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DELIVERABLE 3.2:

Preliminary design studies on timber reuse and innovative prefabricated circular renovation elements (T3.3, T3.4)

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OVERVIEW	
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Project Coordinator	RINA-C
Project Duration	42 months
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Lead Authors	**Christos Tzivanidis (NTUA), Dimitris Pallantzas (NTUA)**
Main Contributor Authors	Christos Sammoutos (NTUA), Georgios Kosmadakis (NTUA), Andrea Klinge (KIT), Natascha Steiner (KIT), Simone Schiller (ZRS), Mariza Gkadri (HPHI)
Other Contributors	George Mansoudis (NTUA), Felix Dingeldein (KIT)
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Peer Reviewers	Adriana Pacifico (STRESS), Anu Sarnet (EKYL)

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Abbreviations and Acronyms

ACRONYM	DESCRIPTION
BIM	Building Information Modeling
BNB	German Sustainable Building Certification System
EN	European Norm
EPB	Energy Performance of new and existing Buildings
EPS	Expanded Polystyrene
FOS	Factor of Safety
GEG	German Building Energy Act
GWP	Global Warming Potential
HPL	High Pressure Laminate
HVAC	Heat, Ventilation, and Air Conditioning
ISO	International Organization for Standards
LCA	Life-Cycle-Assessment
LCC	Life-Cycle-Costing
MHHR	Model High-Rise Directive
MVHR	Mechanical Ventilation with Heat Recovery
OSS	One-stop-shop
PA	Polyamide
PEB	Positive Energy Building
PENTR	Non-Renewable Primary Energy Demand
PIR	Polyisocyanurate
PLA	Polylactic acid
PU	Polyurethane
PV	Photovoltaic
PVC	Polyvinyl Chloride
SS	Stainless Steel
TRL	Technology Readiness Level
U	Thermal transmittance coefficient
UBA	German Environment Agency
XPS	Extruded Polystyrene
ZEB	Zero Energy Building

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Background: About the SIRCULAR project

SIRCULAR is coordinated by RINA-C and combines the expertise of 22 partners from six European countries, including universities, SMEs, NGOs, and industries. During the next three-and-a-half-years, SIRCULAR will contribute to transform the building sector into a circular and sustainable industry, aligned with the Built4People partnership principles.

The SIRCULAR project will test and demonstrate innovative technologies and services across four regional clusters: initially in Estonia and Spain, followed by Germany and Greece. These clusters will engage construction companies, housing companies, universities, and local administrative entities, focusing on buildings owned or occupied by vulnerable population groups, in line with the SIRCULAR just and affordable transition approach.

Executive Summary

In the scope of this report, innovative retrofitting solutions for achieving the ZEB status are presented. The proposed solutions are based on the idea of prefabrication retrofitting solutions, aiming to speed up the renovation procedures in order for the European Union to achieve its 2030 and 2050 goals. Two different prefabrication solutions are proposed, a timber reuse-based solution, and a solution based on prefabricated components directly attached to the building envelope. More specifically, the proposed prefabricated component is a small-scale and flexible unit.

The main conclusions of this report emphasize the advantages of prefabrication in retrofitting, and the benefits resulting from applying this approach in terms of speed in renovation, streamlined renovation procedures, building's resilience, energy efficiency of buildings, and thermal comfort for the occupants. Prefabrication also limits human errors during construction or retrofitting, reduces the construction cost, and minimizes the disturbance to the occupants.

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1. Introduction

The SIRCULAR project aims to create a methodology that combines sustainable and low-carbon techniques for construction, deconstruction, and reuse in the building sector. The main objective of this project is to transform the construction sector into a sustainable and low-carbon industry by creating and highlighting alternative low-carbon building materials and techniques.

In this direction, the SIRCULAR project aims to introduce two innovative construction and renovation approaches based on timber reuse and exploitation of prefabricated solutions. The proposed solutions directly contribute to the technical and technology-related objective of the SIRCULAR project for improving the availability of creative plans for environmentally friendly buildings by developing new and creative construction and renovation strategies and components. Furthermore, it contributes to the objective of spreading the knowledge for reusing building elements by providing holistic and innovative technology solutions, integrating reused components, and prefabrication elements.

The main objective of Deliverable D3.2 is to develop a technical report regarding the activities carried out in tasks T3.3 and T3.4 for timber reuse and prefabricated renovation elements respectively. In particular, “Karlsruhe Institute for Technology” (**KIT**) and “ZRS Architekten Gesellschaft von Architekten MBH” (**ZRS**) have designed and proposed a holistic renovation strategy for an existing building based on reused and recycled timber. This design process addresses all the sustainability, economic, and social aspects throughout the whole development. Moreover, an innovative waste wood harvesting and processing strategy has been developed, maximizing the reusability of building components. Also, a zero-carbon timber facade has been developed and examined in a virtual demo building. In addition, specific practices for achieving a zero-building emission standard have been defined. Regarding the prefabricated renovation component, the “National Technical University of Athens” (**NTUA**) and the “Hellenic Passive House Institute” (**HPHI**) have designed and proposed a flexible and simple universal prefabricated construction system based on sustainable and recyclable materials. A detailed description of all the design and construction aspects of the prefabricated element is presented, and the adopted methodology is defined. The design of these element emphasizes on minimizing the disturbance to building’s occupants during the construction or renovation process, and easy installation while following the design for deconstruction methodology. These solutions will be exploited during the demo implementation process in WP4 of the project. Also, the solutions have been virtually tested using the virtual demo sites of KIT and HPHI.

In conclusion, Deliverable D3.2 will present a holistic renovation strategy based on timber reuse, and a prefabricated circular renovation component, providing new, creative, and sustainable technical solutions for energy retrofitting in the building sector. Thus, the available range of choices for achieving decarbonization of the sector will be broadened, and the industrial sector will increase its knowledge on energy-efficient and environmentally friendly technologies and techniques.

