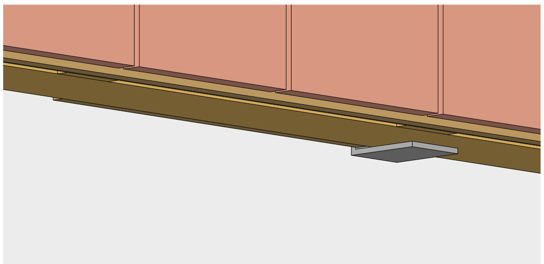
MOUNTING SEQUENCE BRACKETS



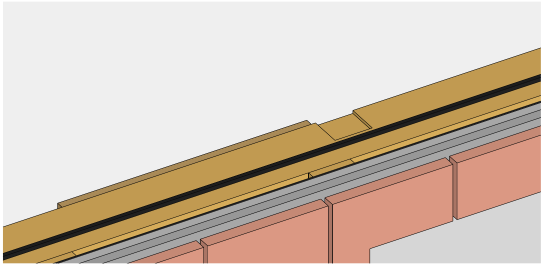
1. The brackets are bolted to the bearing wall, Steel shims can be used to level the brackets.



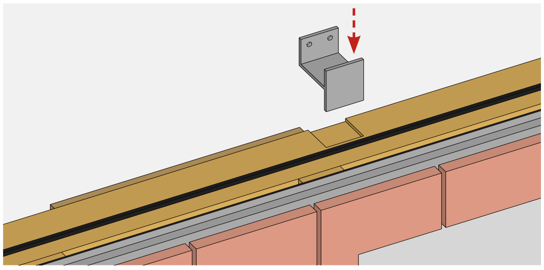
2. Milled slits in the beam at the bottom of the façade system allow it to slide over the brackets.



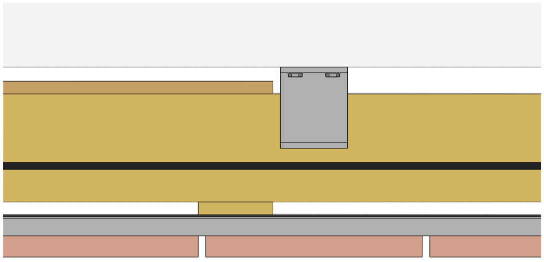
3. No additional fasteners are needed, as the façade system is secured in all directions.



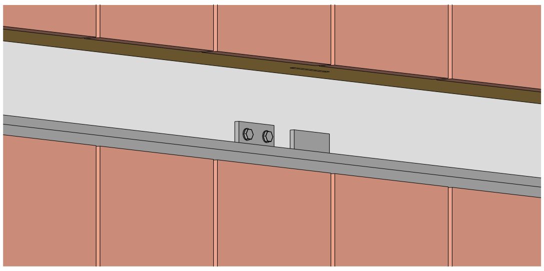
4. Compressible sealing tape is placed in between the bottom and top façade system.



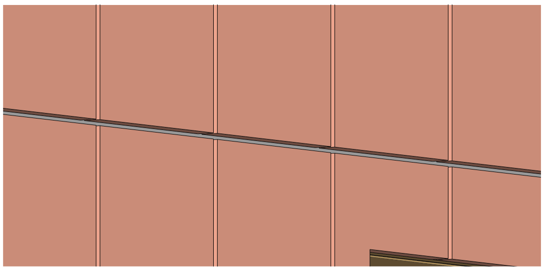
5. A slit and notch have been milled into the top of the façade system to allow the brackets to fit.



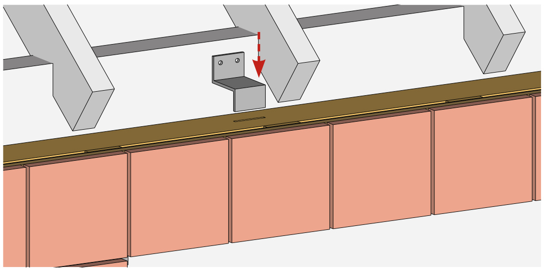
6. This top view shows the 20 mm space between the bearing wall and façade system.



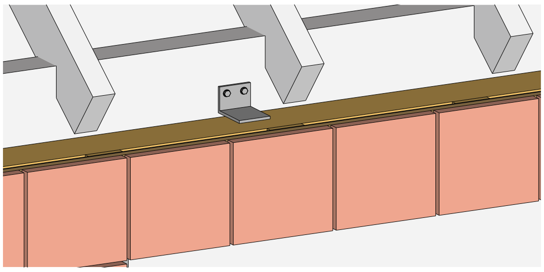
7. The beams of the façade system on top has slits as well.



8. The two façade systems connect and the cladding runs continuously.



9. No additional façade system will be placed on top, so only a slit is needed, not a notch.



10. The brackets at the top fully clamp the façade system, preventing movement in any direction.

The image below illustrates the placement of the joints and the integration of the ClickBrick cladding. The ClickBricks are installed after the facade system has been positioned. Like the facade structure, the ClickBrick cladding is supported by the concrete footings, ensuring consistent load transfer to the foundation. The cladding rests on a concrete lintel, which distributes its weight evenly. Due to the limited width of the existing foundation, the concrete footings extend at the location of the lintel to provide adequate support. Despite the cantilevered configuration, the centre of gravity of the masonry remains within the footprint of the concrete footing, ensuring its stability and preventing overturning. The concrete lintel is positioned below ground level to remain concealed. One or two rows of ClickBrick are placed beneath the surface, resting directly on the lintel to maintain visual continuity. Only the bottom two lintels are placed before the facade systems. The top two beams shown in the image below are part of the facade system, this can also be seen in the mounting sequence.

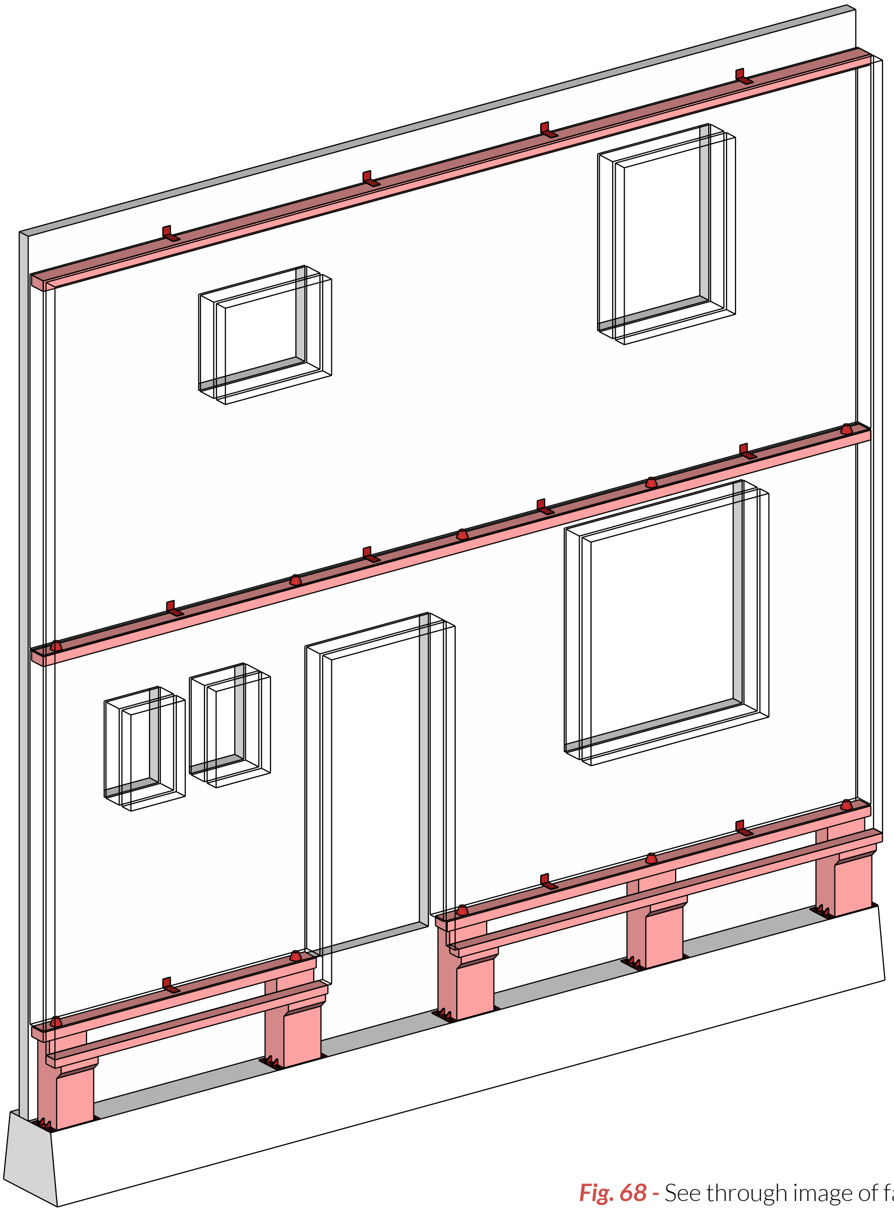
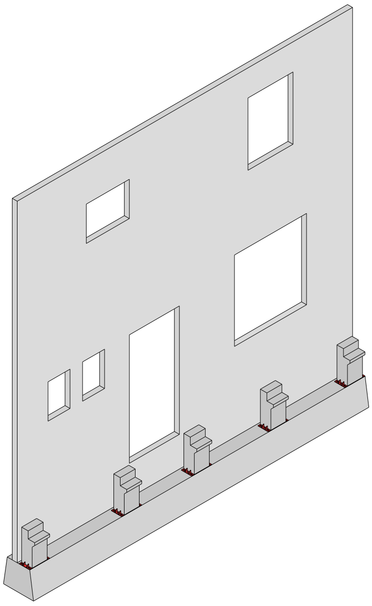
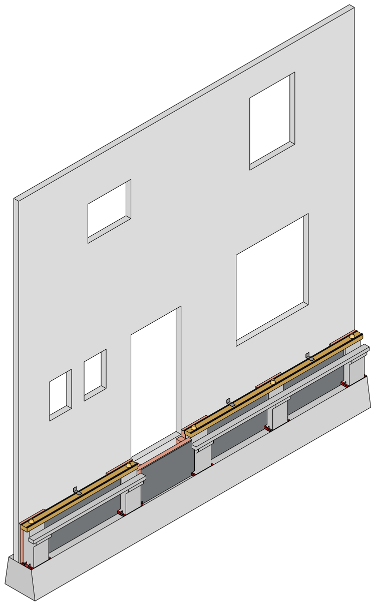


Fig. 68 - See through image of façade elements and placement of connections (own image, 2025)

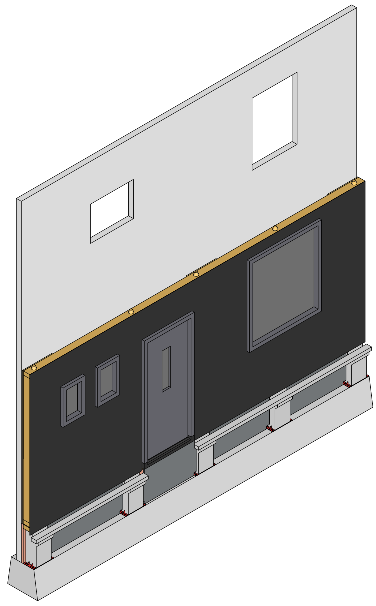
MOUNTING SEQUENCE CONES



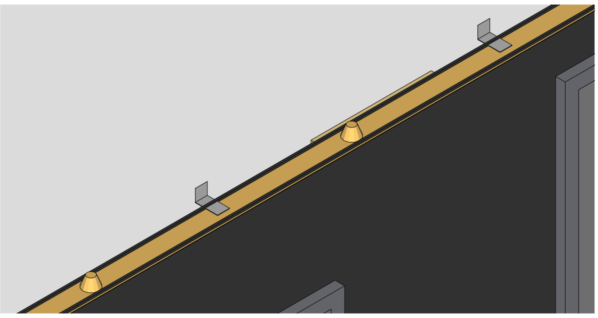
1. The prefabricated concrete footings are placed.



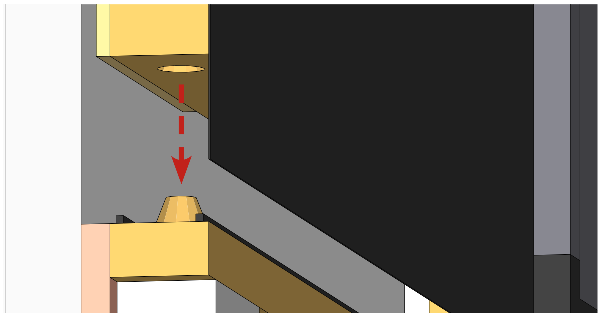
2. Next are the lintels, timber beams and Insulated skirt boards.



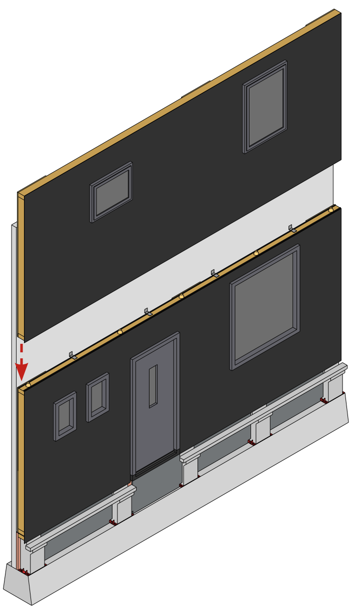
3. The facade system is placed on top of the timber cones.



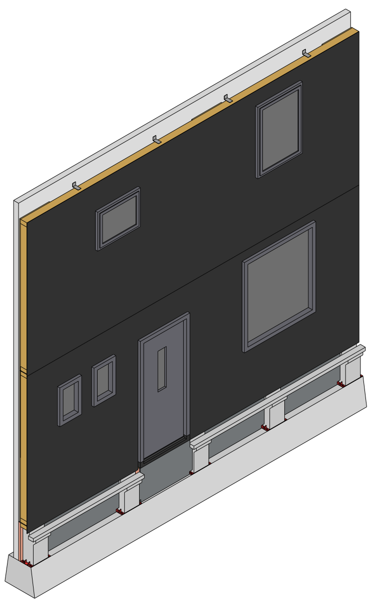
4. Steel brackets connect the facade system to the existing bearing wall, compressible sealing tape is placed on top.



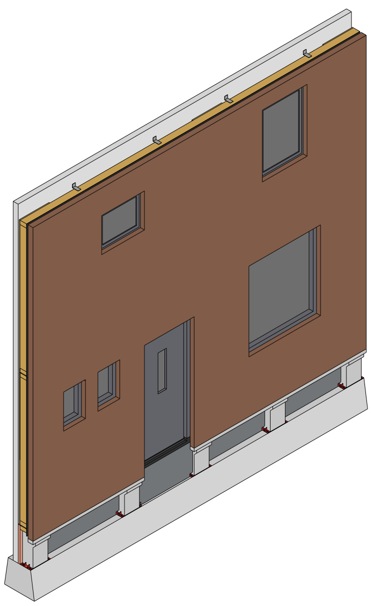
5. Milled holes in the beam at the bottom of the second façade system allow it to slide over the cones.



6. The second facade system is placed on top of the first system.



7. Steel brackets are placed on top of the second facade system.



8. The ClickBrick cladding is placed on the concrete lintels.

Conclusion

Both the steel bracket and timber cone connection method have their own advantages and drawbacks. The first consideration is the potential for thermal bridging between the two facade systems.

The steel bracket method places the facade units directly on top of each other, separated by a single layer of compressible sealing tape. This results in a relatively tight connection. In contrast, the timber cone connection leaves a 1 cm gap between the systems, which is filled with two layers of sealing tape. This design allows the bottom cones to engage more effectively with the milled holes above. The weight of the facade elements ensures that the connection tightens. The 1 cm gap also provides room for minor vertical adjustments, accommodating construction tolerances and avoiding the need for precision fitting.

Although the steel bracket connection minimises the space between facade systems, it is more difficult to execute accurately on site. The brackets must slide into precisely milled slits in the timber beams. While this level of accuracy is achievable in a factory setting, on a renovation site, where existing bearing walls may be uneven and installation conditions less controlled, it is challenging. For the bracket system to work without additional fixings, all components must be placed with millimetre-level precision. Enlarging the slits is not a viable solution, as it would compromise the clamping fit and allow unwanted movement.

In contrast, the timber cone method is better suited to renovation projects due to its tolerance for installation variation. Only the top of the facade units needs to be fixed, allowing the cladding to be pre-installed in the factory (with the exception of ClickBrick cladding, which would be too heavy and unstable for hoisting). Thermal bridging in the cone system is negligible and has minimal impact on the overall thermal performance, as the connection remains airtight.

3.6 Second façade

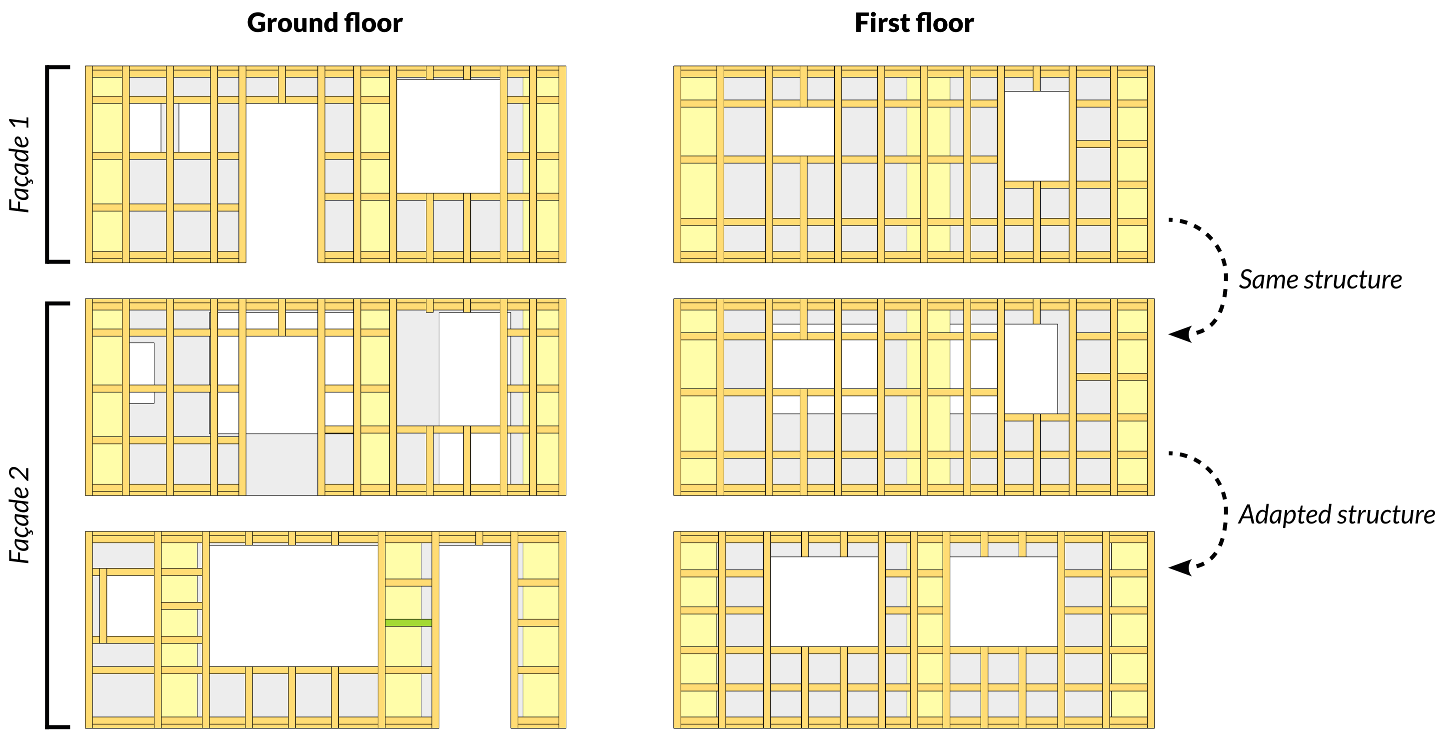
The preliminary designs will be tested on the second case study façade as a scenario planning test to see if and how the façade element can be reused. In this scenario-planning test, the façade system is used for 30 years on the first building and then reused on a second one. This means the materials from the first façade are directly transferred to the second, with no additional façades added and only virgin materials used where necessary. The goal is to identify what modifications are needed to enable the reuse of components and materials. This also gives an insight if the components can be reused as whole pieces or only when separated into individual materials. The height and width of the two façades are the same but the placement of the door and window openings is different.

Placement on second façade

The first structure of the façade element, consisting of plywood planks and aluminium brackets, must be adjusted to fit the new façade. The image below shows how the structure's layout needs to be modified. When the plywood-aluminium structure is transferred from case study façade 1 to façade 2, a small piece of virgin plywood (less than 1% of the total structure) is needed for the ground floor (shown in green). The first floor has enough pieces to create a new element. Some small pieces will be cut to ensure a proper fit, but in the end, more than 95% of the materials used in the structure can be reused. During the transformation, the top and bottom brackets of the vertical planks can remain in place, as the height of both façades is the same.