1.1 Objectives of the Deliverable

The Deliverable D3.2 addresses both the Tasks T3.3 and T3.4 for design studied on timber reuse and prefabricated components for renovation respectively. KIT and ZRS are the responsible partners for the activities of T3.3, while NTUA and HPHI are the responsible partners for the activities of T3.4. Thus, this deliverable has some individual objectives for each task, but also some critical common objectives.

The main objectives for T3.3, “Preliminary design studies on timber reuse” are:

- To develop a renovation strategy for an existing building based on reused and recycled timber.
- To define off-set time for achieving zero-emission.
- To develop a waste wood harvesting and processing strategy.
- To develop a zero-carbon timber facade and roof for the renovation of a virtual demo.

The main objectives for T3.4, "Innovative prefabricated circular renovation components" are:

- To develop a universal prefabricated construction system.
- To minimize the disturbance of buildings during the renovation process.
- To minimize the duration of deep-retrofitting processes.

The target audience of the Deliverable D3.2 consists of all the project partners, and especially it is crucial for all the partners involved in the exploitation of the developed solutions during the demo implementation phase of the SIRCULAR project. The main goal is to provide the project partners with creative, sustainable, low-carbon, and energy-efficient techniques and solutions for renovation or construction of buildings. Moreover, the outcomes of this deliverable will reach out industrial and public stakeholders to increase their knowledge and awareness on innovative renovation solutions.

1.2 Structure of the Document

This document is structured into six distinct sections, leading to a detailed and comprehensive investigation on timber reuse and prefabrication solutions for construction and renovation. **Section 1** introduces the main scope, goals, methodology, and approach of this deliverable. **Section 2** focuses on the design studies for timber reuse, emphasizing possible restrictions and the real potential of this technology. Also, the second section points out the related available design strategies, concluding with an overall renovation strategy regarding timber reuse, followed by an assessment and validation methodology. This section is associated with task T3.3, "Preliminary design studies on timber reuse". **Section 3** presents and analyses a circular renovation component. The third section introduces the methodology for prefabrication solutions and addresses the materials and techniques utilized, conducting simulations and feasibility studies on component and system-level analyses. This section is associated with task T3.4, "Innovative prefabricated circular renovation components". **Section 4** concludes all the results and valuable outcomes of this deliverable to be used by all the project partners for the demonstration phase of the project. **Section 5** showcases any supporting material considered as necessary, thus completing the analysis of the proposed innovative solutions. Finally, **Section 6** presents the references and bibliography used.

1.3 Relation to Project Documents

This deliverable is a technical report, thus it is related to other technical reports of the SIRCULAR project and with the activities regarding the demo implementation phase. Some documents were used as input, and some other documents require input based on the results and conclusions of this deliverable.

Project documents whose results are used as input in this deliverable:

- Deliverable D1.4 – Health, IAQ and construction materials correlations report (T1.4) [1]: Material composition and circularity. Evaluating recycling construction and demolition-based waste materials, bio-based alternatives, and hybrid solutions.

Project documents that will utilize the results from this document:

- Deliverable D4.1 – Local supply chain formation (T4.1) [2]: Take into consideration the materials used for the timber facade and the prefabricated elements to implement them in the formation of a local supply chain, enhancing circularity and advancing local markets.
- Deliverable D4.4 – Impact assessment of the SIRCULAR technologies and monitoring activities report (T4.4, T4.5) [3]: Given all the details for the timber and prefabricated solutions, an analysis on the environmental, technological, economic, socio-economic and comfort perspective impacts of these technologies will be conducted.
- Deliverable D5.3 – Innovative contractual schemes for sustainable construction and renovation value chain (T5.4) [4]: Based on the prefabricated and timber solutions proposed from this document, an analysis to address the stakeholder needs will be carried out.

1.4 Overall Approach

The main scope of this deliverable is to investigate and propose two new and creative renovation ideas, thus providing energy-efficient and low-carbon solutions for the project partners to implement, and new solutions for the building renovation and construction industry. These solutions are timber reuse facades and prefabricated components. KIT and ZRS have investigated the potential of timber reuse in detail, providing low-carbon timber solutions for an existing building. Furthermore, they have emphasized on waste wood harvesting and processing techniques, and passive strategies for improving occupants’ thermal comfort and health. NTUA and HPHI have designed a small-scale prefabricated component to provide real solutions covering many aspects of a complete renovation strategy. In this direction, partners considered the detailed report of the Deliverable D1.4 for the material selection [1]. In conclusion, a holistic approach to present innovative and feasible technologies were conducted by the project partners, providing to the SIRCULAR project realistic and efficient solutions.

2. Design studies on Timber Reuse

The construction industry, as a major consumer of resources and producer of waste, plays a critical role in the transition toward sustainable and circular practices. In this context, Task 3.3 focused on developing a holistic renovation strategy for existing university or office buildings to achieve the Zero Emission Building (ZEB) standard—using reused, recycled, or natural materials, with a special focus on reclaimed wood.

The design addressed all building envelope components (facade, roof, and basement) based on circular principles, enabling future dismantling and reuse. A building survey was conducted to define the design approach, supported by Life-Cycle-Assessment (LCA) analysis and Life-Cycle-Costing (LCC) related aspects. Innovative methods for reclaiming and processing waste wood, including treated timber, were explored. Key aspects include energy efficiency, user comfort, health, and climate resilience—prioritizing passive solutions and minimizing emissions. A concept for building services and a timeline toward zero emissions were also developed. The reuse potential of materials was assessed, and a Circularity Index was introduced to measure outcomes. The following sections present in detail the methods, strategies, and results of this work.

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2.1 Restrictions and Potentials of Timber Reuse

In light of climate change and resource scarcity, reclaimed wood offers significant potential for sustainable construction aligned with circular economy principles. Achieving this requires a fundamental transformation of the construction sector, addressing material efficiency, emission reduction, and the development of resilient value chains [5].

Despite its advantages, timber remains underutilized in European multi-storey construction, with a market share of only 2.7% [6]. Yet, its capacity to store approximately one tonne of carbon dioxide (CO_2) per cubic meter, coupled with advances in prefabrication, makes it a key material for reducing emissions, shortening construction times, and increasing energy efficiency.

In Germany, timber construction is gaining momentum, supported by public funding and strategic initiatives [7]. However, growing reliance on primary wood from intensively managed forests raises ecological concerns, including overexploitation, drought stress, and pest damage. This challenges the long-term viability of timber supply and highlights the urgency of reclaiming wood from the dismantled building stock [8]. Furthermore, in Germany, roughly 10 million tonnes of reclaimed wood are incinerated annually, releasing around 15 million tonnes of CO_2 instead of being reused [9]. The CO_2 emissions from burning wood exceed the original wood mass by a factor of about 1.5, because during combustion, the carbon stored in the wood (approximately 50% by mass) oxidizes by binding with atmospheric oxygen to form CO_2, where the molecular weight ratio results in the range of 1.5 to 1.8 tonnes of CO_2 per tonne of wood burned. This widespread reliance on thermal utilization reflects a structural gap in current construction and waste management systems, where end-of-life timber is rarely reintegrated into the building cycles.

2.1.1 Current Status: Reclaimed Wood Harvesting and Evaluation Process

The reuse of reclaimed timber in construction is gaining attention in research and practice but remains limited by significant practical and regulatory barriers. In this section, the most significant limitations and barriers, such as regulatory and certification framework, design and construction of timber-based materials, digital tools, material passports, and other social and economic factors, are presented and discussed.

Regulation and Certification: Despite ongoing research efforts, the lack of consistent classification standards remains a key challenge. Ageing, damage, wood preservatives, insufficient documentation, and others often compromise the usability of reclaimed timber. Non-destructive testing methods, such as visual grading (DIN 4074-1) [10] and machine strength grading (DIN EN 14081-1) [11], offer formal means to assess and certify reclaimed elements for structural reuse. However, these methods are rarely implemented in practice due to high technical and personnel requirements, time intensity, and the challenge of achieving lower strength values with manual sorting, as safety factors must be applied to account for the reduced accuracy compared to machine grading. A major step forward is the “Guideline on Reuse of Load-Bearing Components from Steel and Timber Construction” by the Ministry of State Development and Housing in Baden-Württemberg 2025, as well as the Norwegian Standard “prNS 3691-1: Evaluation of Recycled Wood 2024” [12], which provides the first practice-oriented framework for approving reclaimed structural elements, including timber. It highlights the importance of early assessment, controlled deconstruction, and technical evaluation (e.g., density, cracking, load-bearing capacity) [13].

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Although political support for circular construction is growing, the reuse of structural timber remains legally complex, similar to structural elements manufactured from other materials. The German Waste Wood Ordinance primarily regulates waste wood management by categorizing it into four classes (A to I-IV) based on contamination and treatment history, establishing specific recycling and recovery pathways for each class. On the other hand, direct material reuse as structural components is only permitted in exceptional cases. [14]. A clear regulatory pathway for structural applications of reclaimed timber is still missing.

Design and Construction: From a design perspective, reclaimed timber offers significant potential for innovative and resource-efficient architecture. Key advantages include easier deconstruction, lower weight, the possibility of dry jointing, and the flexibility to cut structural elements such as columns or beams to required dimensions on-site. Demonstration projects such as RE4: Strategies for Circular Prefab Buildings from Waste Wood [15] and Roof Kit's Housing Unit [16] show how modular systems, traceability, and intentional reuse can be successfully applied. However, standardized reversible connection systems enabling damage-free reuse of timber components are still lacking—posing a major research gap in construction methods.

Digital Tools and Material Passports: Digital platforms increasingly support the documentation, cataloguing, and traceability of reusable building components. Sustainability certification systems such as DGNB (German Sustainable Building Council) incorporate material passports and circularity assessment as integral evaluation criteria [17]. German-based commercial enterprises such as Concular provide market-ready solutions for material documentation and marketplace platforms. The research project BauCycle [18] develops scientific foundations for circular construction practices, while the Urban Mining Index [19] functions as an evaluation framework that establishes standardized criteria for assessing reuse potential. These diverse approaches collectively aim to transparently map material flows throughout the entire building lifecycle and facilitate the integration of circularity principles into design and planning processes. Yet, reclaimed timber remains underrepresented and inconsistently integrated into these systems. The systematic inclusion of reclaimed wood in digital material passports and BIM-based workflows, especially for assessing conditions, planning deconstruction, and defining circularity metrics, remains a key area for future research.

Social and Economic Factors: The acceptance of reclaimed timber in design, construction, and among clients remains limited. Concerns regarding quality, availability, liability, and financial risk often hinder wider market uptake [20]. Simultaneously, emerging market niches such as deconstruction services, processing, and reuse design remain under-researched. Currently, practice-oriented models for assessing reclaimed timber quality, designing reusable components, and integrating reclaimed wood into planning and approval processes are largely missing. The goal of Task 3.3 was to address these gaps by developing an applied toolkit combining design, construction, legal frameworks, technology, and environmental assessment. The approach is demonstrated through a digital prototype based on a real building, aiming to promote circular timber construction in practice.