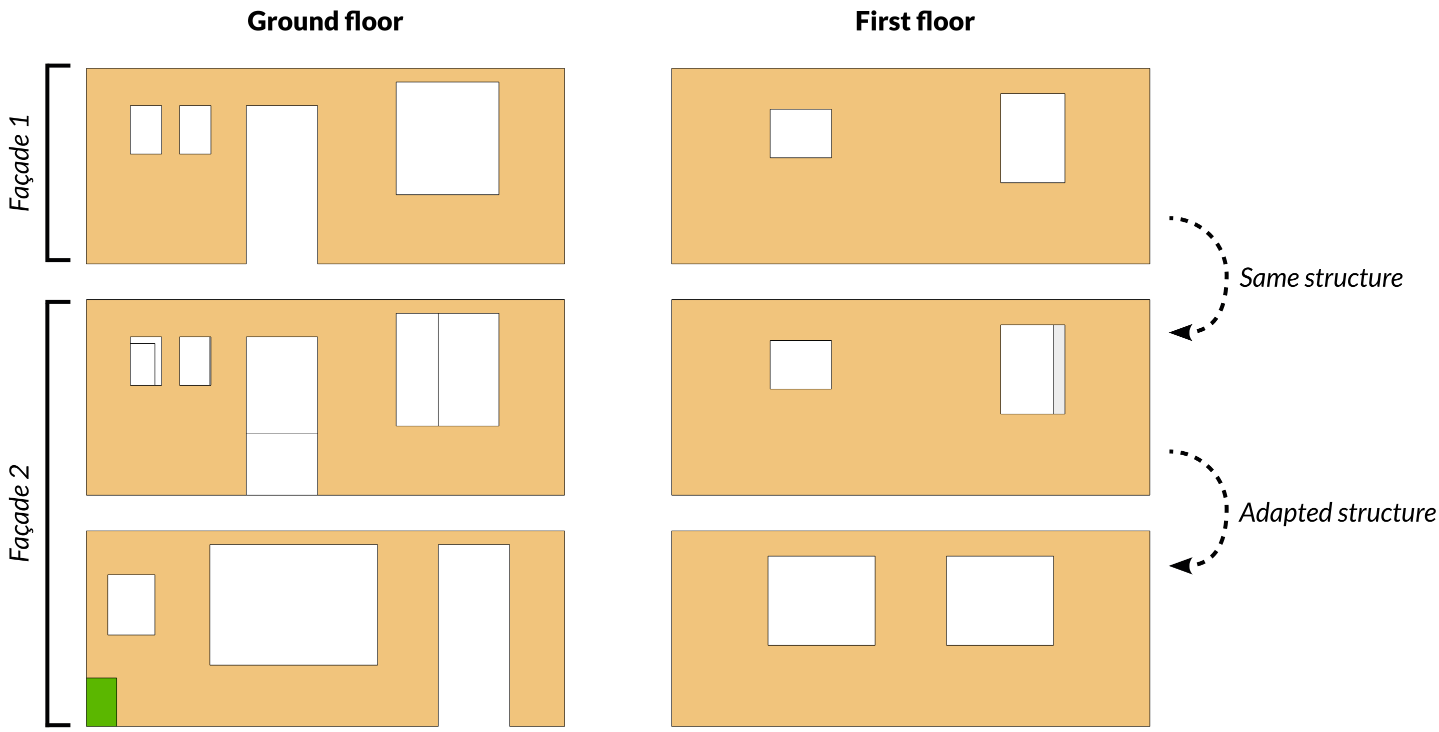
For the second structure, made of timber and steel connections, about 95% of the materials can be reused, and less than 10% of the new structure is made from virgin materials (shown in green). For the other designs, the percentages of new materials are as follows: Flax 2%, Pretty Plastic 1%, Pretty Plastic supporting structure 7%, and Accoya 5%.

Plywood-aluminium frame structure

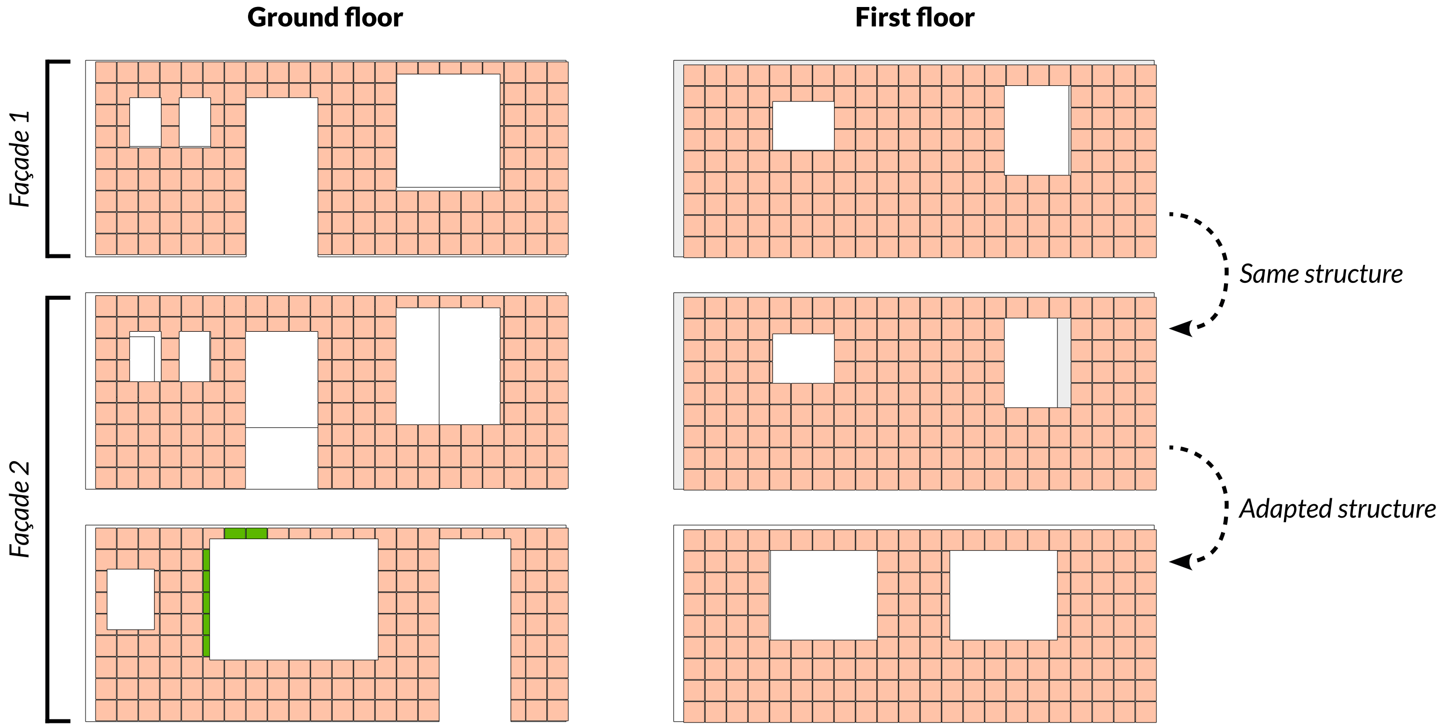


Timber frame structure

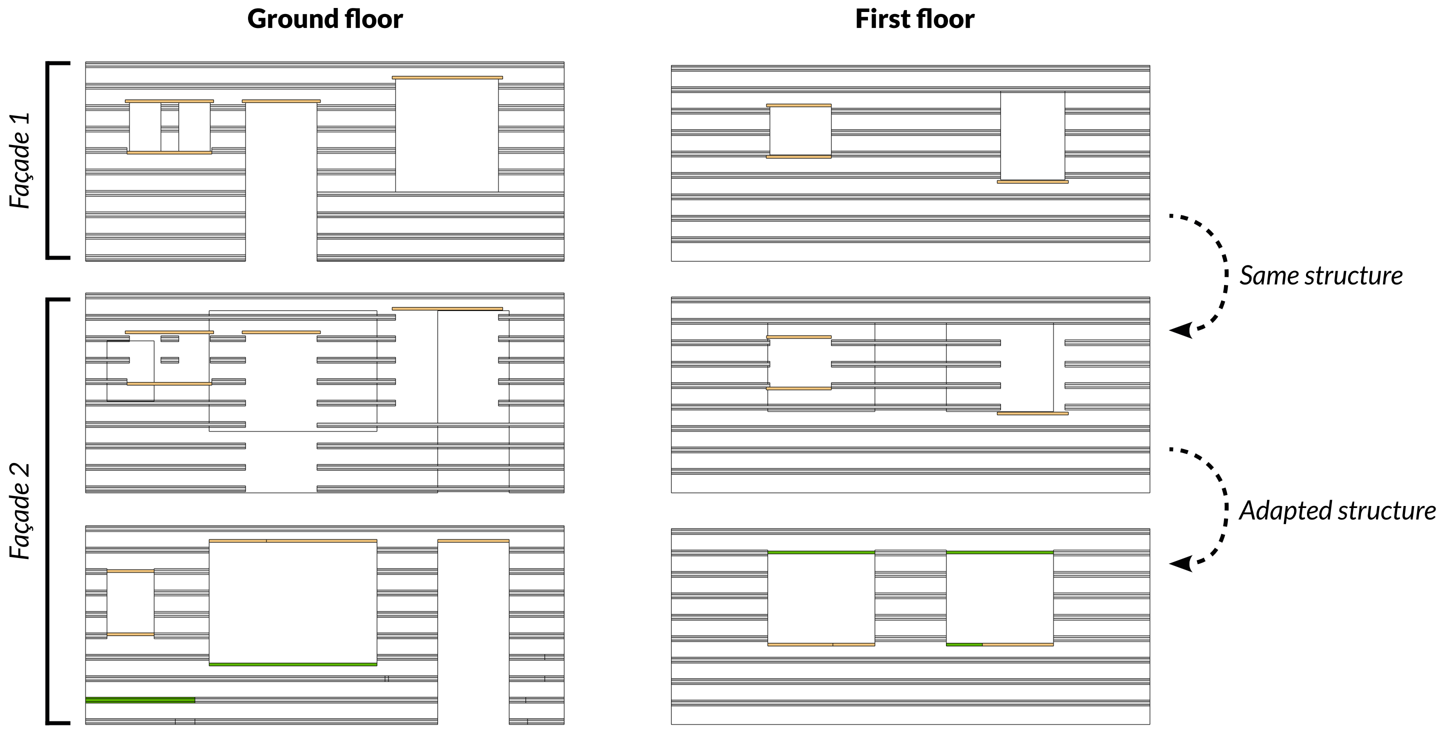
Flax insulation



Pretty Plastic cladding



Cladding supporting structure



Accoya cladding

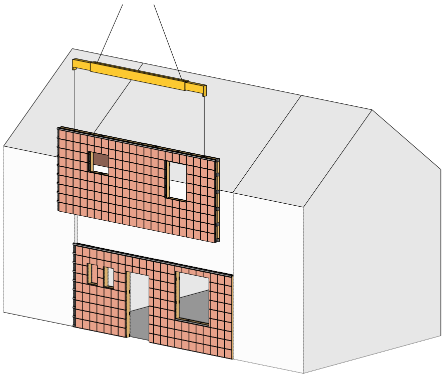
Conclusion

Based on the previous illustrations, it becomes clear that each layer of the façade system must be changed in different locations to adapt to a new façade layout. This requires all layers to be separated before reassembly can take place. Some layers require more virgin materials than others during this process. This means that the façade system is being remanufactured and the materials it is made from are being reused. According to the ten R-strategies remanufacture means: reuse parts of discarded products to create new products with the same function. In the case of these facade system designs the amount of reused parts is rather high.

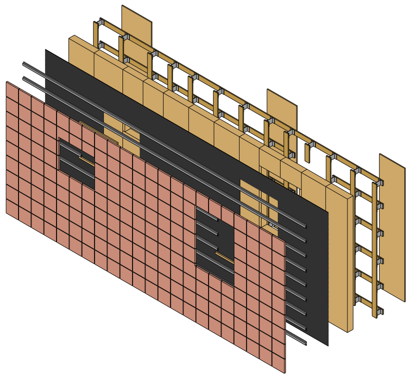
Among the options, the plywood-aluminium structure and ClickBrick cladding use the least new material when adapted to a second façade. Smaller components, like ClickBrick's modular units, result in less material loss, making it highly adaptable, which is why it wasn't included in earlier visualisations. However, ClickBricks' weight and dry connections prevent pre-installation at the factory. While both Accoya and Pretty Plastic cladding support structures are functionally the same, they differ in material: timber for Accoya and aluminium for Pretty Plastic.

The reuse process is as follows: the existing façade system is removed from the building and transported either to a warehouse or directly to a factory. There, the layers are separated. Prior to this, the second layout has been designed to identify which components can remain intact and do not require full disassembly. After separation, the second façade layout is constructed using the reclaimed materials. All materials used in the system were selected for their resilience, and all connections were designed to allow for easy disassembly and reuse. This sequence is shown on the next page. A aluminium-plywood structure in combination with Pretty Plastic cladding is used as an example to show this process.

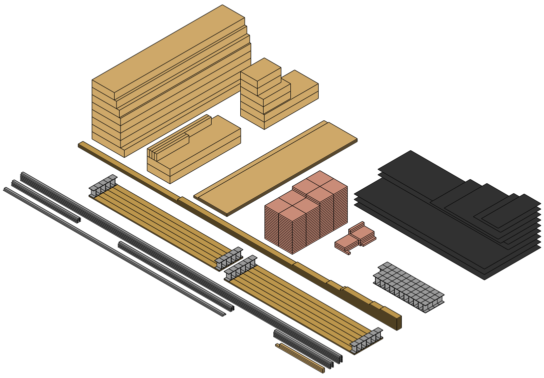
REUSE SEQUENCE



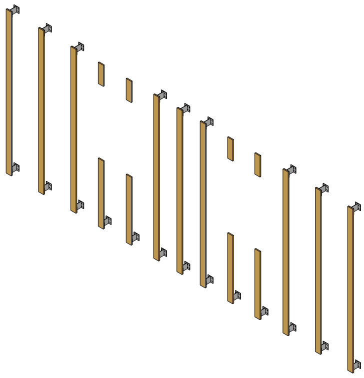
1. The old façade system is removed.



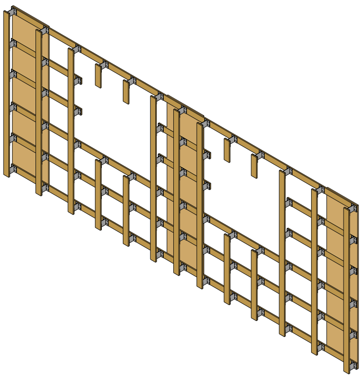
2. All the layers are separated and brought to the factory



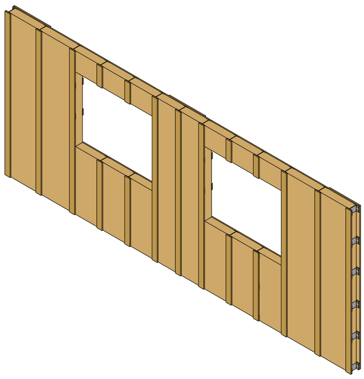
3. Some components don't need total disassembly.



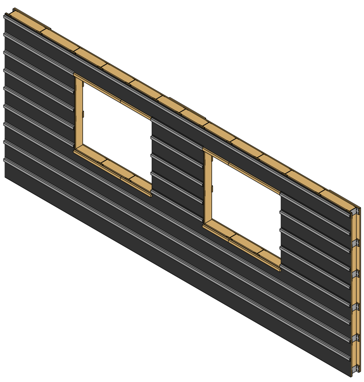
4. The new façade layout is being constructed.



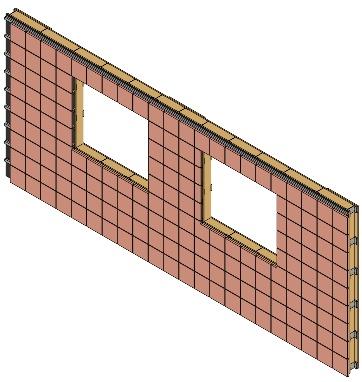
5. The new structure is complete.



6. The compressible insulation is easy to reuse.



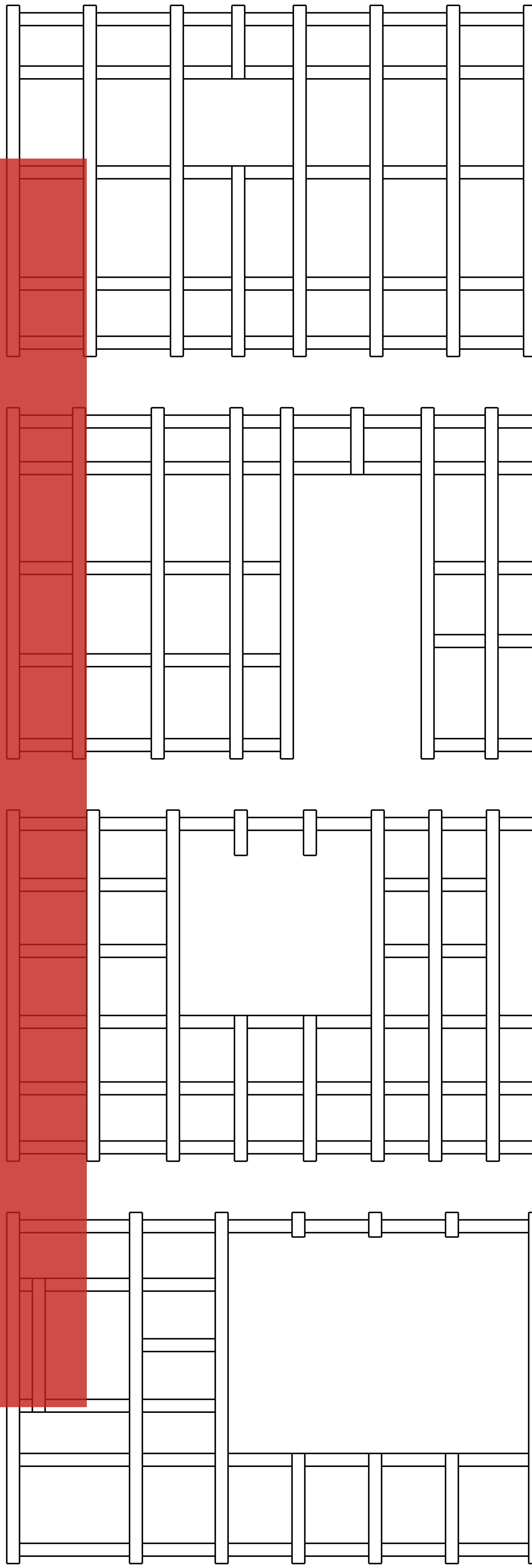
7. The water-repellent foil and supporting structure are next.



8. The final part is the cladding.

4 EVALUATION OF THE VARIANTS

Various methods will be used to quantify circularity. Life Cycle Assessment (LCA) measures environmental impact but not circularity. Material Circularity Indicator (MCI) assesses how materials are sourced and retained within the building industry after use. The 3DR method evaluates circularity by calculating ease of disassembly and material reusability.



4.1 Assessment methods

A circular construction economy aims to use as few new primary raw materials as possible and make optimal use of used materials. Products are designed in such a way that they require as few resources as possible, are used for as long as possible and are then processed in a high-quality manner. In doing so, resource use is brought back within the planet's ecological limits. All these ideas can be summarised in four principles (De circulaire bouweconomie, 2023):

1. Narrow the loop (build less, think more about how buildings can be (re)used differently)
2. Slow the loop (use fewer materials and handle materials more efficiently)
3. Substitute (use alternative materials that are renewable and have no environmental impact)
4. Close the loop (high-quality reuse)

All four circular economy principles have been discussed and applied throughout this report. The core topic is the renovation of existing façades. This is a strategy that aligns with the principle of *narrowing the loop*, which emphasises building less and rethinking how existing structures can be retained and reused. This principle is fundamental to the overall design approach of the report.

The remaining three principles: *slowing the loop*, *substituting materials* and *closing the loop* have guided the design of the façade systems. In this chapter, the final preliminary designs will be assessed using three evaluation methods: LCA (Life Cycle Assessment), MCI (Material Circularity Indicator) and 3DR (Disassembly, deconstruction and resilience). The layout of the ground floor from the first case study façade serves as a base for the assessment. Each time, a conventional cavity wall façade is also assessed for reference.

The three assessment methods were selected to reflect the principles of circularity and evaluate how various structural and cladding options perform in terms of environmental impact and circularity. Each method aligns with at least one of the material related circular principles. The diagram below shows the relationship between the four circular principles, the core topic (façade renovation) and the assessment methods used in this report.

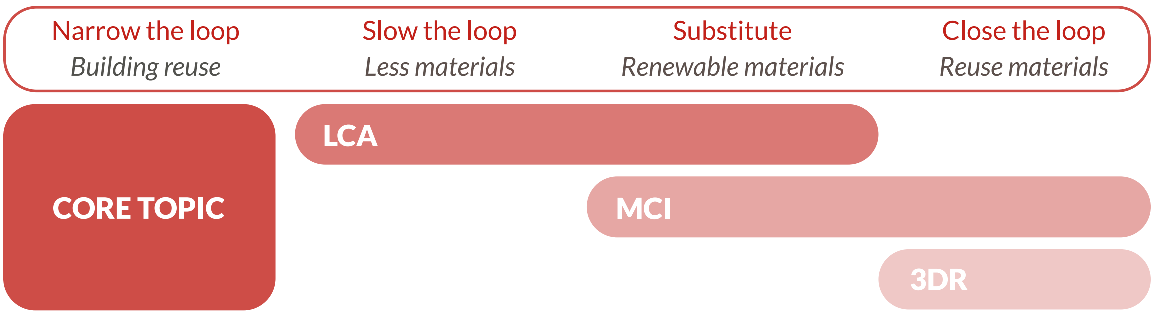


Fig. 69 - Comparison of assessment methods (own image)

The Life Cycle Assessment (LCA) evaluates the environmental impact of materials and processes across their entire life cycle. However, it only takes the environmental impact into account and not the circularity. However, the End-of-life option of recycling will result in a lower score than choosing to landfill the material. The Material Circularity Indicator (MCI) measures the degree to which materials are sourced from circular streams and retained in the system after use, providing a numeric score to assess sustainability. Finally, the 3DR method offers a calculation method for assessing the simplicity of a building's circularity. The calculation takes into account how easy components are to take apart and how strong and reusable their materials and components are.