2.1.2 Future Prospects: Reintegration of reclaimed wood into value chain

A central challenge for future-oriented resource strategies is the current reliance on incineration: in Germany, approximately 10 million tonnes of reclaimed wood are burned annually, leading to the release of 15 million tonnes of CO_2 and highlighting the urgent need to reintegrate end-of-life timber into the material value chain [9]. While energy recovery provides short-term utility, it results in the irreversible loss of both carbon storage potential and valuable resources. To align with climate and resource goals, future strategies must shift towards a circular approach: reclaimed wood should first be reused in construction or recycled into high-value applications. Only when these pathways are no longer viable should cascading use be applied, extending the material's service life through successive stages, from structural reuse to secondary products like composite materials or bio-based substances, with energy recovery as a final step.

Figure 1 illustrates a circular value chain for reclaimed wood, offering a structured alternative to the prevailing practice of incineration. The process begins with the non-destructive dismantling of timber components, followed by sorting and relevant contaminant removal, such as metal fittings, fasteners, and other harmful substances. Subsequently, material testing and strength grading are conducted to determine reuse potential. Based on the results, components are dimensioned and matched to suitable applications. New elements are then manufactured and reintroduced into the construction cycle.

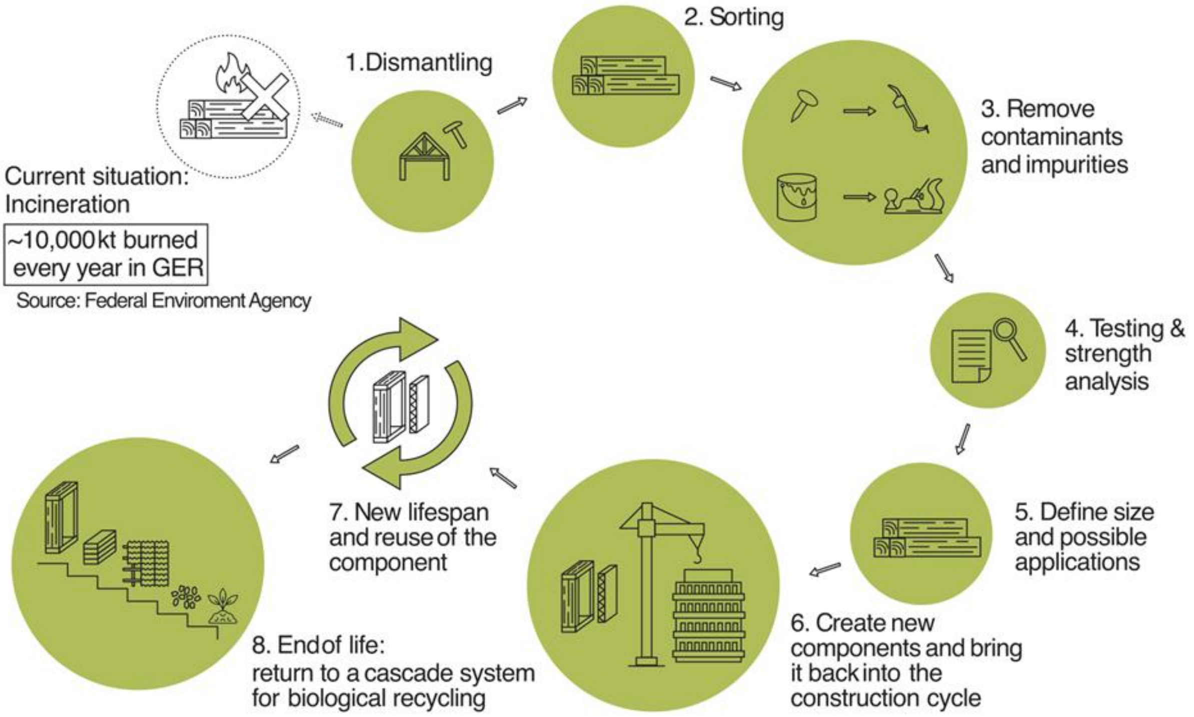

Figure 1. Process of recycling reclaimed wood.

Following a second service life, materials that are no longer suitable for direct reuse are directed to recycling either at the same level or into a cascading utilization system, where they are gradually repurposed for lower-grade applications such as engineered wood products or insulation materials before ultimately entering biodegradation. This approach maximizes resource efficiency, prolongs carbon storage, and supports the transition toward a circular construction economy.

2.2 Design strategies for Timber Reuse

2.2.1 Existing Building under Investigation

Planning in timber construction requires a high degree of precision, especially in existing buildings. A detailed analysis of the existing structure is a prerequisite for developing suitable strategies. The design-based approach aims to develop a transferable solution for a specific building typology. The building under investigation serves as a pilot project. Due to the lack of adequate existing

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documentation, a new building survey was conducted by KIT as part of Task 3.3. The set of existing building plans of this investigation is presented in the Appendix section, **Figures A1-A8**. The selection of the existing building is based on its typological representativeness: it is a structure that is not only common on the campus of the Karlsruhe Institute of Technology (KIT) but also widespread throughout Germany. An overview of comparable buildings is provided right below, in **Figure 2**.