4.2 Life cycle assessment (LCA)

The environmental impacts of buildings over their entire life cycle (from construction to demolition) are structured and categorised in different life cycle stages according to the EN 15978 and EN 15804 standards. It starts with the material extraction stage (A1–A3), followed by the construction stage (A4–A5), the use stage (B1–B5) and finally the End-of-life stage (C1–C4). For this assessment, the use stage has not been taken into account, as the energy use of all dwellings will be nearly the same due to the identical R-value of the insulation used in all designs.

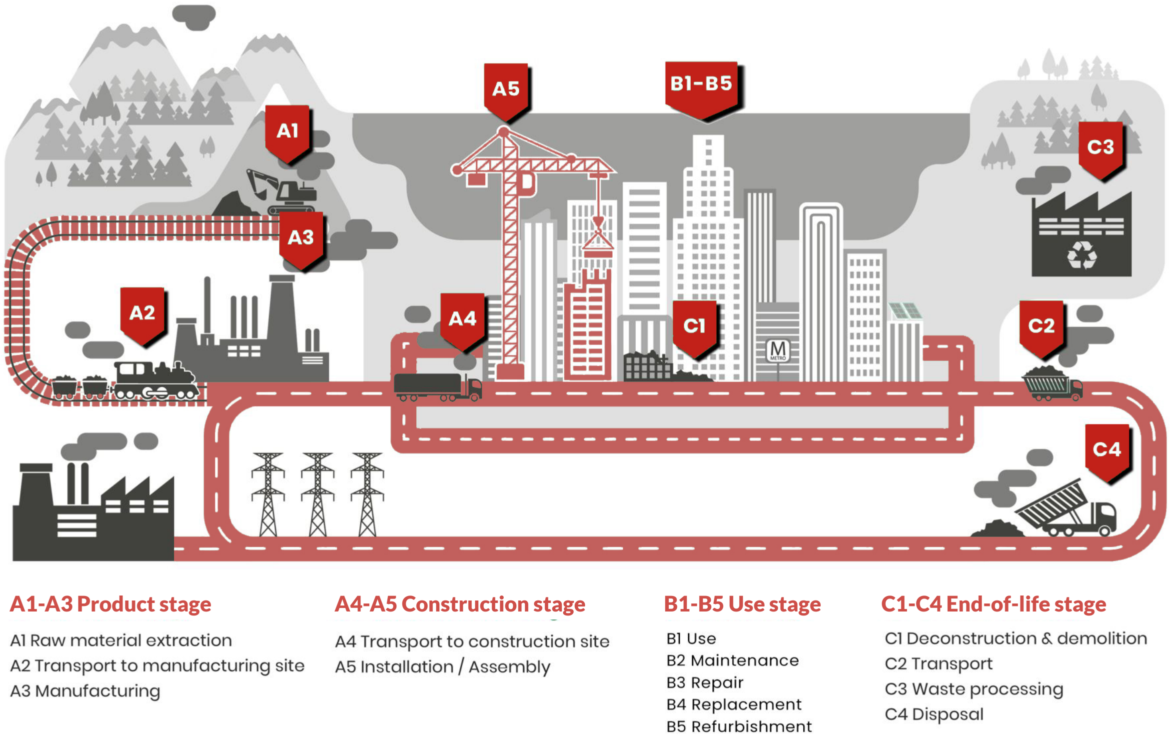


Fig. 70 - Material lifecycle depicted (One Click LCA, 2024)

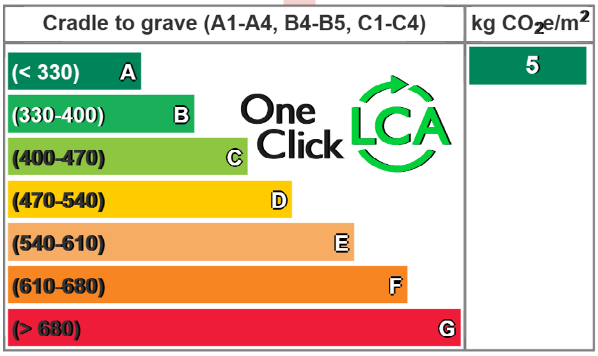
The outcome of a Life Cycle Assessment (LCA) is expressed in kg CO_2e, which represents the total climate impact of all greenhouse gas emissions, calculated using their Global Warming Potential (GWP) values relative to CO_2. One Click LCA calculates two types of life cycle assessments: the +A1 and +A2 variants. The +A1 variant reports the GWP as a single total value, which includes emissions from fossil fuels, biogenic sources and land use change. In contrast, the +A2 variant separates these emissions into distinct categories: GWP-fossil, GWP-biogenic and GWP-luluc. Additionally, the +A1 variant does not account for carbon storage in bio-based products and only looks at extraction, transportation and manufacturing. The +A2 variant on the other hand provides a more detailed assessment of carbon storage and release throughout the life cycle, which can result in lower or even negative GWP values, particularly for bio-based materials such as timber.

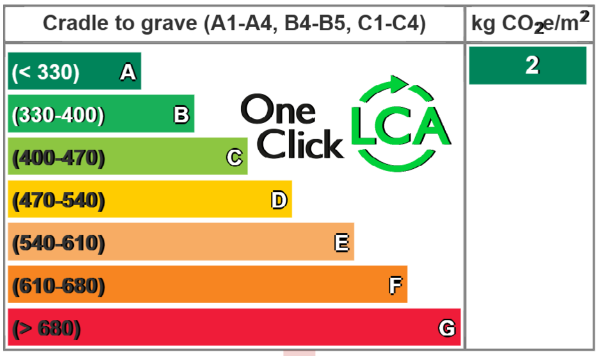
The following tables and graphs show the emissions of various structural and cladding systems. The Carbon Benchmark graph compares the designed façade systems with other Dutch buildings in the One Click LCA database, using kg CO_2e/m^2 based on the +A1 LCA variant. While this is a simplified model, it offers a useful performance comparison. The material tables are based on the more detailed +A2 LCA calculation. One Click LCA uses Environmental Product Declarations (EPDs) to provide accurate, manufacturer-specific data for building life cycle assessments. Information such as service life, end-of-life scenarios and CO_2e per kilogram is all sourced from the EPDs.

Plywood-aluminium frame structure

Material	Plywood planks	Aluminium brackets	Steel brackets	Flax insulation	Water repellent foil
Mass (kg)	55	17	18	72	2
Service life	70	100	100	70	70
End-of-life	Energy recovery	Recycle	Recycle	Compost	Plastic-based incineration
CO_2e (kg)	-62,67	12	13	-77,36	7,4

CO_2e (kg) **total: -132**





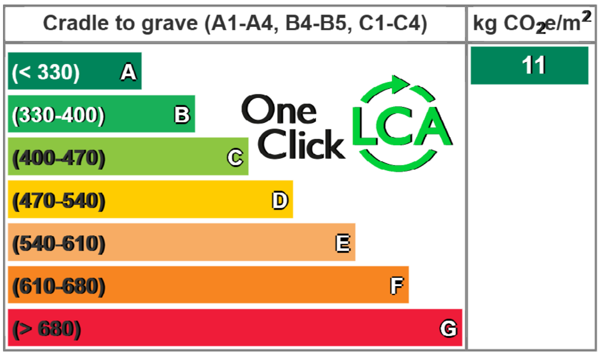
Timber frame structure

Material	Timber beams	Steel connections	Steel brackets	Flax insulation	Water repellent foil
Mass (kg)	244	13	18	72	2
Service life	100	100	100	70	70
End-of-life	Energy recovery	Recycle	Recycle	Compost	Plastic-based incineration
CO_2e (kg)	-274,84	10	13	-77,36	7,4

CO_2e (kg) **total: -322**

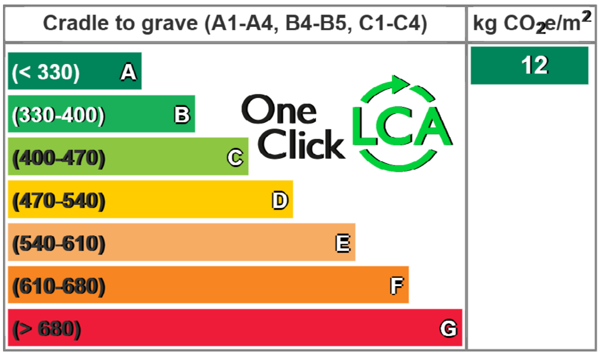
Accoya cladding

Material	Accoya	Timber frame
Mass (kg)	136	11
Service life	70	70
End-of-life	Energy recovery	Energy recovery
CO_2e (kg)	88	-10,08
CO_2e (kg) total: 78		



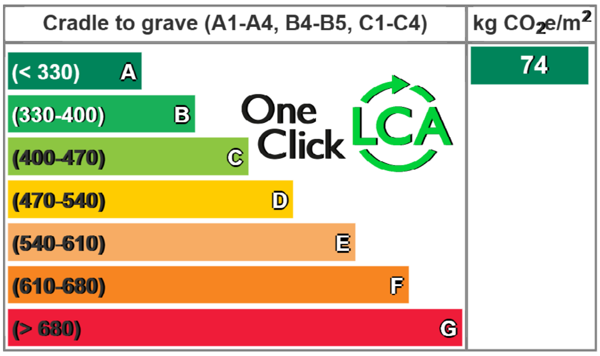
Pretty plastic cladding

Material	PVC panels	Aluminium frame
Mass (kg)	174	50
Service life	70	100
End-of-life	Reuse	Recycle
CO_2e (kg)	220	36
CO_2e (kg) total: 258		



Clickbrick cladding

Material	Bricks	Aluminium rails
Mass (kg)	2273	15
Service life	100	100
End-of-life	Brick crushed to aggregate	Recycle
CO_2e (kg)	560	11
CO_2e (kg) total: 571		



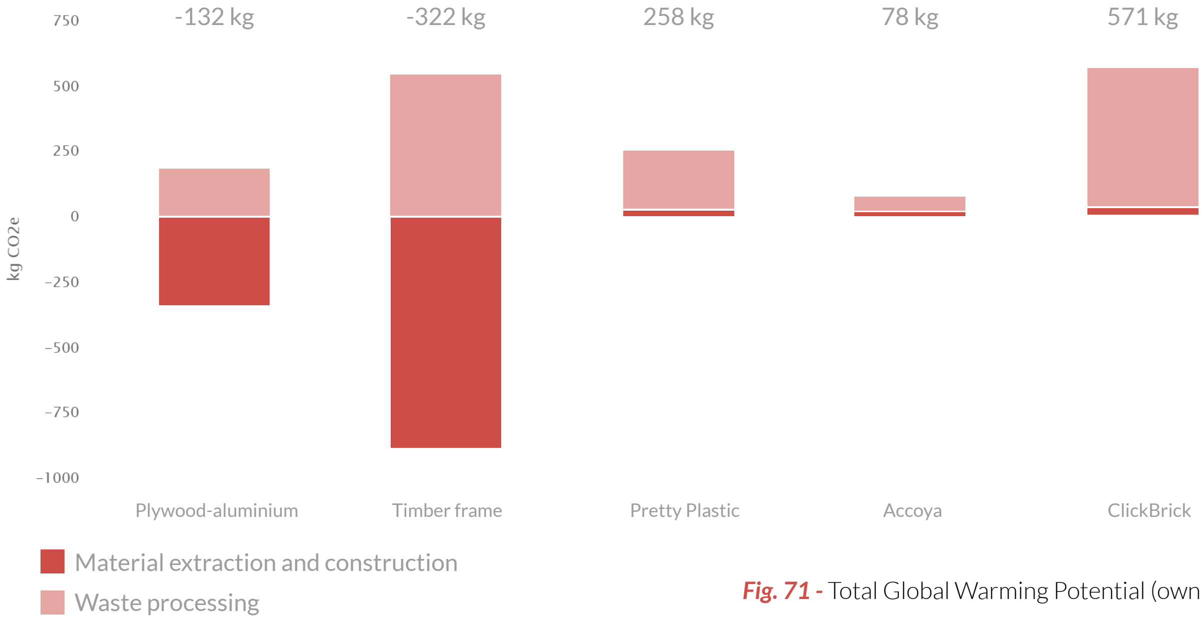


Fig. 71 - Total Global Warming Potential (own image)

Both structural systems and all three cladding options were assessed using two LCA variants: +A1 and +A2. The +A1 results are presented in the Carbon Benchmark graph, while the +A2 results appear at the bottom of the material tables and are also summarised in the table above. This table includes data on the product stage and End-of-life stage. It excludes the use stage, as it remains identical across all designs.

Timber-based components store carbon during the growth phase (dark red) and release it at their End-of-life through composting or incineration for energy recovery (light red). Non bio-based components generally show lower CO_2 emissions during waste processing, as many are recycled rather than incinerated or composted.

Structural systems

The timber frame structure outperforms the plywood-aluminium frame in both the +A1 and +A2 assessments. This is largely due to its higher wood content, which results in greater carbon storage. Both structures show a negative CO_2 balance in the +A2 calculation. However, from a material efficiency perspective, the plywood-aluminium structure is more favourable, as it uses less timber while incorporating a similar amount of metal.

Cladding systems

The ClickBrick system is the heaviest cladding type. With a Global Warming Potential (GWP) of 0.24 kg CO_2e/kg in the production stage, its overall emissions are the highest when multiplied by its weight. However, it offers the longest service life among the options studied.

The two lighter claddings, Pretty Plastic and Accoya, have similar CO_2 emissions per kilogram as ClickBrick but perform better overall due to their low weight. Although Accoya is wood-based, its GWP remains positive because of the energy- and chemical-intensive acetylation process. Still, Pretty Plastic scores slightly worse, as it uses an aluminium substructure, while Accoya uses timber.

An +A2 calculation was also performed for a conventional cavity façade with limestone, glass wool insulation and masonry cladding. With a total GWP of 2,793 kg CO_2e, nearly five times higher than the ClickBrick cladding. It was excluded from the graph to enhance clarity.

4.3 Material Circularity Indicator (MCI)

The Material Circularity Indicator assesses a product's life cycle by analysing its inputs (materials and their sources) and outputs (End-of-life outcomes). The calculation will result in a value between 0 and 1, where 0 indicates a "take-make-dispose" product and 1 represents a fully circular product (ellen macarthur foundation, 2024).

The façade system is designed for multiple Cycles of use, each cycle serving a different building. The first cycle involves the use of virgin materials for the construction of the system. In the following cycles, the system and its components are reused on new façades. This process of reuse can be repeated several times; the more cycles, the better the mci score. The final cycle represents the End-of-life phase, in which the materials reach their ultimate destination.

All of these cycles are captured in a single calculation. This approach considers the origin of the virgin materials (like bio-based, recycled, or non-renewable), the number of cycles of use the materials can withstand before arriving at their End-of-life destination (such as landfill, energy recovery, composting, etc.). As a result, materials that are not renewable but are highly recyclable can still achieve a strong score in this assessment. How the calculation works can be seen in the diagram below.

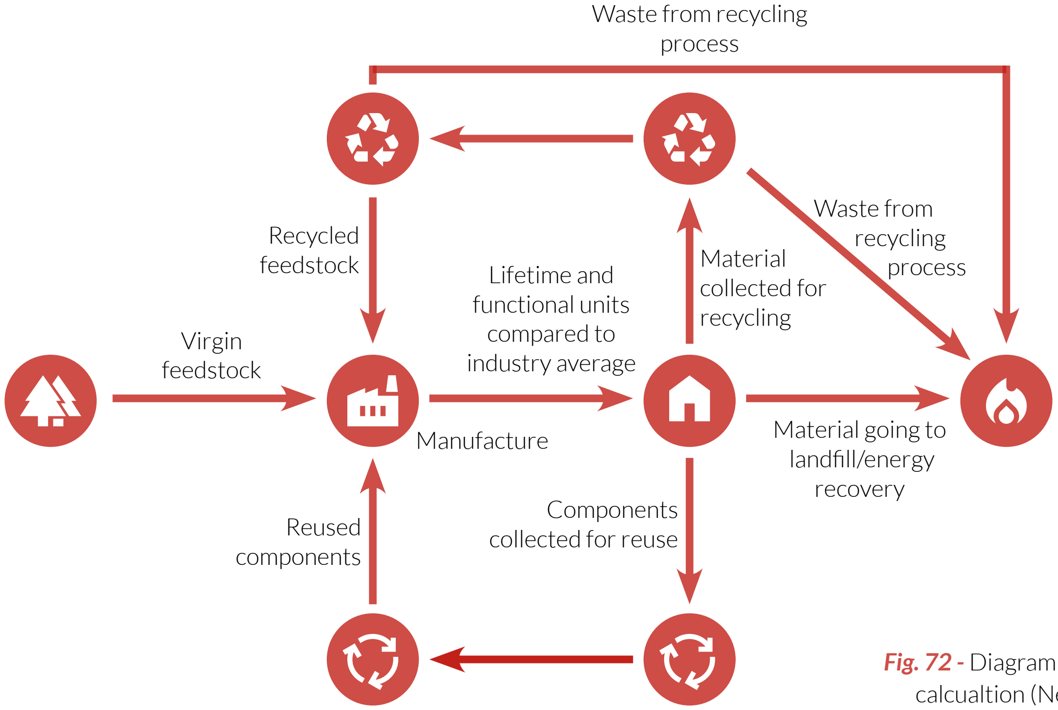


Fig. 72 - Diagram of the MCI calcualtion (Nebel, 2020)

The tables on the following page present the key material data required to perform the MCI calculation. The materials are combined in the tables to form a structural or cladding component. The total MCI score for each component is shown at the bottom of the corresponding table.

Most materials consist of recycled content and are expected to be recycled at the end of their life. However, recycling efficiency varies significantly. For example, bricks and LDPE foil have low recycling efficiencies (0–5%), whereas steel and aluminium retain nearly all of their properties during recycling, achieving efficiencies of around 80%. As a result, some materials receive low MCI scores despite being made from recycled content.

Plywood-aluminium frame structure

Material	Plywood planks	Aluminium brackets	Steel brackets	Flax insulation	Water repellent foil
Mass (kg)	55	17	18	72	2
Material type	Timber	Aluminium	Steel	Timber	LDPE
Source	Virgin	Recycle	Recycle	Virgin	Virgin
Cycles of use	2	4	5	2	2
Collection rate	90%	95%	95%	90%	90%
End-of-life	Energy recovery	Recycle	Recycle	Compost	Plastic-based incineration
MCI	**0,87**	**0,90**	**0,92**	**0,98**	**0,56**
MCI total: 0,92					

Timber frame structure

Material	Timber beams	Steel connections	Steel brackets	Flax insulation	Water repellent foil
Mass (kg)	244	13	18	72	2
Material type	Timber	Steel	Steel	Timber	LDPE
Source	Virgin	Recycle	Recycle	Virgin	Virgin
Cycles of use	3	5	5	2	2
Collection rate	90%	95%	95%	90%	90%
End-of-life	Recycle	Recycle	Recycle	Compost	Plastic-based incineration
MCI	0,86	0,92	0,92	0,98	0,56
MCI total: 0,89					

ClickBrick cladding

Material	Bricks	Aluminium rails
Mass (kg)	2273	15
Material type	Ceramics	Aluminium
Source	Virgin	Recycle
Cycles of use	4	3
Collection rate	90%	90%
End-of-life	Recycle	Recycle
MCI	0,78	0,86
MCI total: 0,78		

Accoya cladding

Material	Accoya	Timber frame
Mass (kg)	136	11
Material type	Timber	Timber
Source	Virgin	Virgin
Cycles of use	2	2
Collection rate	90%	90%
End-of-life	Energy recovery	Energy recovery
MCI	0,8	0,8
MCI total: 0,8		

Pretty Plastic cladding

Material	PVC panels	Aluminium frame
Mass (kg)	174	50
Material type	PVC	Aluminium
Source	Recycle	Recycle
Cycles of use	3	3
Collection rate	90%	90%
End-of-life	Reuse	Recycle
MCI	0,85	0,86
MCI total: 0,85		

Conventional façade

Material	Limestone	Glass wool	Masonry
Mass (kg)	2400	45	2273
Material type	Ceramics	Fibreglass	Concrete
Source	Virgin	Virgin	Virgin
Cycles of use	1	1	1
Collection rate	90%	90%	90%
End-of-life	Recycle	Recycle	Recycle
MCI	0,14	0,34	0,11
MCI total: 0,12			

Input data for the tables

The material weights refer to those used in constructing the bottom façade system of the first case study façade. In the MCI calculator, only a limited selection of materials could be chosen. When a specific material used in the façade system was not available in the list, an alternative material type with similar production processes and recycling potential was selected.

All materials are categorised as either virgin or recycled. The use of recycled materials is particularly relevant for aluminium and steel, as approximately 75% of aluminium and 70% of steel ever produced are still in productive use today (EuRIC AISBL, n.d.).

Environmental Product Declarations (EPDs) are used to provide information such as service life and end-of-life scenarios. The number of use cycles is based on the service life of each material. For example, when the service life is around 70 years, two cycles of use are assumed, since this report considers a 30-year usage scenario. A service life of 100 years is translated into three, four or five cycles of use, depending on the resilience of the material. Aluminium, being softer than steel, is assigned three cycles, while steel is given four. Bricks, known for their durability over centuries (Rotor vzw/asbl, 2021), are assigned five cycles.

The collection rate is based on the reuse potential researched in Chapter 3.5. Each structural and cladding element requires a certain amount of virgin material when applied to a new façade. During this process, some material will be lost. Brackets made from steel and aluminium are assigned a 95% collection rate, as they are standardised and highly resilient. All other materials are considered less resilient or less standardised and are assigned a 90% collection rate. For instance, bricks can break easily if not handled properly, cladding can be damaged by weather exposure and structural timber often needs to be cut in ways that result in material loss.

Structural systems

The MCI assessment highlights how effectively materials are sourced, reused and recycled across multiple life-cycles. Of the two structural systems, the Plywood-aluminium frame achieves the highest circularity score (0.92), owing to its high share of recyclable components and multiple cycles of use of both timber and metal brackets. The timber frame also performs strongly (0.89) but scores slightly lower due to its greater reliance on virgin timber.