Year of constr.	Building name	Type of use	Picture	Description	Res.
1968	KIT Campus South Building 20.11-20.14	Teaching Building		Flat-proportioned grid facade with regular window spacing and simple concrete parapets	https://www.kit.edu/kit/pi_2025_054_kit-startet-generalsanierung-der-pavillons-am-schlossplatz.php?utm_source
1968	TU Berlin Mathematics Building	Teaching Building		External pergolas made of steel and concrete on the long sides serve as horizontal escape routes and facade structuring elements	https://www.baunetz.de/meldungen/Meldungen-Georg_Kohlmaiers_oekomoderne_in_Berlin_4507719.html
1970er	Heidelberg University Campus Neuenheimer Feld Building 364 Pharmacy	Teaching Building		Building block with concrete escape balconies running completely around the perimeter as a horizontal access level, with external stair towers	https://de.wikipedia.org/wiki/Neuenheimer_Feld
1970er	Heidelberg University Campus Neuenheimer Feld Building 368	Teaching Building		Building block with concrete escape balconies running completely around the perimeter as a horizontal access level, with external stair towers	https://de.wikipedia.org/wiki/Neuenheimer_Feld
1970er	KIT Campus South Bldg. 30.43 Biotower, Building 30.44 Chemistry-Tower II	Teaching Building		Vertically structured exposed concrete façade with regular window band grid and clearly protruding emergency stair tower at the front	https://www.laborjournal.de/rubric/hintergrund/hg/hg_19_05_01.php?utsource
1971	KIT Campus South SCC Building 20.20-20.21	Teaching Building		Horizontal exposed concrete façade with continuous, projecting gallery levels and visible escape staircases along the long side	https://www.gaiser-partner.de/kopie-von-laufendes-projekt-02?utm_source
1975	University of Hamburg "Geomatikum"	Teaching Building		Reinforced concrete slab high-rise building with galleries running along the sides as escape routes and vertical stair towers	https://de.wikipedia.org/wiki/Geomatikum_(Hamburg)
1970	Mannheim Helmut Striffler House	Office Building		Steel and glass façade with delicate stainless steel mullions in an integrated grid, clear horizontal window bands, no escape balconies	https://koros-mannheim.de/das-gebaeude.html

Figure 2. Comparison of similar building types (in Germany) with the building under investigation.

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This typology, typical of buildings constructed in the 1960s and 1970s, is characterized by a clearly defined modular grid structure. The buildings are usually based on a reinforced concrete skeleton with a repetitive structural grid of 3.75 by 3.75 meters. This regularity is visibly reflected in the facade and enables the use of prefabricated concrete elements in a repetitive manner. A distinctive architectural feature is the continuous balconies surrounding the building. Originally, these balconies served not only for maintenance access but also had a fire safety function. However, due to today's stricter fire protection requirements, the widths of these balconies are often insufficient, posing challenges for compliance with current regulations. In case of renovation, existing building rights protection no longer applies, and fire protection concepts must be redesigned according to current standards. These issues are discussed in Section 2.4.5.

A further challenge lies in the building's thermal performance. Many of these structures are either poorly insulated or not insulated at all. The load-bearing elements that cantilever beyond the thermal envelope to support the balconies create numerous thermal bridges, resulting in significant heat losses. This leads to elevated energy consumption, increased CO_2 emissions, a reduced level of thermal comfort for users, and, in the worst case, also to construction defects. Moreover, many materials used during the original construction period were contaminated with hazardous substances. For example, asbestos-containing panels are often still found behind suspended ceilings and must be carefully addressed in any renovation process.

Within the framework of this demonstrator, the proposed approach will be tested for its replicability in the context of non-residential building stock. To identify suitable renovation strategies, an evaluation matrix that maps different levels of intervention in the existing structure — ranging from minimally invasive to comprehensive approaches — was developed. The assessment was conducted based on the following criteria:

- **Impact**: Reduction of energy consumption, improvement of user comfort, extension of building lifespan, and potential for replication.
- **Feasibility**: Compatibility with existing building use, cost efficiency, and low technical complexity.
- **Sustainability and circularity**: Use of existing structures, avoidance of carbon-intensive materials, low waste generation, and robustness and adaptability of the proposed solutions.
- **Architectural appearance**: Preservation of the original appearance, clarity of the design concept, and spatial and daylight quality.

The complete assessment is documented in the Appendix section, in **Figure A9.** Based on the results, three main strategies were selected for further development and detailed planning. These strategies are described in the following section, Section 2.2.2.

2.2.2 Comparison of Different Retrofitting Strategies

In the following analysis, various renovation strategies were compared with one another, ranging from the least invasive to the most invasive interventions. **Figure 3** presents a schematic preliminary representation of the facade renovation strategies. In the subsequent section of this investigation, several of these strategies were examined and evaluated in more detail.

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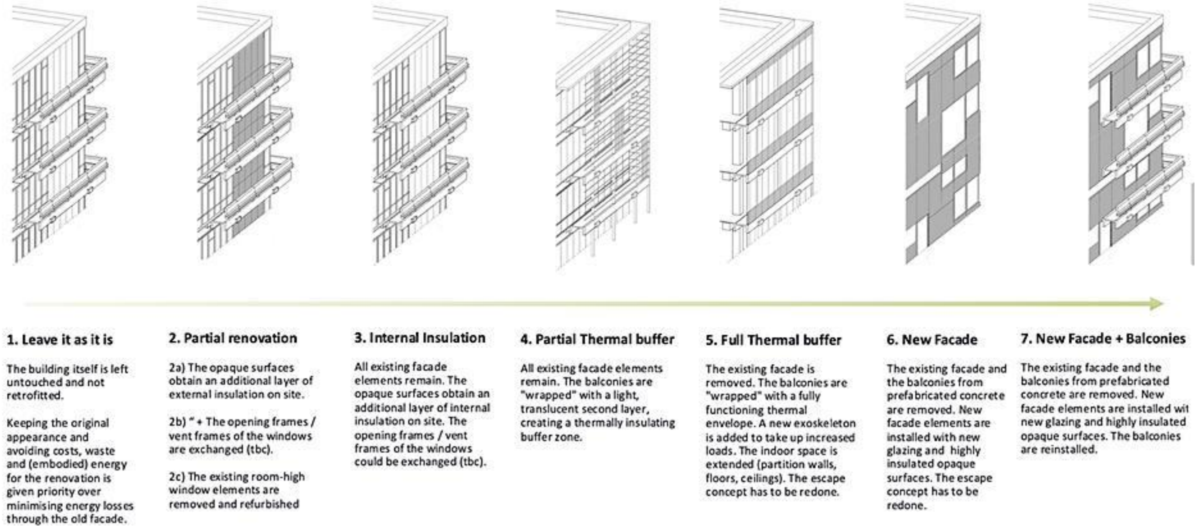

1. Leave it as it is

The building itself is left untouched and not retrofitted.