The cycles of use are determined based on the service life of each material. In this assessment, the façade is assumed to be reused every 30 years. For example, if a material has a service life of 70 years, it would theoretically support only two cycles of use within that time frame. However, since the structural components are well protected by a water-repellent foil, their actual service life, and consequently their reuse potential, could be longer. Despite this possibility, such assumptions have not been incorporated into the current calculations.

Cladding systems

Among cladding options, the Pretty Plastic system attains the best MCI (0.85), driven by its predominantly recycled PVC panels and aluminium substructure with robust collection and reuse potential. Accoya (0.80) and ClickBrick (0.78) follow. Compared to a conventional façade (0.12), all circular designs vastly outperform industry norms. Overall, pairing the Plywood-aluminium frame with Pretty Plastic cladding creates the best performing façade system.

4.4 Test deconstructability and resilience (3DR)

The 3DR method is a way to measure how well buildings follow circular principles. It focuses on how they are designed, how easy they are to take apart (disassemblability), how they can be carefully dismantled (deconstructability), and how strong and reusable their materials and components are (resilience). This method only looks at circularity and does not consider environmental impacts. The 3DR method calculates a building's circularity using the 3DR index, which combines the building's disassemblability (DI), deconstructability (DE), and resilience (R). The formula for the index is:

$$3DR = DI \times a + DE \times b + R \times c$$

The value of the 3DR ranges from 0 to 1. A higher 3DR value, closer to 1, means the building is easy to take apart, reuse, and made with strong, reusable materials, allowing it to go through many cycles of reuse. A lower 3DR value means the building is designed in a way that makes it hard or impossible to take apart, reuse, or recycle, with a value of 0 meaning none of these is possible.

The 3RD method can be applied in two main situations:

1. In the End-of-life scenario, the building is completely disassembled, so *b* = 0, and the remaining influencers (*a* + *c*) add up to 1.
2. In the moving or reusing scenario, the building is carefully deconstructed instead, so *a* = 0, and the influencers (*b* + *c*) also add up to 1.

For this report only the deconstructability (DE) is important. That is why *a* will always be 0. The index influencers can be adjusted to focus on what is most important. For example, in the moving or reusing scenario, increasing *b* and decreasing c would make disassembly a bigger priority than resilience. In this report they will be equal, that means that b and c both will be 0,5. This means that the final formula for this report will be: 3DR = (DE x 0,5) + (R x 0,5). The following formulas can be used to find the disassemblability (DI), deconstructability (DE) and resilience index (R):

$$DI = \sum_{i=1}^{n}(DIt_i \times DIm_i \times w_i) \Big/ w_T \qquad DE = \sum_{j=1}^{m}(DEt_j \times DEm_j \times w_j) \Big/ w_T \qquad R = \sum_{k=1}^{t}(Re_k \times w_k) \Big/ w_T$$

To solve the equations, the weighted contributions of individual building components must be calculated. For the Disassemblability Index (DI), multiply the values for tools required (DIti), manpower or equipment needed (DImi) and the weight of each component (wi). Then, sum these products for all components and divide the total by the overall building weight (wt). The process is similar for the Deconstructability Index (DE).

For the Resilience Index (R), multiply the resilience score of each component (Rek) by its weight (wk), sum the results for all components (k = 1 to t), and divide by the total weight (wt). Finally, the overall circularity index is calculated using the 3DR formula, which combines DI, DE, and R, each weighted by their respective influence factors (a, b, c) (O'Grady et al., 2021).

The following pages present the step-by-step calculation of the formulas. To enhance clarity, the components of the 3DR formula will be colour-coded, with each part's solution shown separately. The assessment is based on the ground floor layout of the first case study façade. Both structural systems and all three cladding types will be calculated. Additionally, a conventional cavity wall façade is assessed as a reference case.

Symbol	Definition
DIt_i and DEt_j	Tools required
DIm_i and DEm_j	Equipment or people required
w_i and w_j and w_k	Weight of component
Re_k	Resilience of component k
w_T	Total weight of the building

Description	*Re value*
Reusable an infinite number of times	1
Reusable up to three times	0.9
Reusable only once	0.7
Recyclable	0.6
Downcyclable	0.2
Disposable	0

Variable	*Description*	*Operation and tools required*	*Value*
DIt, DEt	Availability, dimensions, and types of tools required to disassemble components (DIt) or deconstruct a building (DEt)	No tool	1
		Hand tool	0.9
		Power tool	0.8
		Gas/pneumatic tool	0.5
		Hydraulic equipment	0.2
DIm, DEm	People or equipment required to move components to another building (DIm) or move components following deconstruction (DEm)	One person: < 20 kg	1
		Two people: < 42 kg	0.9
		Hand trolley: < 50 kg	0.7
		Forklift: < 2,000 kg	0.4
		Crane: > 2,000 kg	0.1

Fig. 73 - Calculations and tables used for the 3DR method (O'Grady et al, 2021)

Plywood-aluminium frame structure

3DR = (DE x 0,5) + (R x 0,5)

$$DE = \sum_{j=1}^{m} (DEt_j \times DEm_j \times w_j) / w_T$$

Aluminium brackets

DEt_j = 0,8

DEm_j = 1

w_j = (1 bracket: 0,267 kg) x 63 = 16,8 kg

Plywood

DEt_j = 0,8

DEm_j = 1

w_j = 55 kg

Total = (13,5 + 44) / 71,8 = 0,8

$$R = \sum_{k=1}^{t} (Re_k \times w_k) / w_T$$

Aluminium brackets

Re_k = 1

w_k = 16,8 kg

Plywood

Re_k = 0,7

w_k = 55 kg

Total = (16,8 + 38,5) / 71,8 = 0,77

3DR = (0,8 x 0,5) + (0,77 x 0,5) = 0,785

Timber frame structure

3DR = (DE x 0,5) + (R x 0,5)

$$DE = \sum_{j=1}^{m} (DEt_j \times DEm_j \times w_j) / w_T$$

Timber beams with reversible connections

DEt_j = 0,9
DEm_j = 1
w_j = 0,543 m^3 x 450 = 244,35 kg

Total = 220 / 244 = 0,9

$$R = \sum_{k=1}^{t} (Re_k \times w_k) / w_T$$

Timber beams with reversible connections

Re_k = 0,9
w_k = 244,35 kg

Total = 220 / 244 = 0,9

3DR = (0,9 x 0,5) = (0,9 x 0,5) = 0,9

ClickBrick cladding

3DR = (DE x 0,5) + (R x 0,5)

$$DE = \sum_{j=1}^{m} (DEt_j \times DEm_j \times w_j) / w_T$$

Bricks

DEt_j = 0,9
DEm_j = 1
w_j = 2273 kg

Aluminium rails

DEt_j = 0,8
DEm_j = 1
w_j = 15 kg

Total = (2046 + 12) / 2288 = 0,9

$$R = \sum_{k=1}^{t} (Re_k \times w_k) / w_T$$

Bricks

Re_k = 1
w_k = 2273 kg

Aluminium rails

Re_k = 0,9
w_k = 15 kg

Total = (2273 + 13,5) / 2288= 1

3DR = (0,9 x 0,5) + (1 x 0,5) = 0,95

Pretty Plastic cladding

3DR = (DE x 0,5) + (R x 0,5)

$$DE = \sum_{j=1}^{m} (DEt_j \times DEm_j \times w_j) / w_T$$

PVC panels

DEt_j = 0,8
DEm_j = 1
w_j = 174 kg

Aluminium frame

DEt_j = 0,8
DEm_j = 1
w_j = 50 kg

Total = (139 + 40) / 224 = 0,8

$$R = \sum_{k=1}^{t} (Re_k \times w_k) / w_T$$

PVC panels

Re_k = 0,9
w_k = 174 kg

Aluminium frame

Re_k = 0,9
w_k = 50 kg

Total = (157 + 45) / 224= 0,9

3DR = (0,8 x 0,5) = (0,9 x 0,5) = 0,85

Accoya cladding

3DR = (DE x 0,5) + (R x 0,5)

$$DE = \sum_{j=1}^{m} (DEt_j \times DEm_j \times w_j) / w_T$$

Accoya cladding

DEt_j = 0,8
DEm_j = 1
w_j = 136 kg

Timber frame

DEt_j = 0,8
DEm_j = 1
w_j = 11 kg

Total = (108,8 + 8,8) / 147 = 0,8

$$R = \sum_{k=1}^{t} (Re_k \times w_k) / w_T$$

Accoya cladding

Re_k = 0,7
w_k = 136 kg

Timber frame

Re_k = 0,7
w_k = 11 kg

Total = (95,2 + 7,7) / 147= 0,7

3DR = (0,8 x 0,5) + (7 x 0,5) = 0,75

Flax insulation

$3DR = (DE \times 0{,}5) + (R \times 0{,}5)$

$$DE = \sum_{j=1}^{m} (DEt_j \times DEm_j \times w_j) / w_T$$

Flax

DEt_j = 1
DEm_j = 1
w_j = 72 kg

Total = (72) / 72 = 1

$$R = \sum_{k=1}^{t} (Re_k \times w_k) / w_T$$

Flax

Re_k = 0,7
w_k = 72 kg

Total = (50,4) / 72= 0,7

3DR = (1 x 0,5) = (0,7 x 0,5) = 0,85

Conventional brick cavity façade

$3DR = (DE \times 0{,}5) + (R \times 0{,}5)$

$$DE = \sum_{j=1}^{m} (DEt_j \times DEm_j \times w_j) / w_T$$

Masonry

DEt_j = 0,2
DEm_j = 1
w_j = 2273 kg

Glass wool insulation

DEt_j = 1
DEm_j = 1
w_j = 45 kg

Limestone elements

DEt_j = 0,2
DEm_j = 1
w_j = 2400 kg

Total = (454 + 45 + 480) / 4718 = 0,2

$$R = \sum_{k=1}^{t} (Re_k \times w_k) / w_T$$

Masonry

Re_k = 0,2
w_k = 2273 kg

Glass wool insulation

Re_k = 0,2
w_k = 45 kg

Limestone elements

Re_k = 0,2
w_k = 2400 kg

Total = (480 + 9 + 454,6) / 4718= 0,2

3DR = (0,2 x 0,5) + (0,2 x 0,5) = 0,2

Input data for the calculations

The tools required (detj) are based on the installation manuals of all products and connection types. For example, the Structurez connections can be deconstructed using only a hammer (hand tool), as stated in the installation manual provided by Woodinc. The plywood–aluminium system, specially developed for this report, uses screws for fastening and therefore requires a power tool. In contrast, the conventional cavity brick façade relies on chemical bonds that are not designed for disassembly. As a result, heavy equipment such as a demolition hammer or excavator is needed to dismantle it.

The equipment or personnel required (DEmj) is, in all cases, limited to one person, as all components weigh less than 20 kg when separated (O'Grady et al., 2021).

Reusability (Re) is determined by the service life of each material. For instance, when the service life is approximately 70 years, it is assumed that the product can be reused only once, based on the 30-year usage scenario considered in this report. A service life of 100 years corresponds to either three reuse cycles or an infinite number of reuses, depending on the material's resilience. Aluminium brackets are considered infinitely reusable due to their durability and standardisation. ClickBricks, are also assigned infinite reusability. The conventional cavity brick façade on the other hand, is downcycled (bricks are crushed into aggregate) resulting in a low reusability score.

Structural systems

The 3DR method evaluates ease of deconstruction (DE) and material resilience (R). Of the two structural systems, the timber frame achieves the highest 3DR score (0.9), while the Plywood-aluminium frame scores 0.78 due to lower resilience of the plywood elements. The conventional brick cavity façade has an overall score of 0.2, as it is usually demolished using hydraulic machines and the materials are downcycled rather than reused.

Cladding systems

For cladding, ClickBrick achieves the highest 3DR (0.95), reflecting the full recoverability and high resilience of brick and aluminium rails. Pretty Plastic follows at 0.85 and Accoya at 0.75.

The combination of a timber frame and ClickBrick cladding maximises deconstructability and material cycles of use, thereby creating the best-performing façade system.

4.5 Comparison

In this chapter, the circularity evaluation was conducted of the prefabricated façade systems through LCA, MCI and 3DR assessments. As mentioned earlier, the most important principles of the circular building economy are: narrow the loop, slow the loop, substitute and close the loop. All of these principles were considered in the design of the façade systems. The most notable outcome of this evaluation is that no single design dominates across all principles. Instead, different systems do better in different parts of circular design. This is visualised in the diagram on the following page.

In terms of narrowing the loop (prioritising reuse over new construction) the entire design strategy aligns well, as it centres around façade renovation rather than replacement. This reuse approach significantly reduces demand for new materials and construction.

For slowing the loop, which emphasises material efficiency and longevity, the timber frame structure performed best in the LCA (+A2) assessment with a total Global Warming Potential of -322 kg CO_2e, thanks to its high carbon storage and extended service life. The two lighter claddings, Pretty Plastic and Accoya, have similar CO_2 emissions per kilogram as ClickBrick but perform better overall due to their low weight. Although Accoya is wood-based, its GWP remains positive because of the energy- and chemical-intensive acetylation process. Still, Pretty Plastic scores slightly worse, as it uses an aluminium substructure, while Accoya uses timber.

When it comes to substitution, the MCI calculation provides a clear indication of whether renewable and environmentally friendly alternative materials are being used in the design. The results show that the Plywood-aluminium frame is the most circular structural system (0,92), thanks to recyclable materials and multiple reuse cycles. The timber frame also scores well (0,89) but relies more on virgin timber. For cladding, Pretty Plastic performs best (0,85) due to its recycled content and reuse potential, followed by Accoya (0,80) and ClickBrick (0,78).

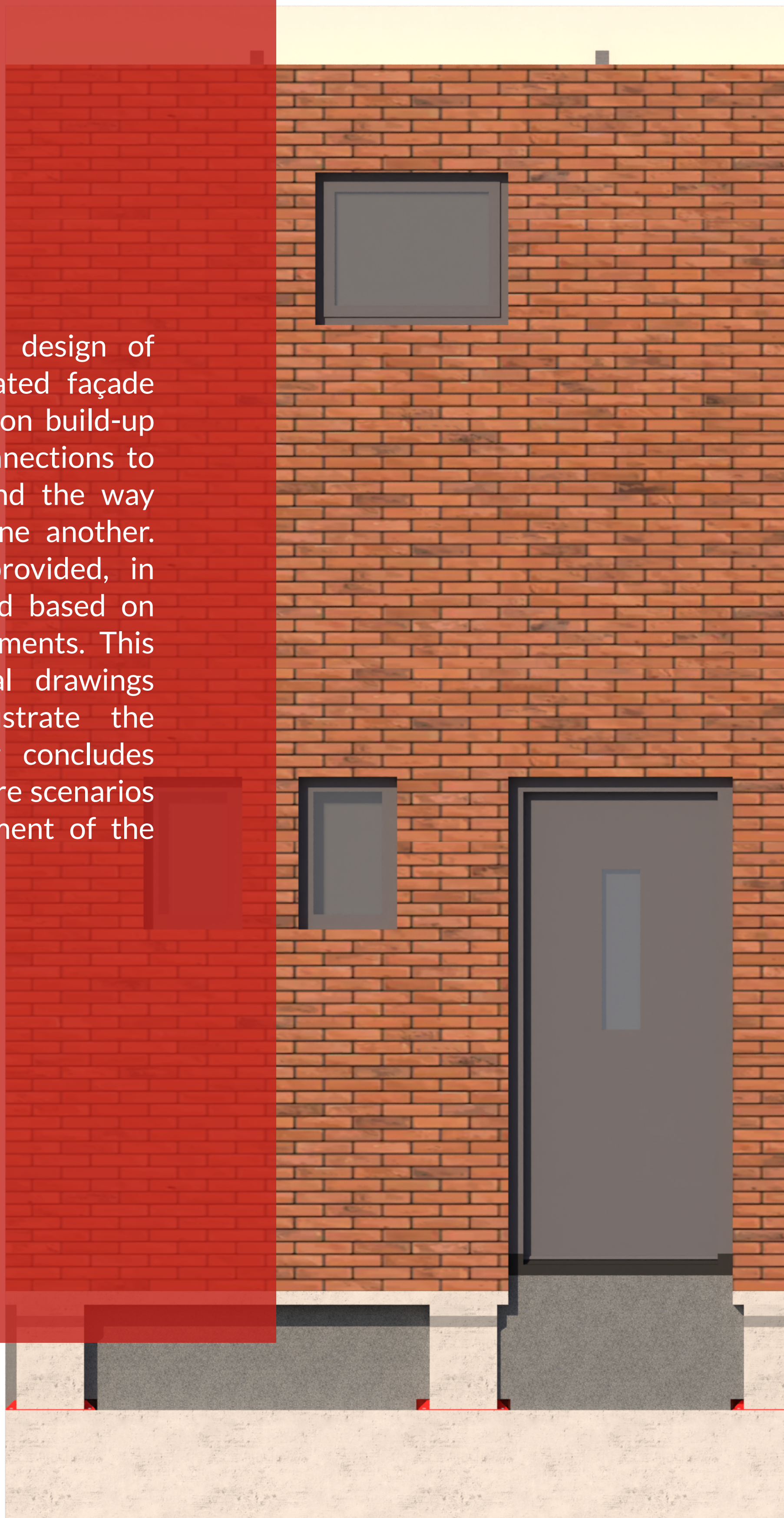
For closing the loop, which emphasises high-quality reuse, the ClickBrick cladding leads with the highest 3DR score (0.95), followed by the timber frame structure (0.9). These systems show excellent disassemblability, resilience and reuse potential. Which are critical for maintaining materials in continuous cycles.

When comparing full façade assemblies, the timber frame with Pretty Plastic cladding, while not the top performer in every assessment, shows strong and consistent results across all three methods and aligns with all four circularity principles. However, for specific project goals (whether prioritising recyclability, carbon reduction or adaptability) other combinations may be more favourable.

	Structures		Cladding			Conventional
	Timber	Plywood-aluminium	Accoya	Pretty Plastic	ClickBrick	Brick cavity facade
Feedstock						
Mass	348	163	147	224	2288	4718
Regenerative	70%	76%	80%	0%	0%	0%
Recycled	9%	21%	0%	96%	10%	5%
End-of-life						
Cycles of use	2	2	2	3	3	1
Recycle	8%	21%	0%	100%	100%	97%
Incinerate	71%	35%	100%	0%	0%	0%
Compost	21%	44%	0%	0%	0%	0%
Evaluation						
LCA (kg CO_2e)	-322	-132	78	258	574	2793
MCI	0,89	0,92	0,8	0,85	0,78	0,12
3DR	0,9	0,79	0,75	0,85	0,95	0,2

5 DESIGN PROPOSAL

This chapter presents the final design of the adaptable circular prefabricated façade system. It includes the construction build-up of the façade elements, their connections to the existing load-bearing wall and the way individual modules connect to one another. A real-case demonstration is provided, in which a final design is developed based on a set of fictional project requirements. This demonstration includes technical drawings and visual renderings to illustrate the proposed solution. The chapter concludes with a discussion of potential future scenarios for the application and development of the system.



5.1 Configuration

Façade system build-up

The final design of the two façade systems consists of two main layers: the structural layer and the cladding layer. Each of these layers is composed of multiple materials. Some materials are fixed components that appear in every configuration, while others can be selected based on specific performance requirements.

Structure

The structural layer provides rigidity to the entire façade system and connects to the existing load-bearing wall. It can be constructed using either a timber frame or a plywood–aluminium frame. The timber frame consists of softwood beams joined with reversible steel connections, allowing for disassembly and reuse. The plywood–aluminium frame is made of horizontal and vertical plywood planks connected by aluminium H-shaped brackets.

Flax insulation is placed between either the timber beams or the aluminium brackets. Other types of soft insulation can also be used, but during the early design stages, flax insulation best met the requirements compared to other materials. A water-repellent, vapour-open foil is installed between the structure and cladding layer to prevent water from entering while allowing interior moisture to escape. This works in combination with the moisture-regulating insulation. Protecting the insulation and structure ensures that the internal components will last at least as long as the cladding, preventing the need to replace inner layers before the outer layers of the façade system.

The timber variant performs better in terms of resilience and disassembly, though it is heavier. However, this added weight ensures greater carbon storage during the material's growth phase. On the other hand, the plywood variant is lighter and combined with materials like flax and steel (which outperform timber in terms of circularity) it achieves a higher material circularity indicator overall.

Cladding

Both structural options can be combined with one of three cladding types: Accoya, ClickBrick, or Pretty Plastic.

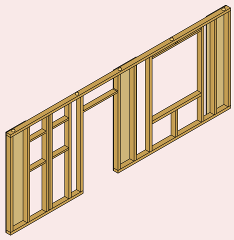
Accoya cladding is made from acetylated wood, which significantly enhances its durability. Due to its extended lifespan and the fact that it is the only fully renewable cladding option (including its substructure), it performs the best in the life cycle assessment that is focused on emissions.

ClickBrick performs best in resilience and ease of disassembly. The bricks are interlocked using metal clips and attached to the façade structure via reusable wall ties mounted on rails. When used in combination with the timber structure, the rail is unnecessary, as the wall ties can be drilled into and removed from the timber directly. However, the high weight of the bricks results in a relatively high environmental impact during production.

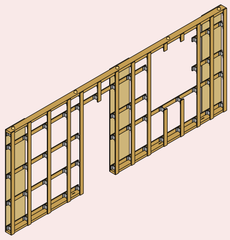
Pretty Plastic cladding, made from 100% recycled PVC, offers the best overall performance across all three assessment categories. It is mounted on an aluminium substructure, which is reusable. However, its horizontal orientation requires the aluminium to be cut on more places compared to, for example, the vertical rail system used for ClickBrick, thereby slightly reducing the efficiency of material reuse.

FACADE SYSTEM CONFIGURATION

Structures

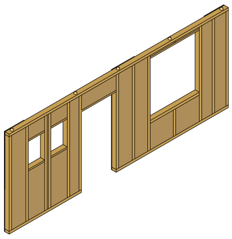


Timber frame

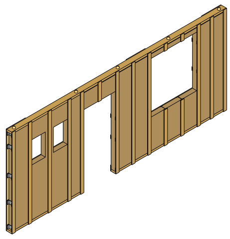


Plywood-aluminium

Insulation

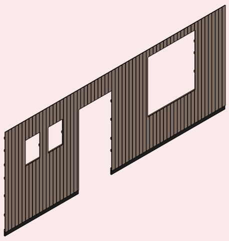


Flax on timber frame

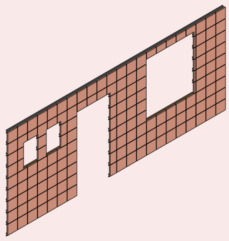


Flax on
Plywood-aluminium

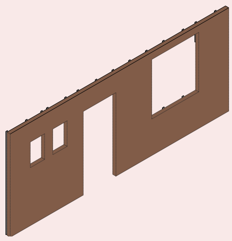
Cladding



Accoya

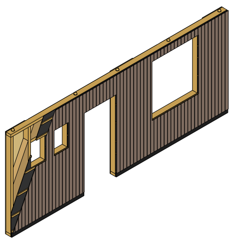


Pretty Plastic

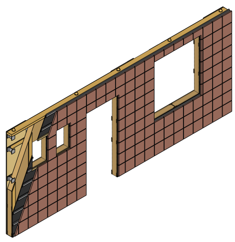


ClickBrick

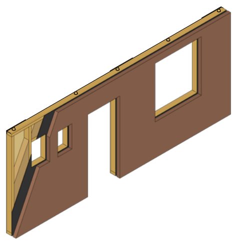
Best Performing
configurations



LCA - Timber & Accoya

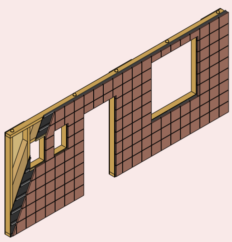


MCI - Plywood-aluminium
& Pretty Plastic



3DR - Timber &
ClickBrick

Best Performing
configuration overall



Timber & Pretty Plastic

Connections

The timber cone connections enable assembly without precise alignment. The upper facade unit slides onto the lower one, forming a secure, self-locking fit through cone-shaped joints with a 1 cm gap. Both units are anchored to the existing wall using steel brackets, which maintain spacing and prevent horizontal movement. The cone connections require no screws or chemical anchors and can be easily disassembled. Compressible sealing tapes between elements ensure airtightness and minimise thermal bridging.

The facade system rests on timber beams which are supported by prefabricated concrete footings bolted to the existing foundation. This method works for both timber and plywood–aluminium systems.

The ClickBrick cladding is added afterward, also supported by the concrete footings and resting on a concrete lintel. To compensate for the narrow foundation, the footings extend locally. The masonry's centre of gravity remains within the footing, ensuring stability. The concrete lintel with one or two ClickBrick rows are placed below ground for a seamless appearance.

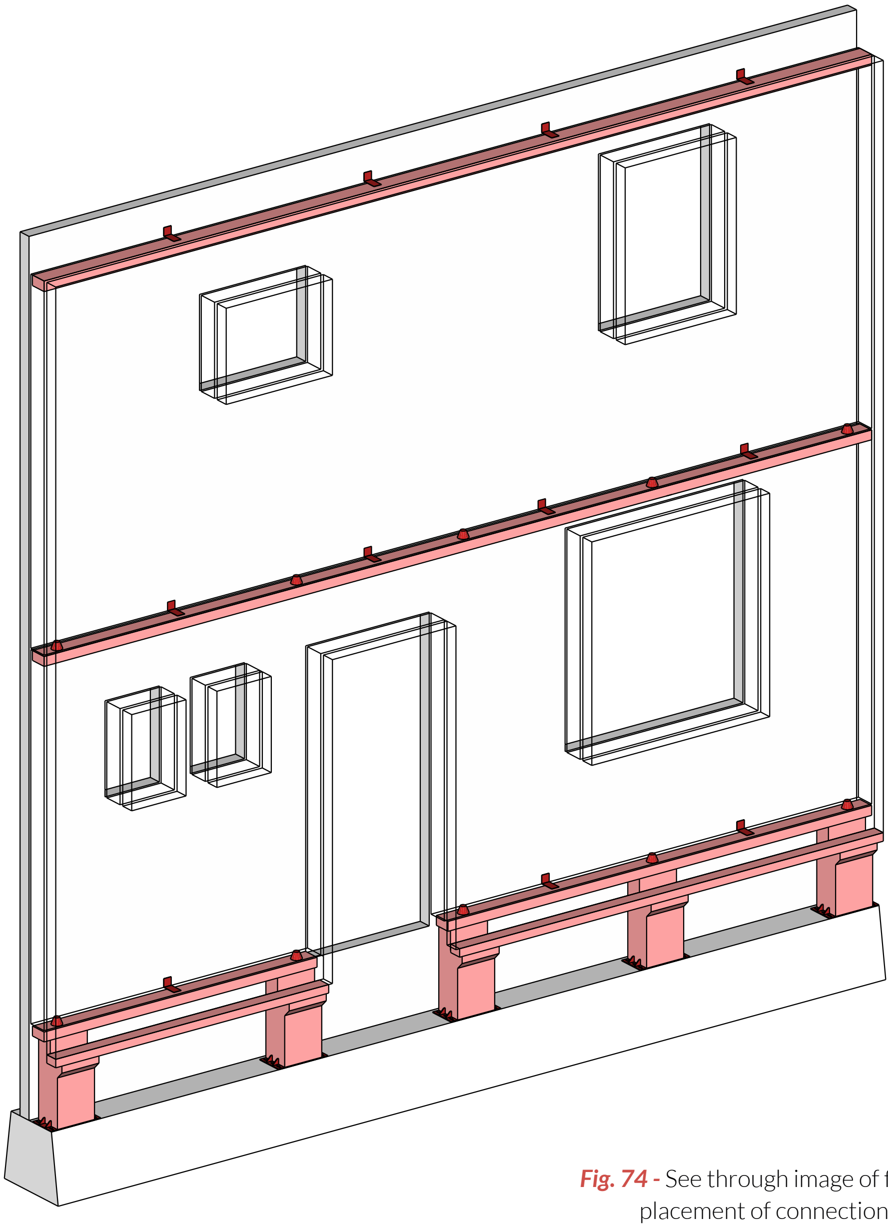
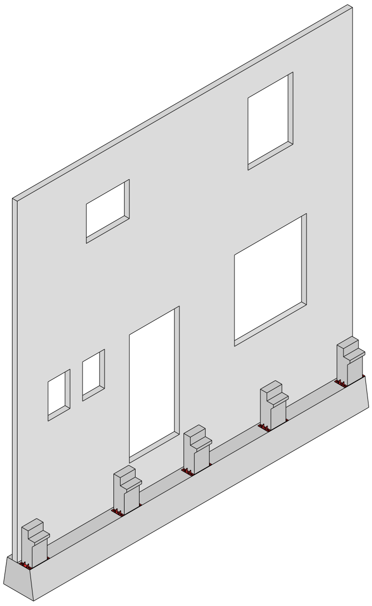
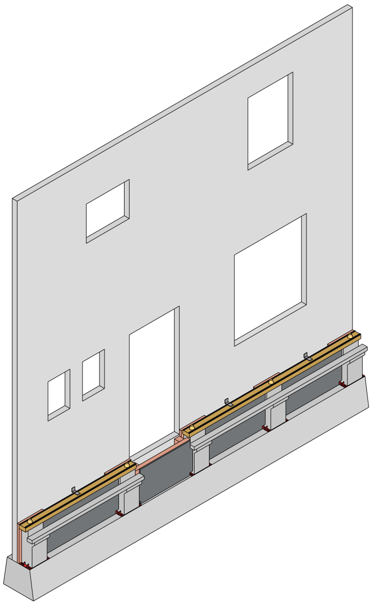


Fig. 74 - See through image of façade elements and placement of connections (own image, 2025)

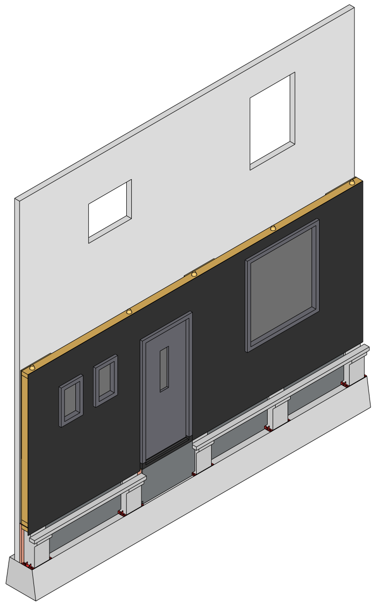
MOUNTING SEQUENCE



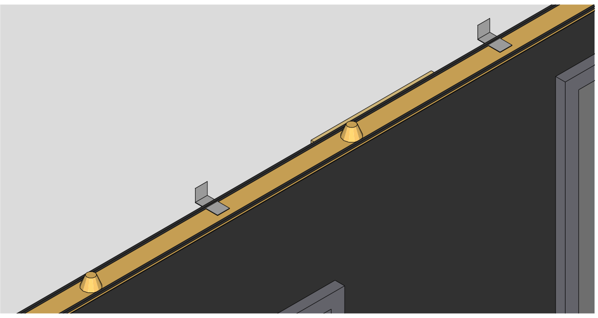
1. The prefabricated concrete footings are placed.



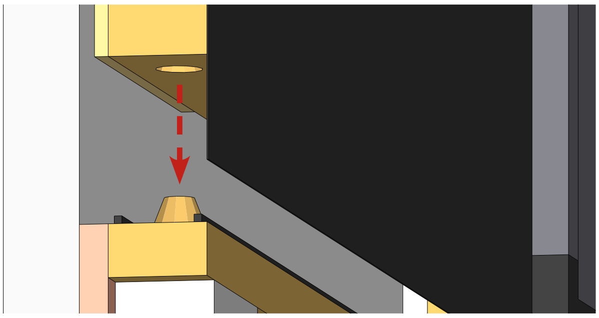
2. Next are the lintels, timber beams and Insulated skirt boards.



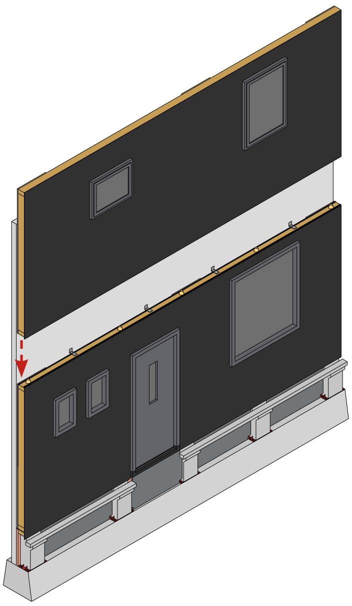
3. The facade system is placed on top of the timber cones.



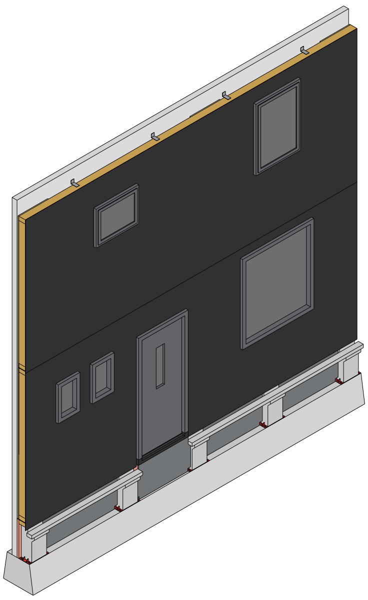
4. Steel brackets connect the facade system to the existing bearing wall, compressible sealing tape is placed on top.



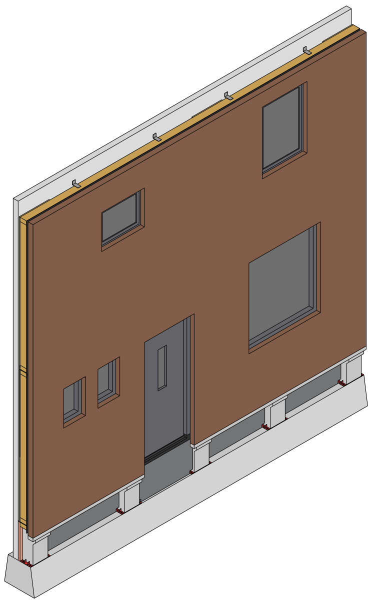
5. Milled holes in the beam at the bottom of the second façade system allow it to slide over the cones.



6. The second facade system is placed on top of the first system.



7. Steel brackets are placed on top of the second facade system.



8. The ClickBrick cladding is placed on the concrete lintels.

5.2 Real case demonstration

This section of the report demonstrates how a design team can utilise the information from this report. The proposed solutions and outcomes are applied to a real case study to illustrate how decisions are made and how a final design is developed. The conditions and requirements for the façade system are based on a scenario that reflects the priorities of a general housing association, as envisioned by the author. These conditions are: delivering a resilient façade that retains value after its initial service life (hence the choice for a reusable option), ensuring sustainability and maintaining resident satisfaction.

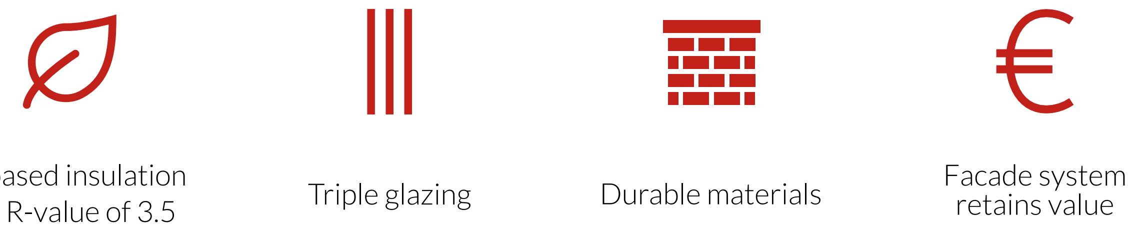
Requirements

This real-life scenario reflects the typical approach a general housing association might take when renovating the façades of post-war row houses. Upgrading the façade to improve its thermal resistance (R-value) reduces energy loss, leading to lower energy and/or gas costs. Enhancing the sustainability of the façade not only improves the association's public image but also reduces annual expenses.

In the Netherlands, landlords and housing associations can benefit from a subsidy scheme aimed at promoting sustainability and maintenance of rental properties. For façade insulation, the use of bio-based insulation material with a minimum R-value of 3.5 m²K/W is required, with at least 10 m² of the surface needing to be insulated (Rijksoverheid, 2024).

Subsidies are also available for installing double or triple glazing. Notably, the subsidy for triple glazing is more than four times higher than that for double glazing. To qualify, the triple glazing must have a maximum U-value of 0.7 W/m²K. An additional subsidy is available for installing new insulating doors with a maximum Ud-value of 1.0 W/m²K and window frames must have a maximum Uf-value of 1.5 W/m²K. A minimum of 3 m² must be insulated to be eligible (RVO, 2025).

The housing association will be responsible for repairs and the future reuse of the facade element. So it is assumed that they would prioritise two more key qualities in a renovated façade. These include durability (ensuring that minimal maintenance or repairs are needed over time) and the ability to retain value in the long term. The materials used should also be of high quality so they remain suitable for potential reuse in the future.



Design process

Configuration

To comply with all the requirements, specific materials must be selected. The first point of consideration is insulation. In the researched façade system, the insulation is always made from flax, which is a bio-based material. Therefore, it complies with the subsidy requirements for insulation.

The façade systems are not designed with integrated glazing; however, an opening has been provided to accommodate various window types. The installation of triple glazing is possible and will be done in the factory together with the rest of the facade system.

The next requirement is the use of durable materials to keep the façade as maintenance-free as possible. First, let's look at the structures. Both options are protected from weather conditions by a water-repellent foil. However, solid wood is more resistant to water absorption and more durable than engineered wood materials like plywood (Aliu & Fakuyi, 2019). Therefore, a solid timber frame structure will be used for this design assignment. For the cladding, a type with a long lifespan will be selected. The cladding options researched in this report that meet this requirement are ClickBrick and Pretty Plastic.

The final requirement is that the materials retain some of their value when reused at the end of their first service life. The timber frame structure uses reversible steel connections, ensuring that the timber beams remain undamaged during disassembly. As a result, both the timber beams and the connections can be reused. Among the three cladding options, ClickBrick is the best choice. Under Wienerberger's "Brick as a Service" program, parties returning used ClickBrick materials receive financial compensation based on the residual value of the returned components (Wienerberger, 2025). This program ensures that the bricks will be reused and that the housing corporation receives guaranteed compensation.

Evaluation

The evaluation process can be done by the design team; how to do so is explained in chapter 4. To evaluate the durability and reusability of the materials, both manufacturer data and the 3DR method were used. The 3DR method assesses not only the durability of a material but also its ease of disassembly and potential for reuse. A score closer to 1 indicates better theoretical performance in terms of durability and reusability.

Ease of disassembly can impact overall costs. Therefore, within the 3DR method, it is recommended to assign equal weight to both durability and disassembly in the calculation.

Both the timber frame structure and the ClickBrick cladding demonstrate excellent disassembly characteristics: they require only a basic hand tool (score: 0.9) and can be dismantled by a single person (score: 1). In terms of reuse potential, the timber frame structure can be reused up to three times (score: 0.9), while the ClickBrick cladding can be reused more than three times (score: 1).

The illustration below presents the performance of the assessed materials. As expected, the timber frame structure and the ClickBrick cladding achieve the highest overall scores, confirming their suitability from a durability and reusability perspective. The calculation can be found in chapter 4.4.

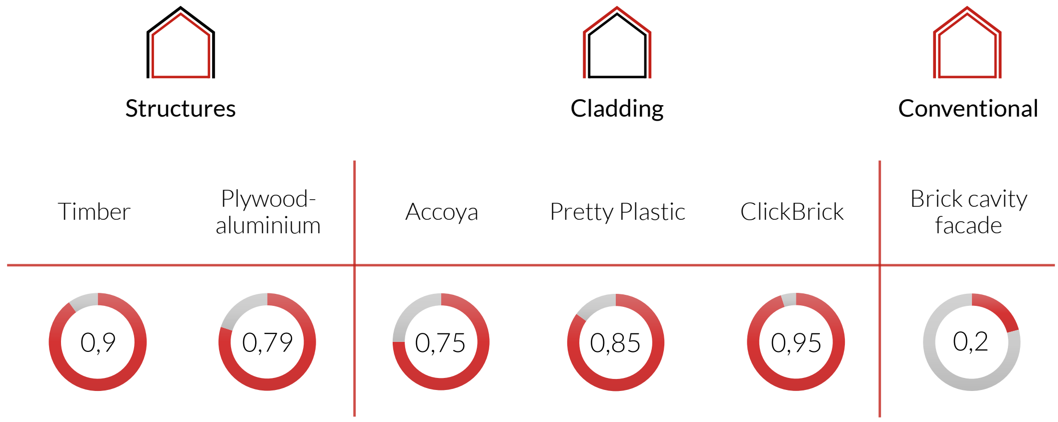
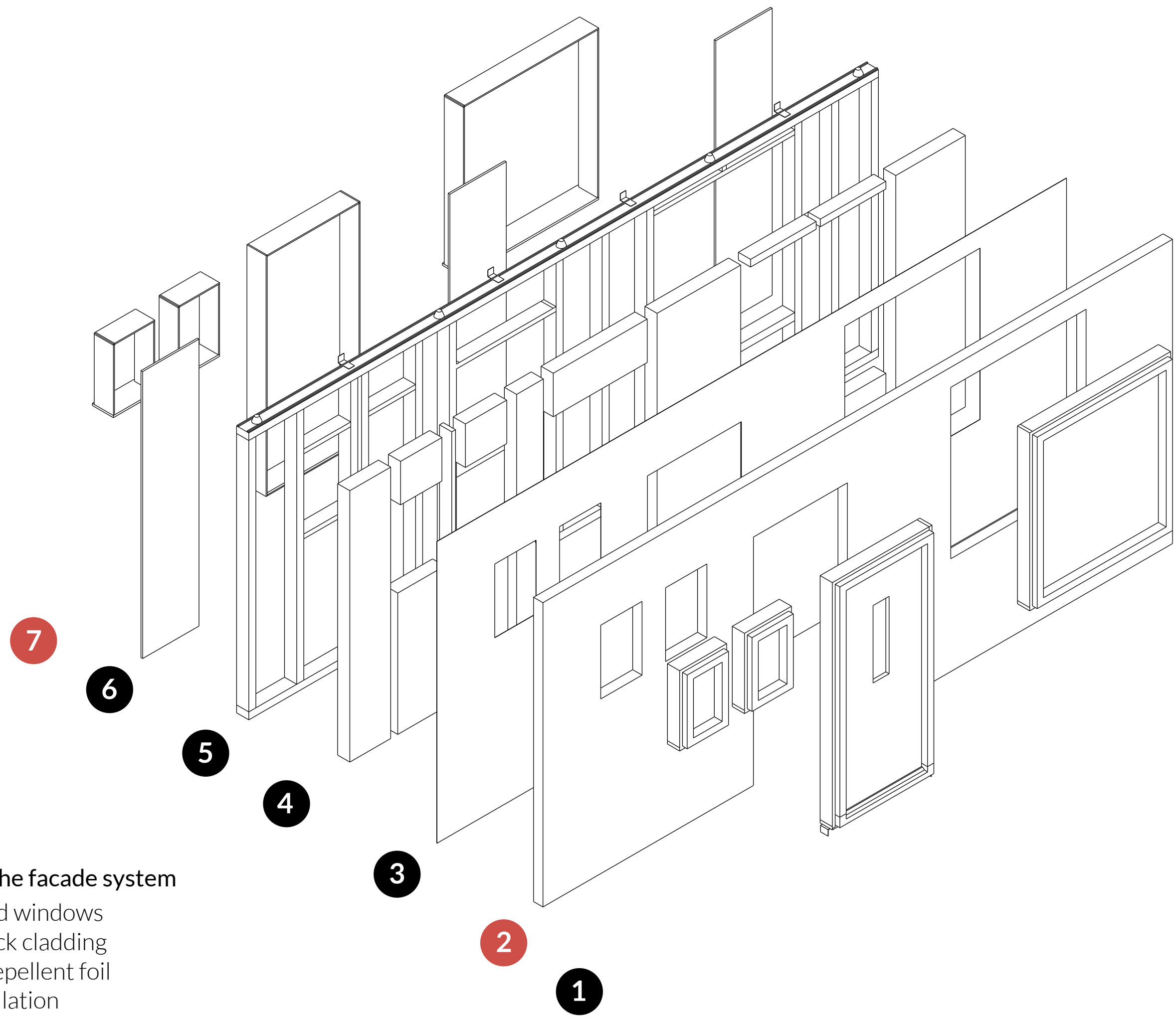


Fig. 75 - All the 3DR scores compared (own image, 2025)

Final design

Now that each layer within the façade system has been defined, the design phase can begin. The next step involves integrating door and window frames into the standard façade configuration. In addition, detailed technical drawings must be produced, including clear views and precise dimensions, to ensure accurate implementation. All these layers are shown down below in an exploded view. The layers with the red numbers will be placed on site.