Keeping the original appearance and avoiding costs, waste and (embodied) energy for the renovation is given priority over minimising energy losses through the old facade.

2. Partial renovation

2a) The opaque surfaces obtain an additional layer of external insulation on site.

2b) " + The opening frames / vent frames of the windows are exchanged (tbc).

2c) The existing room-high window elements are removed and refurbished

3. Internal Insulation

All existing facade elements remain. The opaque surfaces obtain an additional layer of internal insulation on site. The opening frames / vent frames of the windows could be exchanged (tbc).

4. Partial Thermal buffer

All existing facade elements remain. The balconies are "wrapped" with a light, translucent second layer, creating a thermally insulating buffer zone.

5. Full Thermal buffer

The existing facade is removed. The balconies are "wrapped" with a fully functioning thermal envelope. A new exoskeleton is added to take up increased loads. The indoor space is extended (partition walls, floors, ceilings). The escape concept has to be redone.

6. New Facade

The existing facade and the balconies from prefabricated concrete are removed. New facade elements are installed with new glazing and highly insulated opaque surfaces. The escape concept has to be redone.

7. New Facade + Balconies

The existing facade and the balconies from prefabricated concrete are removed. New facade elements are installed wit new glazing and highly insulated opaque surfaces. The balconies are reinstalled.

Figure 3. Comparison of different renovation strategies based on timber reuse.

The aim of developing the spectrum from least invasive (maintaining the building in its current state) to most invasive (complete demolition and replacement with a new facade) was to cover a realistic range of all possible interventions. Based on this preliminary set of options - which served as preparatory work and will not be examined further - three main strategies (A, B, and C) have been developed. For the subsequent, more detailed analysis, the focus was narrowed to the following approaches:

- **Strategy A**: A minimally invasive refurbishment, aiming to preserve as much of the existing structure as possible in order to minimize CO_2 emissions and not to destroy construction-related CO_2 emissions contained in the existing building.
- **Strategy B**: Avoids demolition entirely, no embodied energy is released, existing facade and balconies remain intact, complemented by an external glazed layer creating a thermal buffer zone.
- **Strategy C**: Removal of the existing facade and introducing new reclaimed timber frame elements, which serve as a CO_2 sink, divided into three sub-variants:
    - **C.1**: Retention of the facade's prefabricated elements down to the parapet.
    - **C.2**: Complete removal of balcony elements, with the lost space compensated by a new floor.
    - **C.3**: Relocation of the thermal envelope to the interior, combined with the complete removal of the surrounding balcony structure.

For simplification, it was assumed that both the roof and the basement ceiling would be retrofitted with additional insulation. This measure is identical across all strategies and illustrated in **Figure 4**. In the following subsections of Section 2.2.2, the structural drawings for the retrofitting strategies are illustrated in detail. **Figure 5** refers to Strategy A, while **Figure 6** refers to Strategy B. The following figures, **Figure 7**, **Figure 8**, and **Figure 9**, refer to the retrofitting strategies C.1, C.2, and C.3 respectively.

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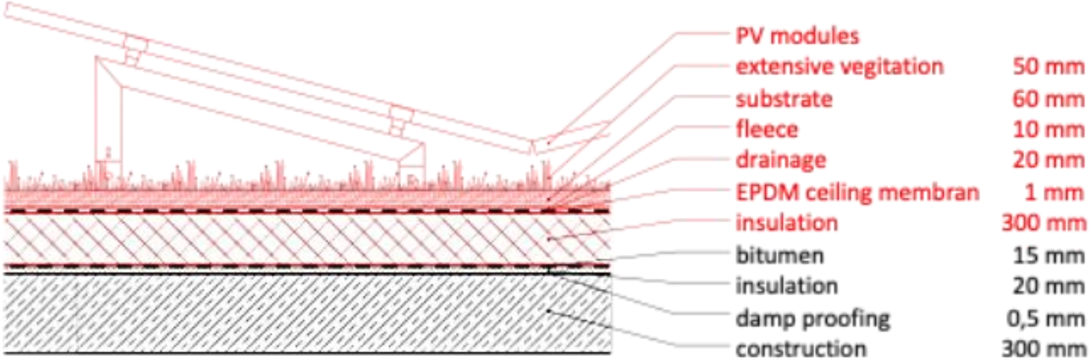
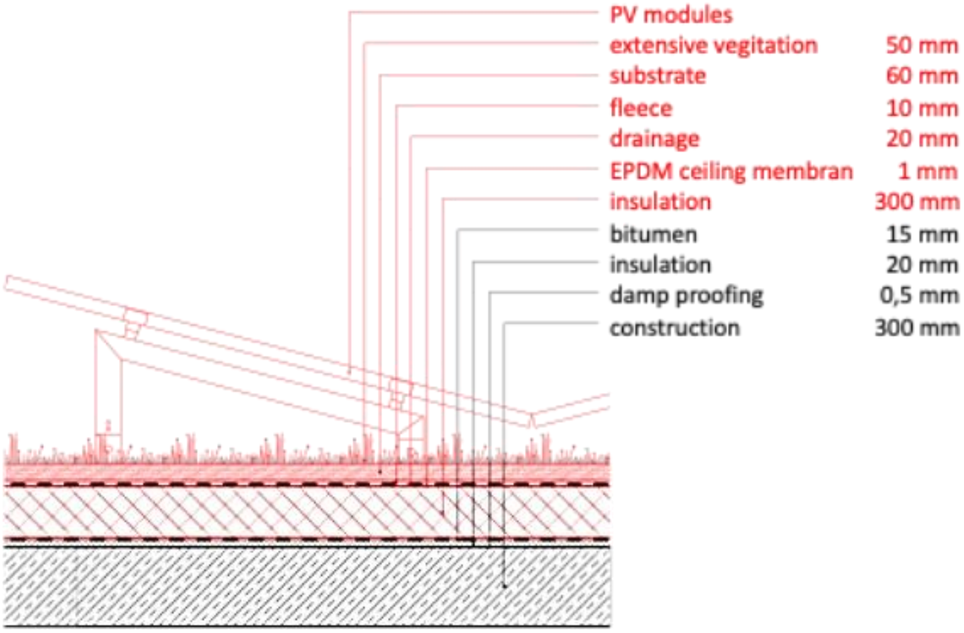
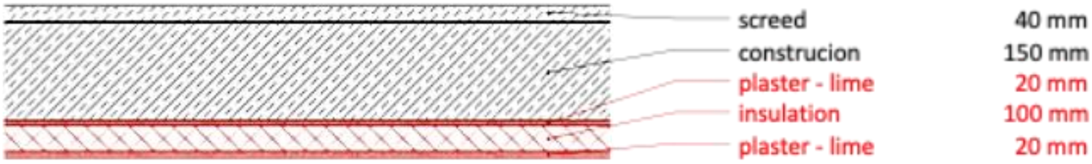