Layers of the facade system

1. Door and windows
2. ClickBrick cladding
3. Water repellent foil
4. Flax insulation
5. Timber frame structure with joints and anchors
6. OSB plates
7. Internal lining

Fig. 76 - Exploded view of all the different layers (own image, 2025)

FRONT VIEW AND DETAILS

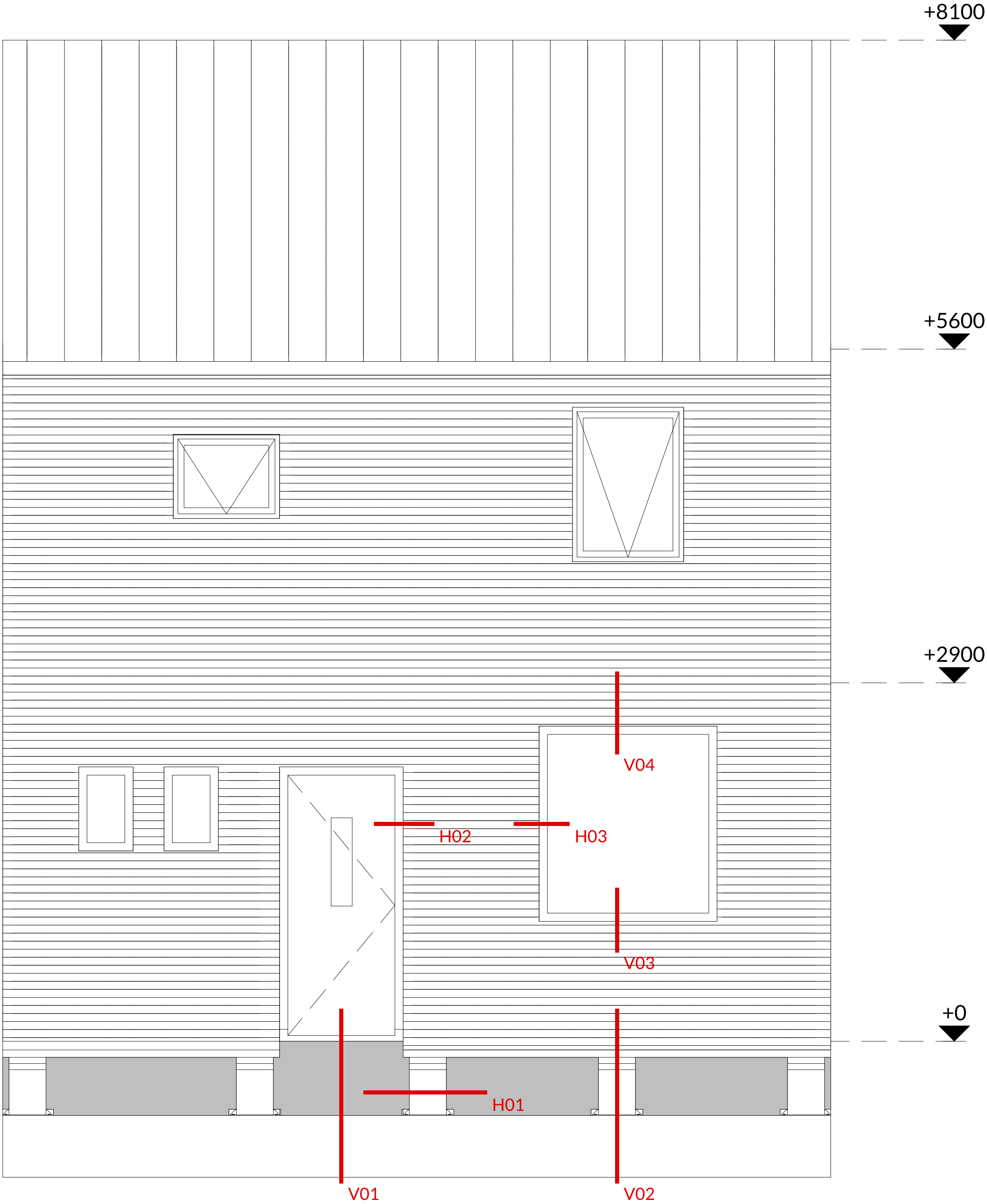
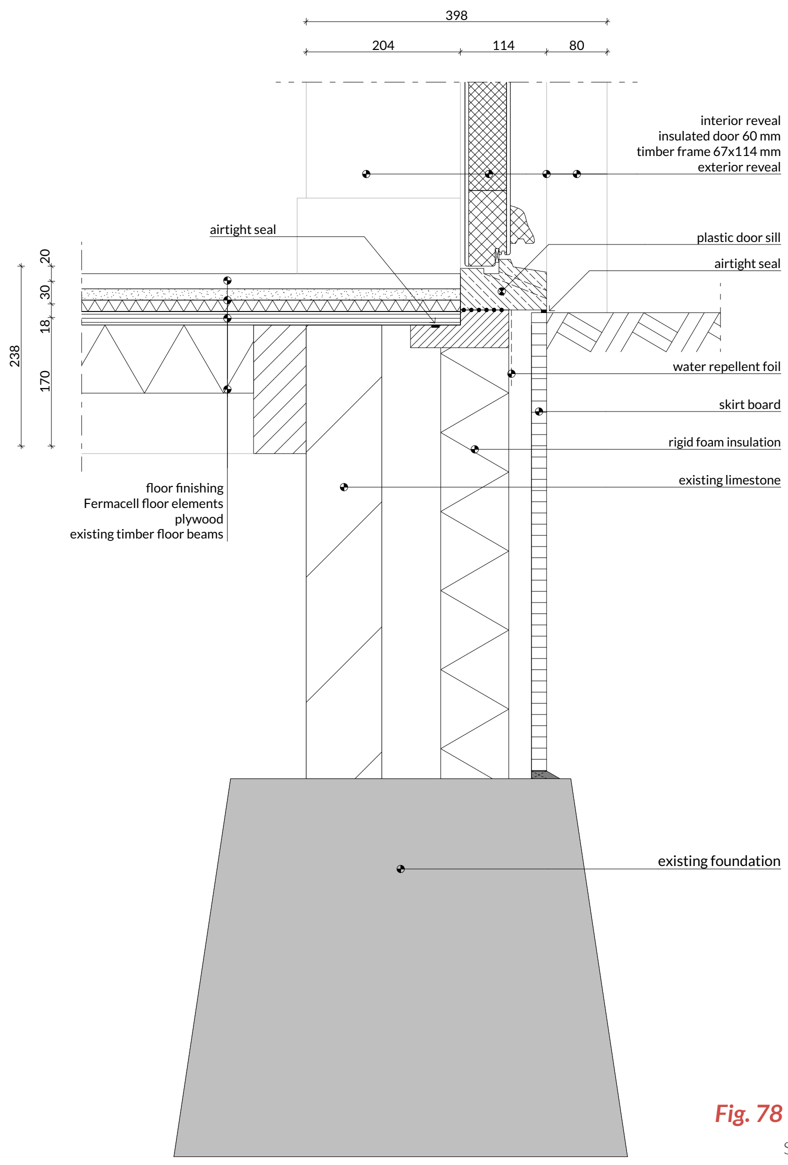


Fig. 77 - Placement of the details on front view, scale 1:50 (own image, 2025)

Foundation & door

This detail shows the connection of the door to the existing floor, limestone wall and foundation. The door is part of the façade system and is installed along with the rest of the system. After that, foam insulation and a skirt board are placed between the door and the foundation; the skirt board is not positioned directly against the insulation to prevent moisture from getting trapped in between. Following this, insulation is added between the existing floor beams and the Fermacell floor and finishing layers are installed on top. When the façade system is reused in the future, the deconstruction must follow the same sequence, but in reverse order.



V01

Fig. 78 - Foundation and door detail, scale 1:10 (own image, 2025)

Foundation & window

The following three details show the connection of the façade system to the existing foundation and load-bearing limestone wall. The timber cone connection between the bottom and top facade system can also be seen in detail V04. Like the door, the windows are pre-installed in the façade system at the factory. As mentioned earlier, the ClickBrick façade will be installed at a later stage. This means that the drip sill and steel lintel will also be installed later.

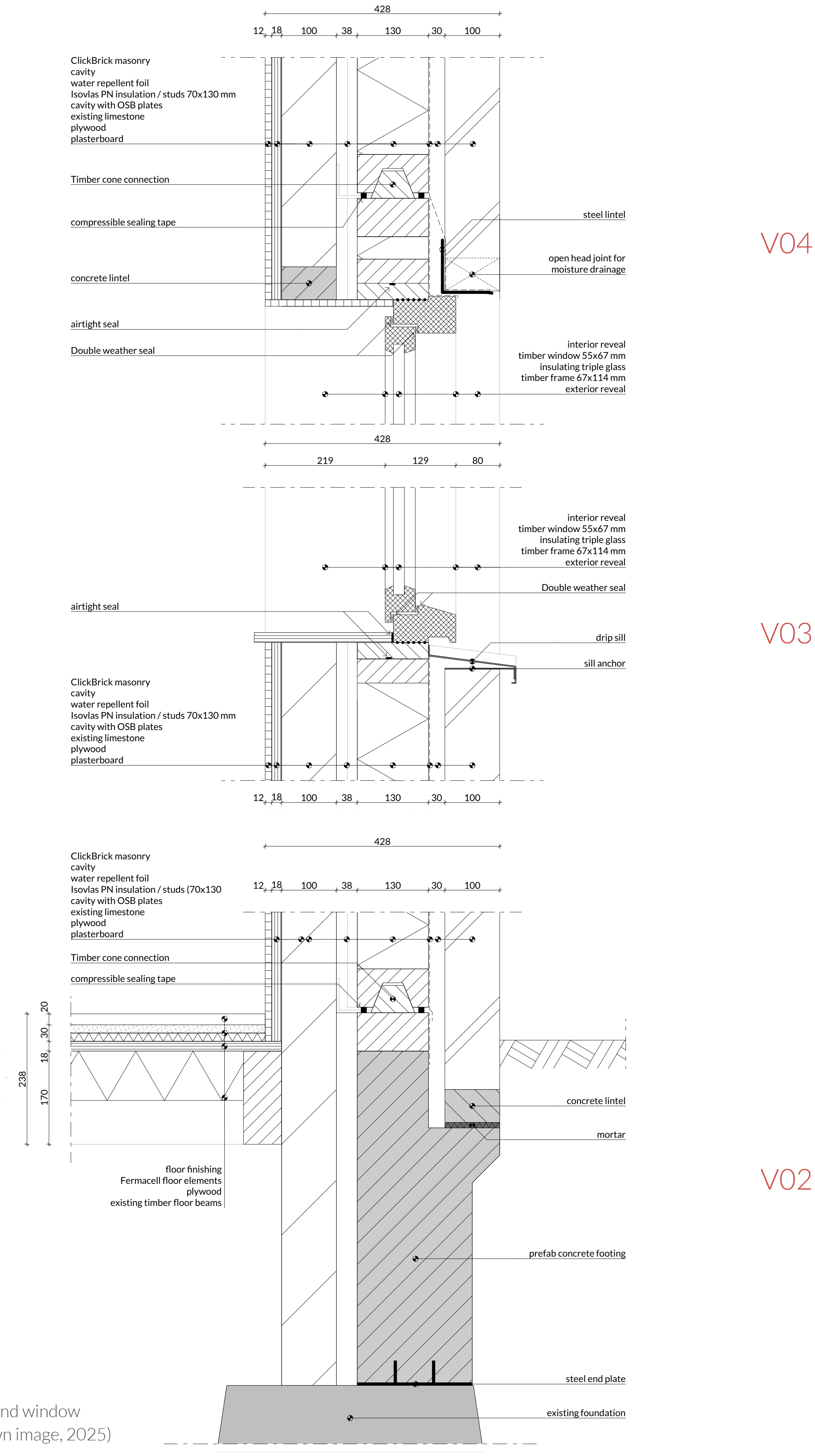
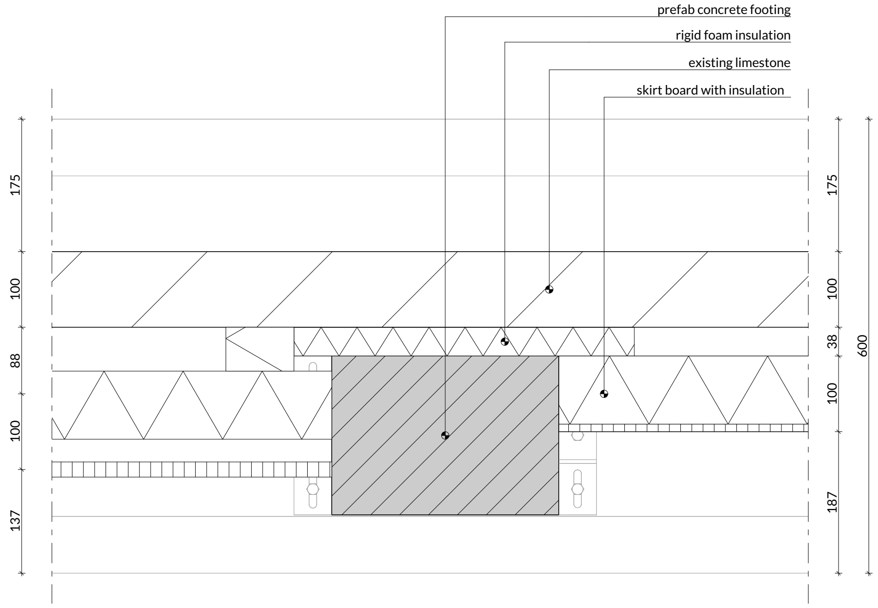


Fig. 79 - Foundation and window details, scale 1:10 (own image, 2025)



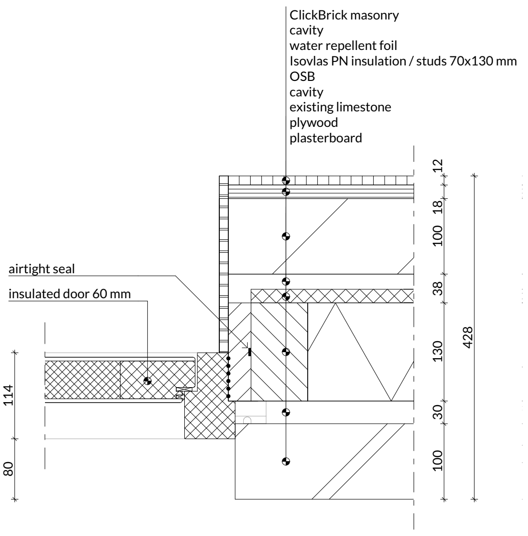
H01

Fig. 80 - Foundation detail, scale 1:10 (own image, 2025)

Foundation, door & window

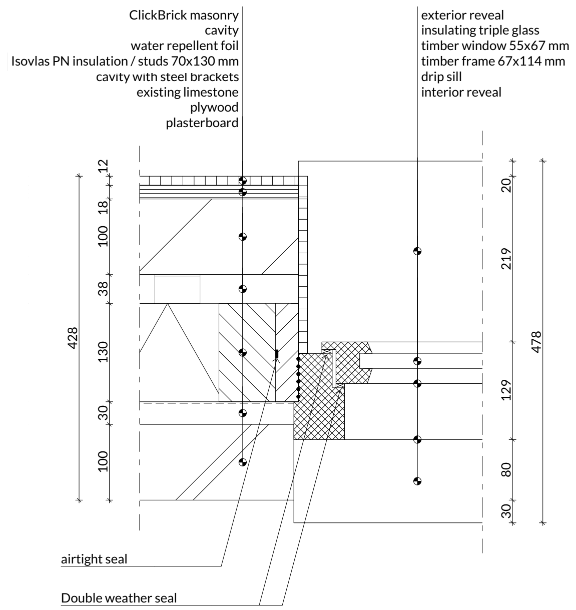
The first horizontal detail shows how the insulation wraps around the prefabricated concrete footing located on the right side of the door. The insulation also extends past the steel end plate that connects the footing to the foundation, as the rigid insulation cannot fully cover that area.

The last two details show that the exterior and interior reveals are identical for both the door and window openings. In the cavity near the door, one of the OSB plates that provide rigidity to the façade system is visible. The cavity near the window shows a top view of one of the brackets connecting the existing load-bearing wall to the façade system.



H02

Fig. 82 - Door detail, scale 1:10 (own image, 2025)



H03

Fig. 81 - Window detail, scale 1:10 (own image, 2025)

Future scenarios

As mentioned earlier, the housing association will be responsible for repairs and the future reuse of the facade element. Therefore, this sub chapter will explore two possible scenarios that could occur in the future when using the facade system.

Scenario 1: Buildings stays unchanged for 70 years

The first scenario assumes that the row houses with the facade systems remain unchanged for 70 years. However, during that time, it is likely that some components will require maintenance or replacement due to normal wear and tear, weather conditions or accidental damage. Additionally, the service life of certain materials may not extend the full 70 years.

According to the Environmental Product Declarations (EPDs) of the materials used in the facade, some components, such as the flax insulation and the water-repellent foil, have a service life of approximately 70 years. This means that there is a possibility that these materials need to be replaced early. To access these materials, the first layer (ClickBrick cladding) must be removed. The ClickBricks can be disassembled piece by piece and after replacing the insulation and foil, the same bricks can be reused to reconstruct the cladding.

If a window frame requires replacement, only a few bricks at the side need to be slid out and the internal lining must be removed.

In the case of a severely damaged brick, it can be chiselled out and replaced with a new one using a small amount of mortar, rather than the standard steel clips. This is necessary when it is not feasible to remove all surrounding bricks.

Fig. 83 - Render of how the facade system would look on the row houses with white window frames (own image, 2025)

Scenario 2: Deconstruction after 30 years

This scenario assumes that the row house will be deconstructed after 30 years. In this case, the facade system can be reused, as the flax insulation and water-repellent foil will still have 40 years of service life remaining and the rest 70 years or more. The system can remain intact and be used for another building in the neighbourhood with the same facade layout or for a new building that adopts the exact same design.

Alternatively, the facade system could be reused for a building with a different facade layout. In that case, the system would need to be disassembled layer by layer and reassembled accordingly. This reuse process is illustrated in the conclusion of Chapter 3.6.

In both scenarios, the concrete footings can also be reused, as they are bolted to the existing foundation. However, the new foundation must be placed at the same depth to ensure proper alignment.

In all of these cases, the façade systems can remain in the possession of the housing association. However, if the materials are to be used for buildings outside the association's portfolio, a third party must be identified, one that is both interested in reusing the materials and capable of designing and building with them. To enable this, the technical drawings and system knowledge must be transferred to the new party. Once this transfer is complete, the design process for new façades can begin.

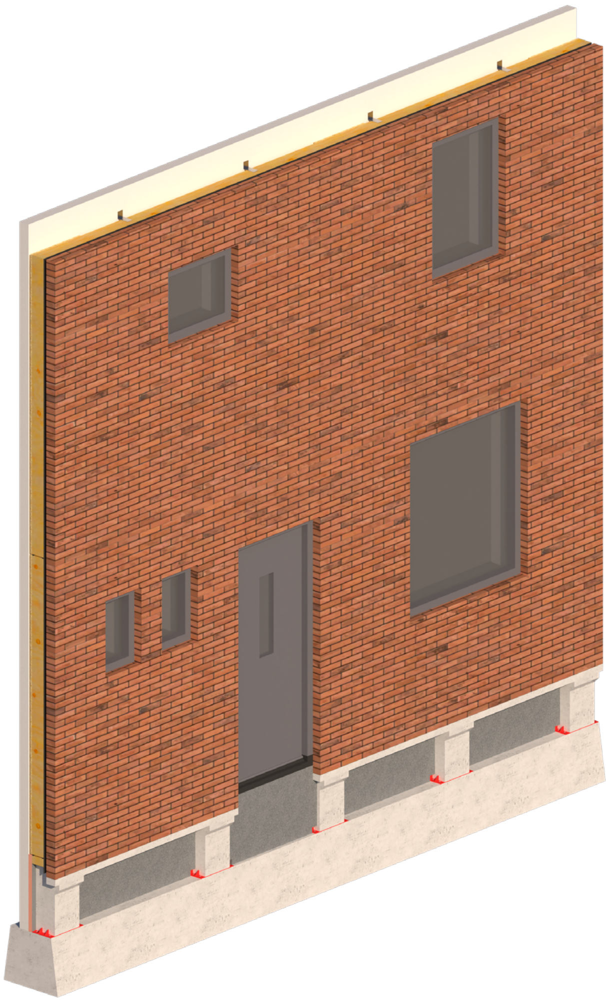
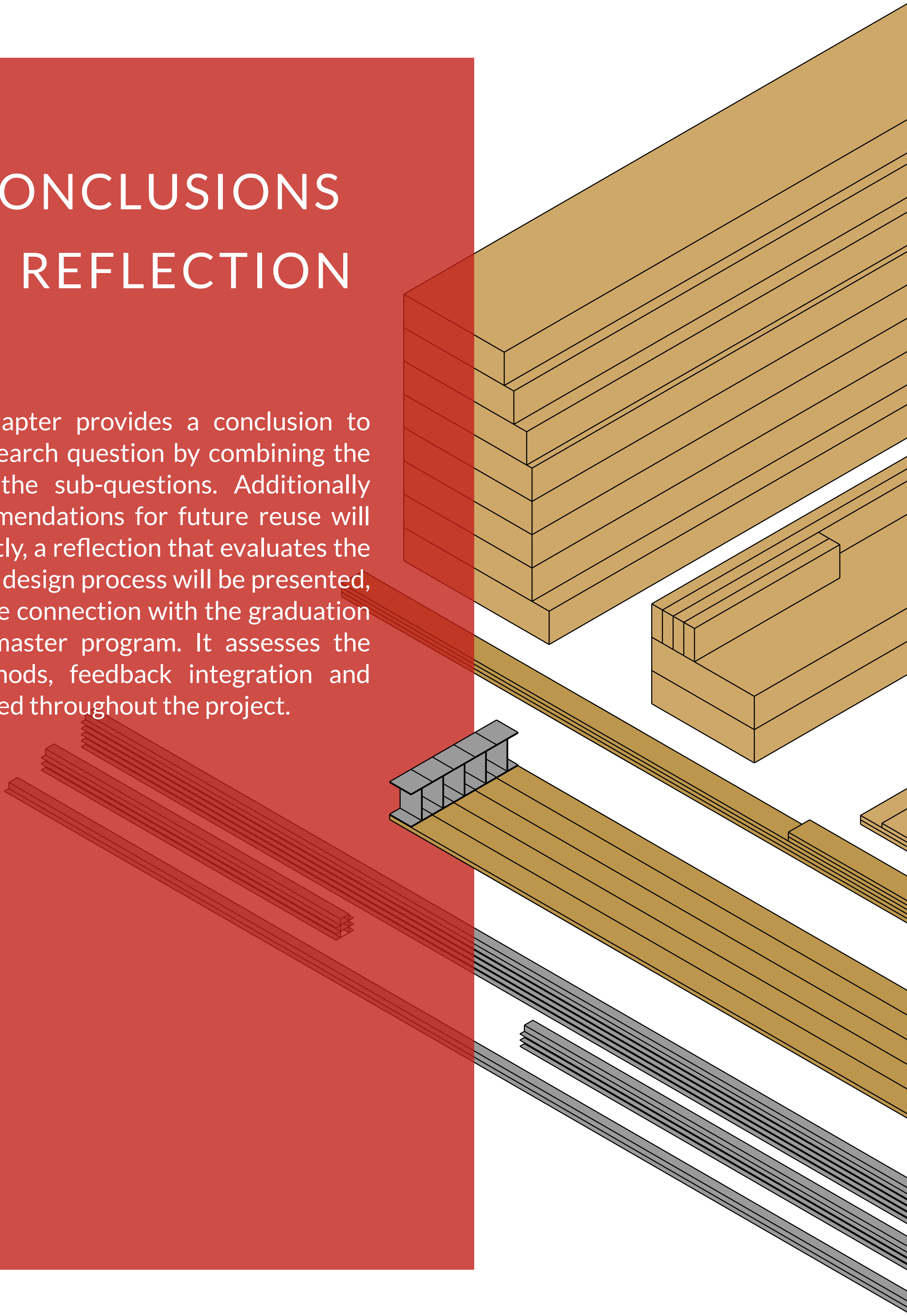


Fig. 84 - Render of the complete facade system for one dwelling with grey window frames(own image, 2025)

6 CONCLUSIONS & REFLECTION

This final chapter provides a conclusion to the main research question by combining the answers to the sub-questions. Additionally some recommendations for future reuse will be given. Lastly, a reflection that evaluates the research and design process will be presented, examining the connection with the graduation studio and master program. It assesses the impact, methods, feedback integration and lessons learned throughout the project.



6.1 Sub-question

Which materials and connection systems are most suitable for reuse in façade renovation, based on an evaluation through circularity assessment methods?

To identify materials and connection systems suitable for reuse, a circular design framework was first developed to exclude materials that emit large amounts of CO_2 during production or cannot be reused at the end of their life. This early filtering step ensured that only materials with high circular potential (based on criteria such as adaptability, reusability and low embodied carbon) were carried forward into the design phase.

The selected materials and structural systems were then evaluated using a combination of circularity assessment methods: Life Cycle Assessment (LCA), Material Circularity Indicator (MCI) and the 3DR method. Together, these methods addressed all four core principles of circularity. Narrowing the loop, slowing the loop, substituting and closing the loop. Closing the loop emphasises reuse. This was specifically addressed through the MCI which assesses how materials are sourced and retained within the building industry after use. The 3DR method also is closely related with closing the loop, which quantified the reuse potential of each system.

As a result, no single material or connection dominates across all principles. Instead, different systems perform better in different aspects of circular design. When considering the entire life cycle from beginning to end, the MCI calculation results show that the plywood-aluminium frame is the most circular structural system, thanks to its high concentration of recyclable materials and potential for multiple reuse cycles. The steel brackets in this system score higher than the plywood, as they can be reused more frequently and recycled without losing their properties. The timber frame also scores well but relies more heavily on virgin timber. For cladding, Pretty Plastic performs best due to its recycled content and reuse potential.

The 3DR method focusses solely on reuse frequency and the effort required to disassemble the different layers the ClickBrick cladding leads, followed by the timber frame structure. These systems demonstrate excellent disassemblability, resilience and reuse potential. The ClickBrick and steel connections in the timber can be assembled using only a hammer and the materials are capable of lasting through multiple reuse cycles.

Crucially, all systems relied on dry, reversible connections, such as screws or drive pins, to support disassembly and future reuse. This choice not only supports easier material recovery but also simplifies adaptation when the facade system is reused.

How can an industrialised façade renovation system be standardised while maintaining adaptability for diverse row house home designs?

Standardisation is achieved by defining a fixed modular grid and using a limited palette of interchangeable components, which are then adapted to suit each specific façade. In this report, all façade systems use either beams or plywood planks with the same width and thickness, allowing horizontal and vertical members to be prefabricated in batches. Steel or aluminium connectors are also standardised across all systems to maintain consistency. The structural members are spaced at 600 mm centre-to-centre, to comply to the specific requirements of the cladding. Digital tools and machines are used to accurately translate the design into a façade system that fits precisely onto the existing building. Finally, cladding types composed of small, modular elements are selected, as they can easily adapt to a wide variety of façade layouts.

How can an industrialised façade renovation system be designed to accommodate the varying service lives of its components while ensuring reusablity for future buildings?

The system is layered so that each component's service life is matched by its accessibility and ease of replacement. A vapour-open, water-repellent foil separates the structural layer (timber or plywood–aluminium with flax insulation) from the cladding, enabling inner layers to outlast the outer finish. Cladding types (such as Accoya and Pretty Plastic) that can be removed individually per panel or plank are preferred, as they can be swapped out without dismantling the entire facade system. This ensures that each element remains in use for as many cycles as its durability allows.

How can a circular façade system be developed based on specific project requirements?

Each renovation project will come with its own specific requirements. A circular façade system can be developed by using these requirements as a foundation for design. Initial requirements related to cost and aesthetics serve as a starting point for selecting appropriate materials. Following that, requirements concerning durability, reusability, and environmental impact can be linked to targeted assessment methods. Each method focuses on a specific aspect. Life Cycle Assessment (LCA) quantifies environmental impact. The Material Circularity Indicator (MCI) assesses how materials are sourced and retained within the building industry after use. The 3DR method evaluates reuse potential and resilience. These tools guide the design toward solutions that are both environmentally sound and practically reusable. For example, a requirement for low embodied carbon aligns with the principle of substitution. The LCA can be used to identify suitable low-impact materials that meet this need.

Once these choices were made, the final configuration followed. The combination of project requirements and evaluation method(s) resulted in a suitable façade system. Technical drawings will how each layer can be integrated into a modular and prefabricated format that fits the existing building façade layout. Rather than relying on inseparable anchoring methods, the system should use dry connections that preserve both the façade and any additional components.

6.2 Research question

How can an industrialised façade renovation system incorporate future component reuse while being adaptable to different façade layouts?

Implementing circularity in façades during renovation projects requires embedding circular principles from the very beginning of planning and design. To achieve this, the process must be structured as an ongoing information loop between client, researcher, manufacturer and designer, supported by building information models and specification documents. In practice, these different strategies should guide the planning and design process:

Break the façade down into layers

Rather than treating the façade as a monolithic element, break it down into distinct layers: structure, weather barrier, insulation and cladding. This approach enables targeted material selection and ensures that each layer can be independently upgraded, repaired or replaced.

Use a standardised grid

Easy reuse can be achieved through a standardised modular grid with uniform components and connection types. Using small cladding elements instead of large panels makes the façade more adaptable to different layouts. Avoiding unnecessary complexities and relying on standardised elements will also accelerate prefabrication because it allows people to become more efficient through familiarity and enabling machines to be programmed in a consistent way.

Prioritise durable and/or bio-based materials
When selecting materials give preference to products with significant recycled content, high reuse potential and bio-based alternatives, as these materials either remain in the technical cycle or the biological cycle.

Design for disassembly with reversible connections
All layers and components must be joined using dry, mechanical fixing methods (clips, screws, drive pins, etc.) and avoid adhesives or permanent chemical bonds. There must be a clear separation of layers, so that individual materials can be recovered at the end of their life without damage. Coordination between façade engineers and contractors ensures proper realisation of these details.

By integrating these strategies into the early stages, project teams can ensure circularity is not an afterthought but a guiding principle. Resulting in façades that preserve material value, reduce waste and remain adaptable over multiple cycles of use.

6.3 Recommendation for future research

Broader material exploration
One key opportunity lies in expanding the range of materials considered. Future studies could evaluate a wider variety of materials using Life Cycle Assessment (LCA), the Material Circularity Indicator (MCI) and the 3DR method (Disassemblability, Deconstructability, and Resilience). The results could be compiled into a database that indicates which materials perform best in which scenarios. This information could then be translated into a practical, guide-like booklet to support designers in making material choices.

Integration of additional assessment methods
Further research could also explore the application of additional environmental assessment tools. A valuable example is the Environmental Cost Indicator (ECI), or Milieukostenindicator (MKI) in dutch. It is commonly used in the Netherlands. This method quantifies environmental impact in economic terms, representing the societal costs of environmental damage over the full life cycle of a product or project. Integrating this or similar tools could enhance the depth of the evaluation.

Broader range of façade types
Another potential research direction is the investigation of a wider variety of façade types. The current study focused on façade systems with similar dimensions but with a different layout. Future research could assess systems with significantly different geometries, structural principles or applications such as high-rise façades or curved façades.

Practical implementation and business models
Finally, further investigation is needed into the real-world feasibility of reusable façade systems managed by housing associations or other stakeholders. Research could focus on identifying

potential industry partners, understanding existing business models (if any) and exploring whether there is market interest or willingness to adopt such systems. This could include intern ships, interviews, pilot projects, or case studies to assess logistical, legal and financial implications.

6.4 Reflection

Graduation process

There are five main topics in the Building Technology studio: circular products, façade design, structural design, energy & climate design and computational design. My graduation project falls under both circular products and façade design. The main objective was to explore how a façade renovation system could incorporate future component reuse while remaining adaptable to different façade layouts.

The methodology I chose was research through design. Because of this approach, I was eager to begin designing as soon as possible. However, thanks to my mentors it became clear for me that the primary goal of the research was not to produce a final product, but to explore and develop a method or approach. Therefore, I had to take a step back and focus on the literature review to gather all the relevant information needed for the next phases. This allowed me to move forward without needing to return to extensive research later on.

When it was time to begin designing, it became a valuable opportunity to apply the knowledge I had gained. I first designed according to circular economy principles and then evaluated the design using three assessment methods. This process was a meaningful test to verify whether the knowledge I had applied was accurate and effective in practice. The research did in fact help me a lot to choose what kind of materials, connections and assessment methods worked best for my design. I was initially focused on finding the perfect design for every possible scenario, but my mentors helped me realise that it's also valuable if one design works well for one situation, while another design is better suited for a different situation. Additionally, I had some trouble with clearly explaining my process and justifying the steps I took throughout the research. My mentors advised me to create diagrams and schemes to make everything more accessible and to include more conclusions between chapters to highlight key milestones.

Academic and societal value

This research expands circular construction knowledge by integrating reuse principles into industrialised renovation, a less-studied area compared to new builds. By combining modular prefabrication with adaptable, circular design, it bridges the gap between theory and implementation in façade refurbishment. Using methods like LCA, MCI and 3DR, the study evaluates materials and connections, translating findings into a practical, replicable design approach for sustainable renovation.

Based on my research, I believe the results are highly applicable in practice, especially given the urgent need to address both environmental concerns and the housing shortage. By proposing a prefabricated, adaptable and circular façade renovation system, I offer a practical solution that aligns with real-world challenges. Particularly in countries like the Netherlands where a outdated post-war housing stock is common. The system I designed responds directly to the shortcomings of current façade solutions by accommodating disassembly and reuse, thus reducing material waste and supporting long-term sustainability goals in the built environment.

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8 APPENDIX

1 Introduction

-

2 Literature review

Placement pyramid and CO2 emissions (for framework)

<0 = 0 points
0 - 100 = 1 point
100 - 1000 = 2 points
>1000 = 3 points

Façade cloth (use PE film): 0,03 m3 x 263 = 7,89 kg CO2 (1 point)
Aluminium frames: 0,032 m3 x 2282 = 73 kg CO2 (1 point)
Wooden supporting structure: 0,062 m3 x 680 = -42,16 kg CO2 (0 points)
EPS 3,8 m3 x 46,8 = 177.84 kg CO2 (2 points)

Pretty plastic: 78kg CO2 (1 points)
Aluminium profiles: 73 kg CO2 (1 point)
Aluminium supporting structure: 48.6 kg CO2 (1 point)
Glass wool: 58 kg CO2 (1 point)

Click brick: 660 kg CO2 (2 points)
Wall ties: 16 kg CO2 (1 point)
Glass wool: 58 kg CO2 (1 point)

3 Design process

Case study houses

Bricks
Layer height 6,5 cm
Length 22 cm
Width: 11

Photo's

Fig. 85 - Picture of the basement of the first case study house
Fig. 86 - (Source:https://www.funda.nl/detail/koop/verkocht/nijmegen/huis-patrijsstraat-36/43646446/media/foto/33)