Green Roof with PV System



Green Roof with PV System



Basement Ceiling

Figure 4. Roof and basement ceiling retrofitting strategy with additional insulation (valid for all the proposed timber reuse-based renovation strategies).

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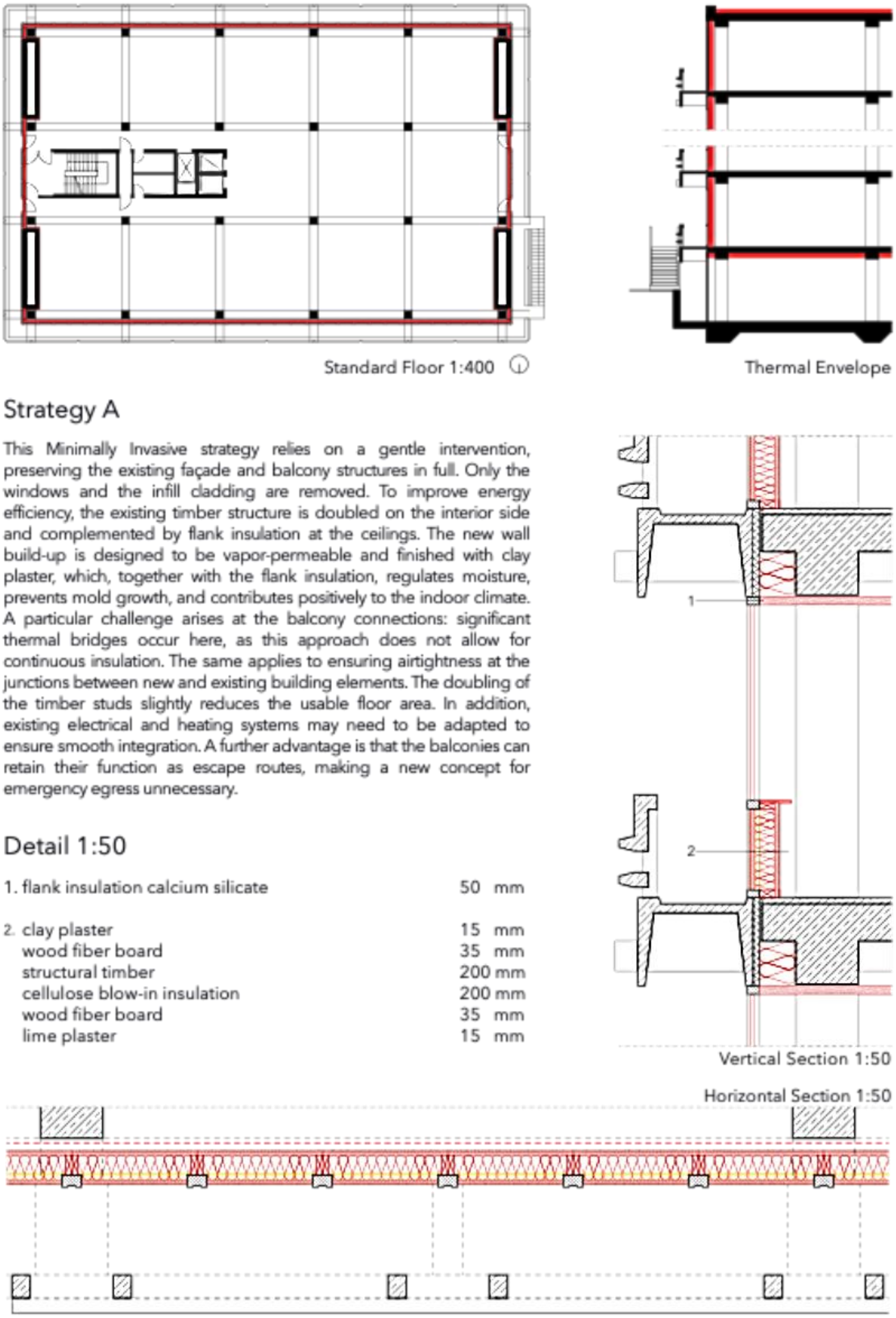
2.2.2.1 First strategy: Strategy A



Standard Floor 1:400

Thermal Envelope

Strategy A

This Minimally Invasive strategy relies on a gentle intervention, preserving the existing façade and balcony structures in full. Only the windows and the infill cladding are removed. To improve energy efficiency, the existing timber structure is doubled on the interior side and complemented by flank insulation at the ceilings. The new wall build-up is designed to be vapor-permeable and finished with clay plaster, which, together with the flank insulation, regulates moisture, prevents mold growth, and contributes positively to the indoor climate. A particular challenge arises at the balcony connections: significant thermal bridges occur here, as this approach does not allow for continuous insulation. The same applies to ensuring airtightness at the junctions between new and existing building elements. The doubling of the timber studs slightly reduces the usable floor area. In addition, existing electrical and heating systems may need to be adapted to ensure smooth integration. A further advantage is that the balconies can retain their function as escape routes, making a new concept for emergency egress unnecessary.