Fig. 87 - Pictures taken on site visit (source: own

Drawings form Municipal Building Archive of Nijmegen

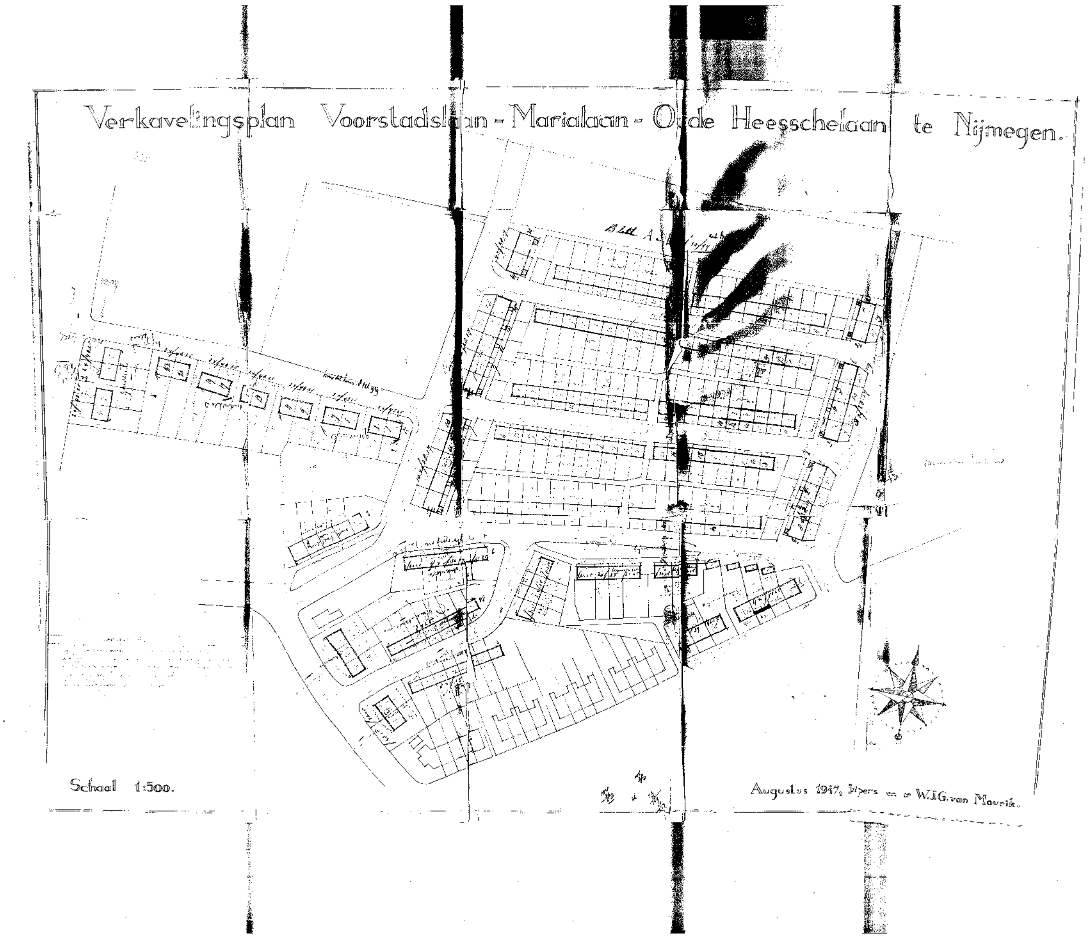

Fig. 88 - Development plan neighbourhood

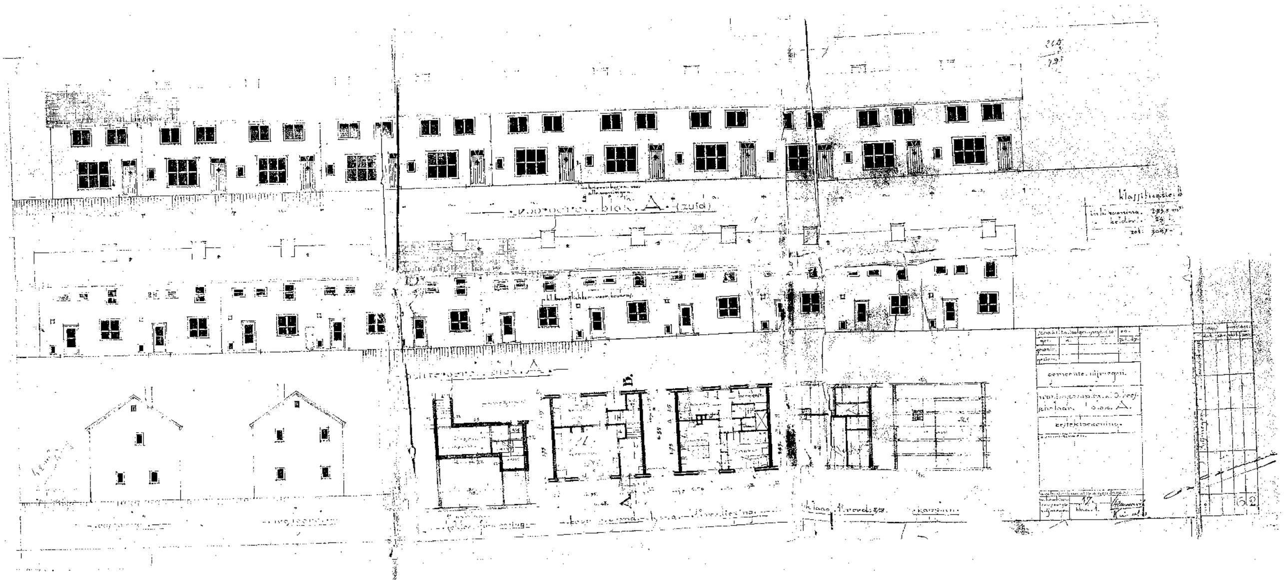

Fig. 89 - Floor plans and views case study dwelling 2

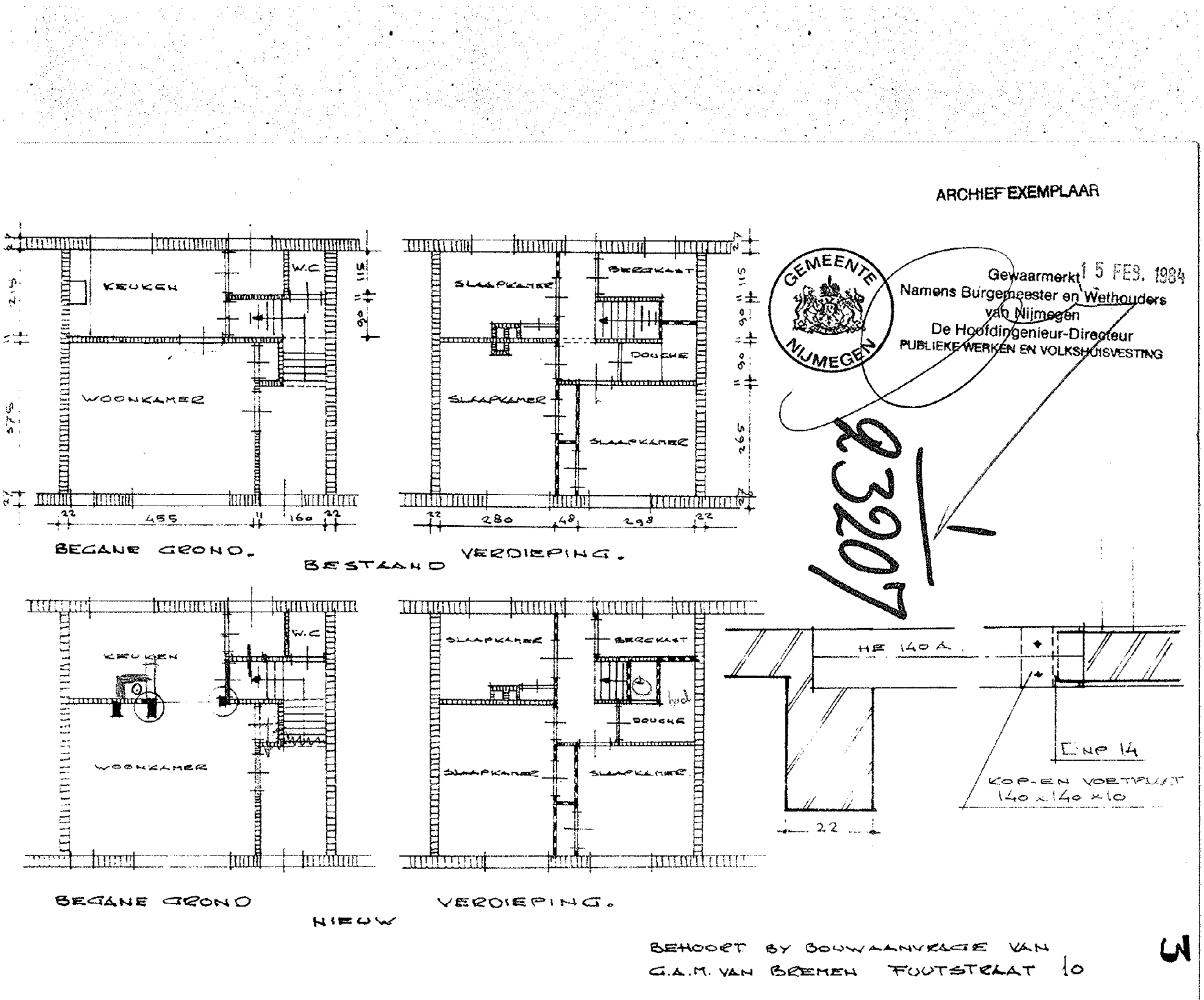

Fig. 90 - Floor plans case study dwelling 2

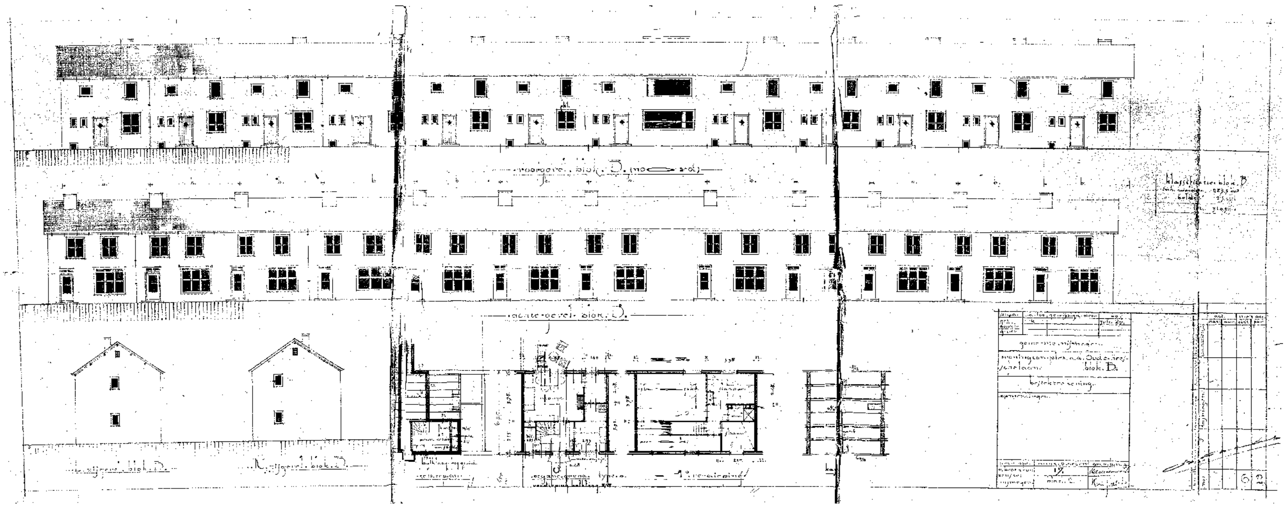

Fig. 91 - Floor plans and views case study dwelling 1

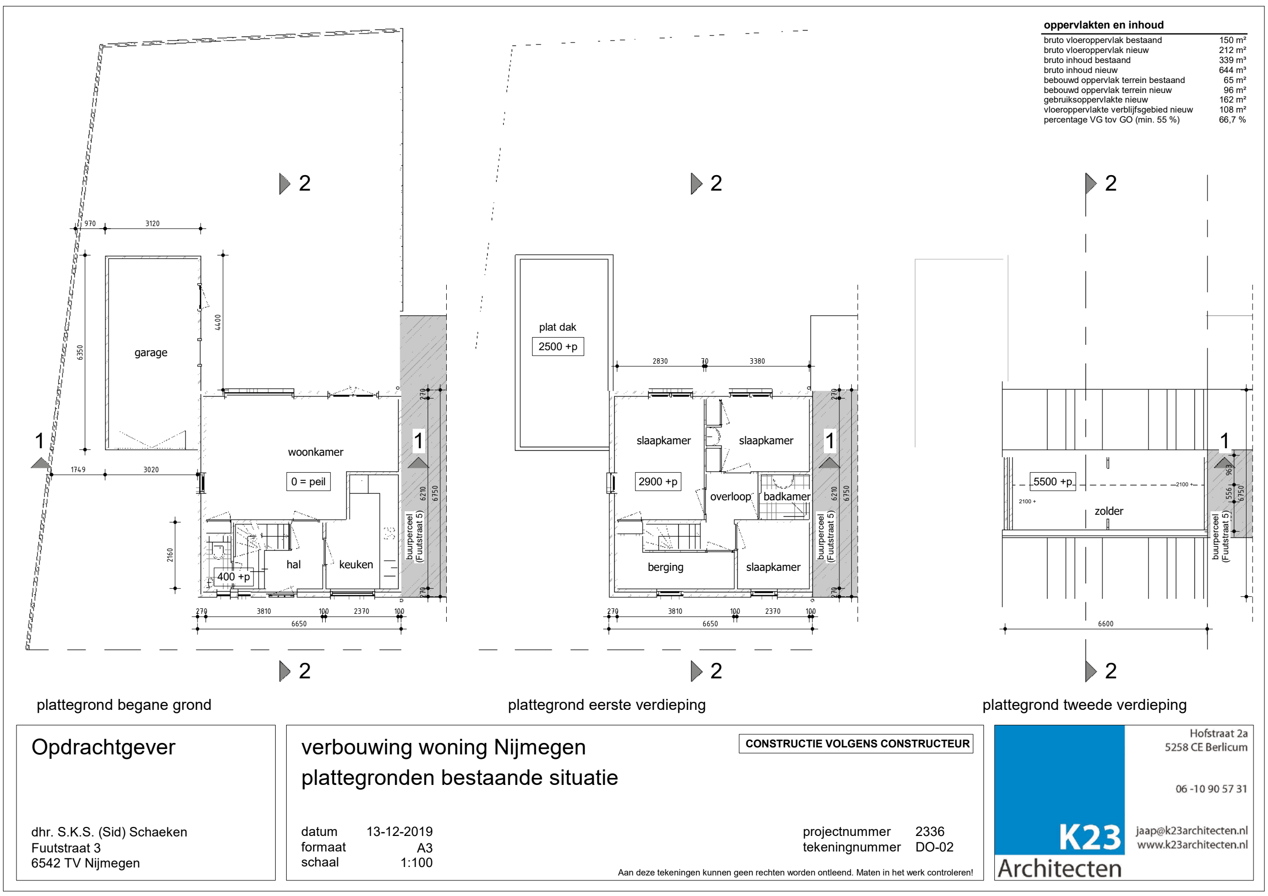

Fig. 92 - Floor plans case study dwelling 1

Fig. 93 - Sections of both case study dwellings

Preliminary designs

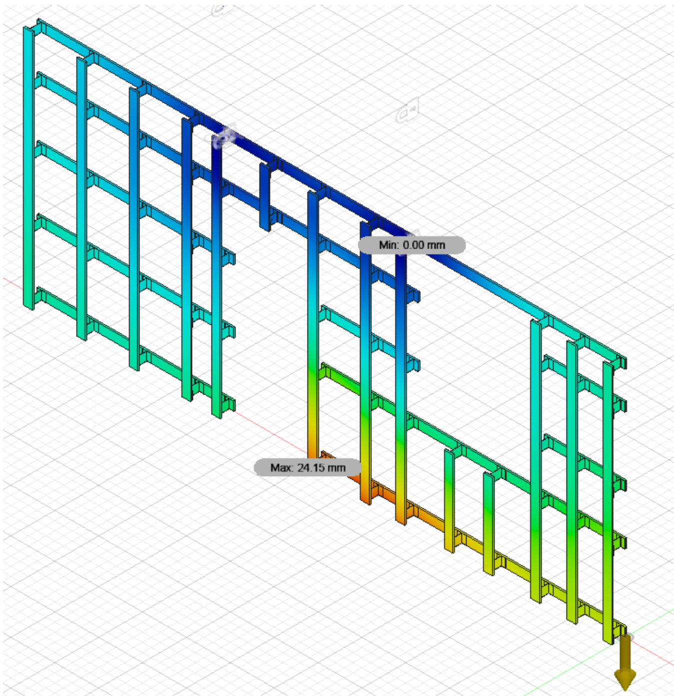

Fig. 94 - Before the placement of the OSB panels the deformation was 24 mm at most.

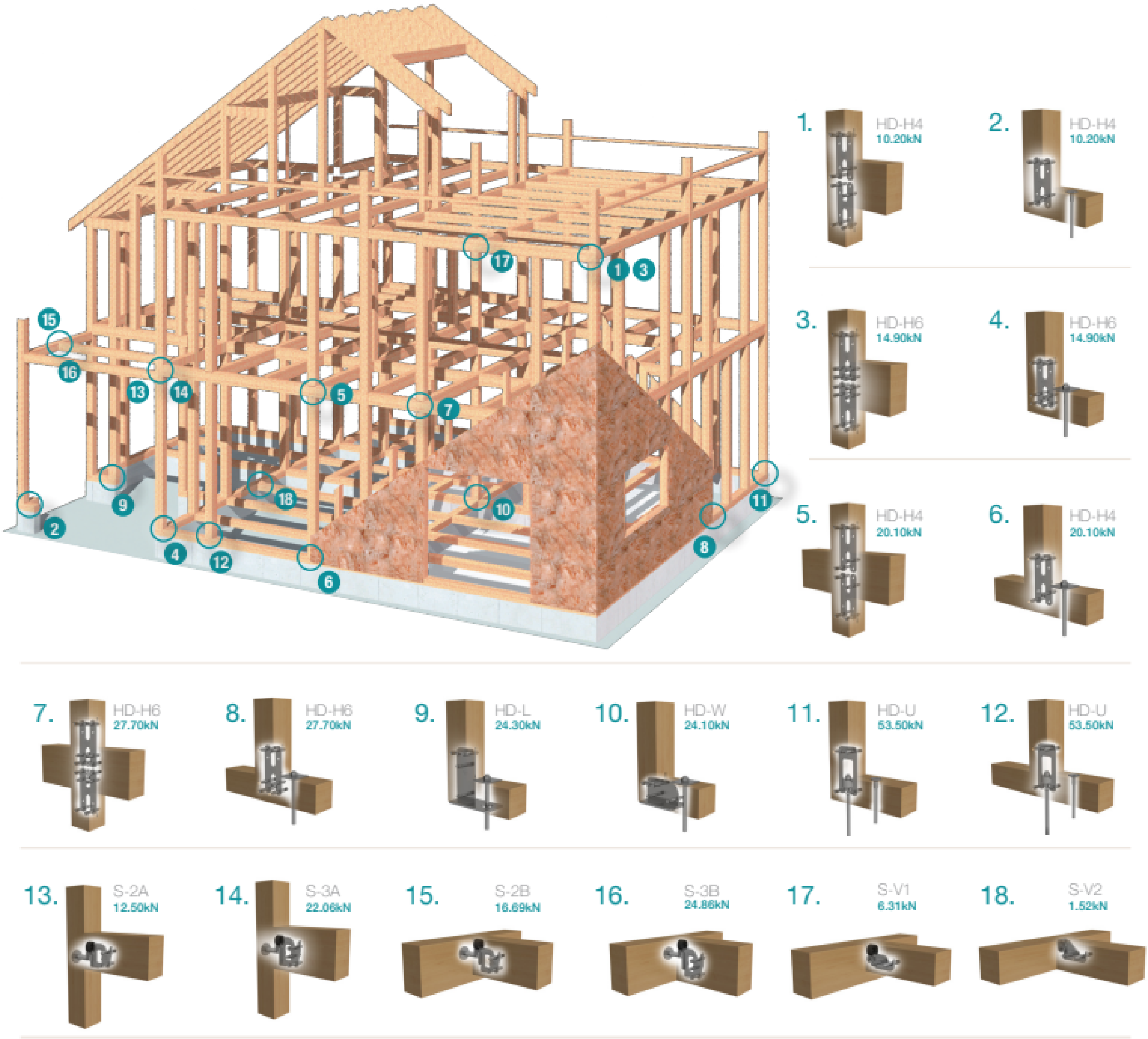

Fig. 95 - All the STRUCTUREZ connection types with design resistance (source: Woodinc.)

4 Evaluation

Life cycle assessment

Timber frame structure

EPD links:

Water repellent foil material: https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=ibu_Extrudedrecycledpolyethyleneproductsforthe2024_EPDLET20240417CBI1EN&profileId=LetbekAS2024

Steel: https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=envdecSteelCelsa_00306&profileId=CelsaSteel2021

Building Part

Resource Name	Details	Quantity	Unit	Thickness mm	CO₂e	Comment
External walls and facade						
Softwood beam, kiln dried, planed, 440 kg/m3, 10% moisture content, coniferous wood (One Click LCA)		244	kg		-274.84 kg	
Flax fibre for concrete reinforcement (One Click LCA)		72	kg		-77.36 kg	
Recycled steel reinforcement products (Celsa Steel (2023))		31	kg		23 kg	
Extruded recycled polyethylene products, 8.79 kg/m2, 927.5 kg/m3, Extruded recycled polyethylene pr...		2	kg		7.4 kg	

Plywood-aluminium structure

EPD links:

Alluminium: https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=itMETRARE_AL_Ealloys&profileId=METRA2023

Resource Name	Details	Quantity	Unit	Thickness mm	CO₂e	Comment
External walls and facade						
Softwood plywood, uncoated, 480 kg/m3, 8% moisture content (One Click LCA)		55	kg		-86.85 kg	
Flax fibre for concrete reinforcement (One Click LCA)		72	kg		-77.36 kg	
Recycled aluminium alloys, RE.AL.E - C1 (METRA)		17	kg		12 kg	
Recycled steel reinforcement products (Celsa Steel (2023))		18	kg		13 kg	
Extruded recycled polyethylene products, 8.79 kg/m2, 927.5 kg/m3, Extruded recycled polyethylene pr...		2	kg		7.4 kg	

Accoya cladding

EPD links:

https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=constrmatRadiataPineWood_ACCOYA&profileId=AccsysTechnologies2022

Resource Name	Details	Quantity	Unit	Thickness mm	CO₂e
External walls and facade					
Softwood beam, kiln dried, planed, 440 kg/m3, 10% moisture content, coniferous wood (One Click LCA)		11	kg		-10.08 kg
Acetylated sawn timber from radiata pine, 515 kg/m3, moisture content 3 - 5%, Accoya wood® (Accsy…		136	kg		88 kg

ClickBrick cladding

EPD links:

Resource Name	Details	Quantity	Unit	Thickness mm	CO₂e
External walls and facade					
Recycled aluminium alloys, RE.AL.E - C1 (METRA)		15	kg		11 kg
Clay brick (One Click LCA)		2273	kg		0.56 t

Pretty Plastic cladding

EPD links:

https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=nibePrettyPlastictiles_EPD-NIBE-20221112-31571&profileId=PrettyPlastic2023

Resource Name	Details	Quantity	Unit	Thickness mm	CO₂e
External walls and facade					
Plastic panels for ventilated facades, 24.4 kg/m2, FirstOne Grey (B4) (Pretty Plastic)		13.28	m2		0.41 t
Recycled aluminium alloys, RE.AL.E - C1 (METRA)		50	kg		36 kg

Material circularity indicator

Material Type	Recycled Content: Default	Recycled Content: Custom	Recycling Efficiency: Default	Recycling Efficiency: Custom	Embodied CO2 (kg/kg) Default	Embodied CO2 (kg/kg) Custom	Material Cost (USD/kg) Default	Material Cost (USD/kg) Custom
ABS	5%		5%		3,20		$ 1,20	
Bioplastics	0%		0%		3,20		$ 4,00	
EPS	0%		0%		3,10		$ 1,30	
HDPE	10%		20%		1,90		$ 1,20	
LDPE	1%		5%		2,10		$ 1,00	
Nylon	5%		5%		7,20		$ 3,50	
PET (Clear)	15%		25%		2,50		$ 1,30	
PET (Coloured)	15%		5%		2,50		$ 1,10	
Polycarbonate	0%		5%		4,30		$ 3,00	
PP	5%		10%		2,10		$ 1,20	
PS	0%		5%		2,60		$ 1,20	
PVC	0%		5%		2,90		$ 1,00	
Silicone	0%		0%		7,40		$ 6,00	
Steel	35%		80%		1,80		$ 0,44	
Aluminium	36%		80%		10,00		$ 2,30	
Brass/Bronze	80%		90%		1,20		$ 8,42	
Copper	32%		60%		4,10		$ 8,96	
Lead	60%		60%		1,30		$ 2,05	
Nickel	35%		60%		10,00		$ 15,88	
Rare Earth Elements	1%		1%		50,00		$ 150,00	
Zinc	20%		60%		2,70		$ 2,68	
Paper	50%		50%		1,70		$ 1,05	
Cardboard	50%		80%		1,70		$ 0,36	
MDF	0%		0%		1,30		$ 0,70	
Timber	0%		10%		0,30		$ 3,50	
Asphalt	10%		90%		0,08		$ 0,20	
Ceramics	0%		2%		1,60		$ 2,00	

Fig. 96 - Default recycled content for the MCI calculation. The glass wool used 60% recycled content

Component Name	Mass Each	Quantity	Resource Inflows				Lifetime Years		Utility Unit		Mass kilograms		Utility	Resource Outflows		MCI	%MCI
	kilograms		Material Type	Source	% Regenerative	Utlity Based on	L	L(av)	U	U(av)	M	M(av)	Function	Collection Rate	Destination		
Pretty Plastic	174	1	PVC	Reman	0%	Utility			3,00	1,00			3,00	90%	Reuse	0,98	97,5%
Aluminium frame	50	1	Aluminium	Recycle	0%	Utility			3,00	1,00			3,00	90%	Reuse	0,89	87,7%
Aluminium brackets	17	1	Aluminium	Recycle	0%	Utility			4,00	1,00			4,00	95%	Reuse	0,92	91,4%
plywood structure	55	1	Timber	Virgin	100%	Utility			2,00	1,00			2,00	90%	Reuse	0,98	97,5%
Flax insualtion	72	1	Timber	Virgin	100%	Utility			2,00	1,00			2,00	90%	Reuse	0,98	97,5%
water-repellent foil	2	1	LDPE	Recycle	0%	Utility			2,00	1,00			2,00	90%	Reuse	0,75	72,8%
Steel connections timber	13	1	Steel	Recycle	0%	Utility			5,00	1,00			5,00	95%	Reuse	0,94	93,0%
Accoya	136	1	Timber	Virgin	100%	Utility			2,00	1,00			2,00	90%	Reuse	0,98	97,5%
Timber structure	244	1	Timber	Virgin	100%	Utility			3,00	1,00			3,00	90%	Reuse	0,99	98,3%
Timber frame	11	1	Timber	Virgin	100%	Utility			2,00	1,00			2,00	90%	Reuse	0,98	97,5%
		1								1,00							
		1								1,00							
		1								1,00							
ClickBrick	2.273	1	Ceramics	Virgin	0%	Utility			4,00	1,00			4,00	90%	Reuse	0,88	86,3%
Aluminium rails	15	1	Aluminium	Recycle	0%	Utility			3,00	1,00			3,00	90%	Reuse	0,89	87,7%
Steel brackets facade	17	1	Steel	Recycle	0%	Utility			5,00	1,00			5,00	95%	Reuse	0,94	93,0%
Bricks	2.273	1	Ceramics	Virgin	0%	Utility			1,00	1,00			1,00	90%	Recycle	0,11	0,9%
Glass wool	45	1	Fiberglass	Virgin	0%	Utility			1,00	1,00			1,00	90%	Recycle	0,34	27,0%
Limestone	2.400	1	Concrete	Virgin	0%	Utility			1,00	1,00			1,00	90%	Recycle	0,14	4,5%
Product Total		**7.797**														**0,43**	**36,8%**

Fig. 97 - MCI calculation for all the materials in total