Detail 1:50

1.	flank insulation calcium silicate	50 mm
2.	clay plaster	15 mm
	wood fiber board	35 mm
	structural timber	200 mm
	cellulose blow-in insulation	200 mm
	wood fiber board	35 mm
	lime plaster	15 mm

Vertical Section 1:50

Horizontal Section 1:50

Figure 5. Structural drawings for the timber reuse-based retrofitting strategy A.

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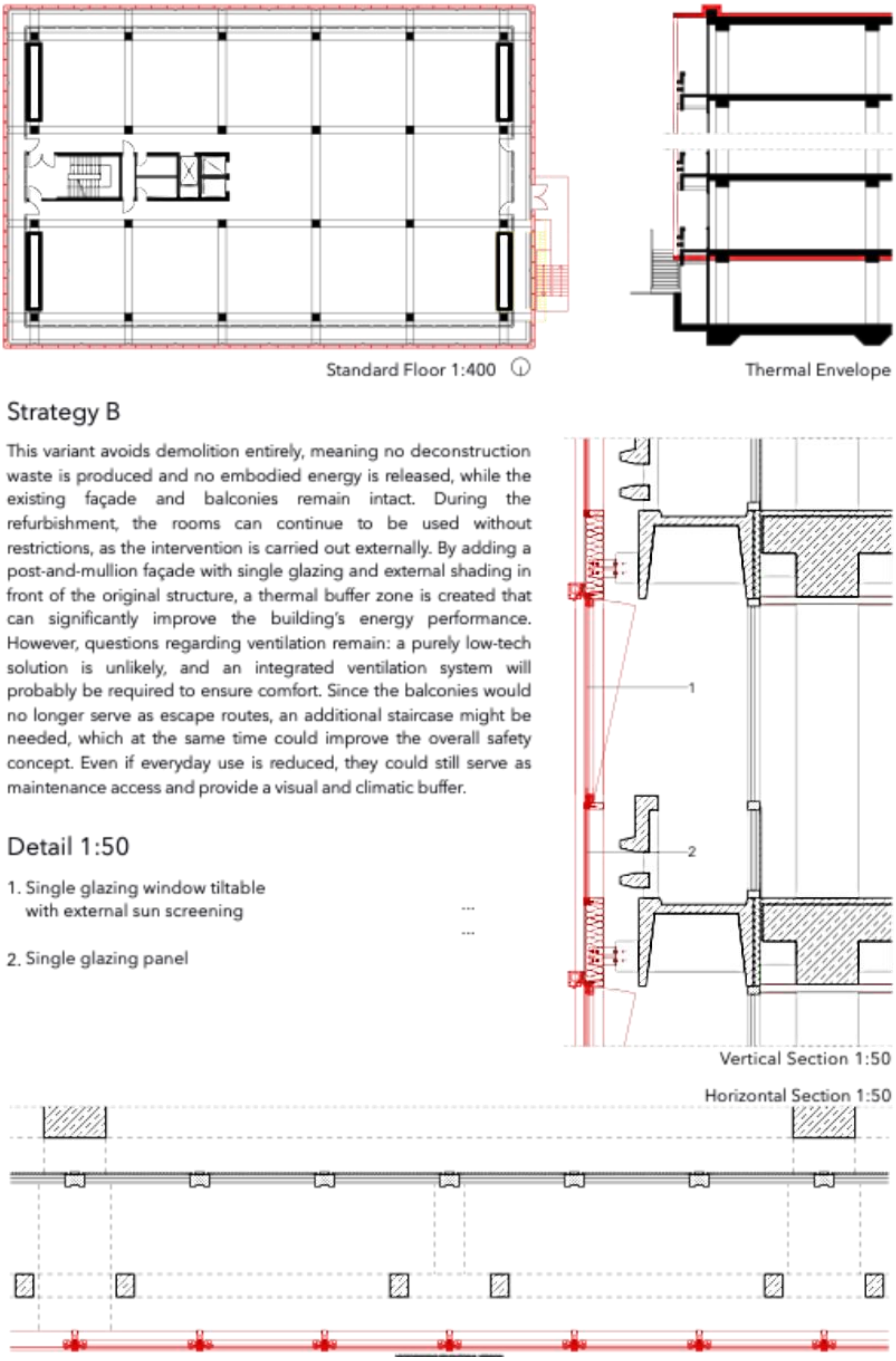
2.2.2.2 Second strategy: Strategy B



Strategy B

This variant avoids demolition entirely, meaning no deconstruction waste is produced and no embodied energy is released, while the existing façade and balconies remain intact. During the refurbishment, the rooms can continue to be used without restrictions, as the intervention is carried out externally. By adding a post-and-mullion façade with single glazing and external shading in front of the original structure, a thermal buffer zone is created that can significantly improve the building's energy performance. However, questions regarding ventilation remain: a purely low-tech solution is unlikely, and an integrated ventilation system will probably be required to ensure comfort. Since the balconies would no longer serve as escape routes, an additional staircase might be needed, which at the same time could improve the overall safety concept. Even if everyday use is reduced, they could still serve as maintenance access and provide a visual and climatic buffer.

Detail 1:50

1. Single glazing window tiltable with external sun screening
2. Single glazing panel

Figure 6. Structural drawings for the timber reuse-based retrofitting strategy B.

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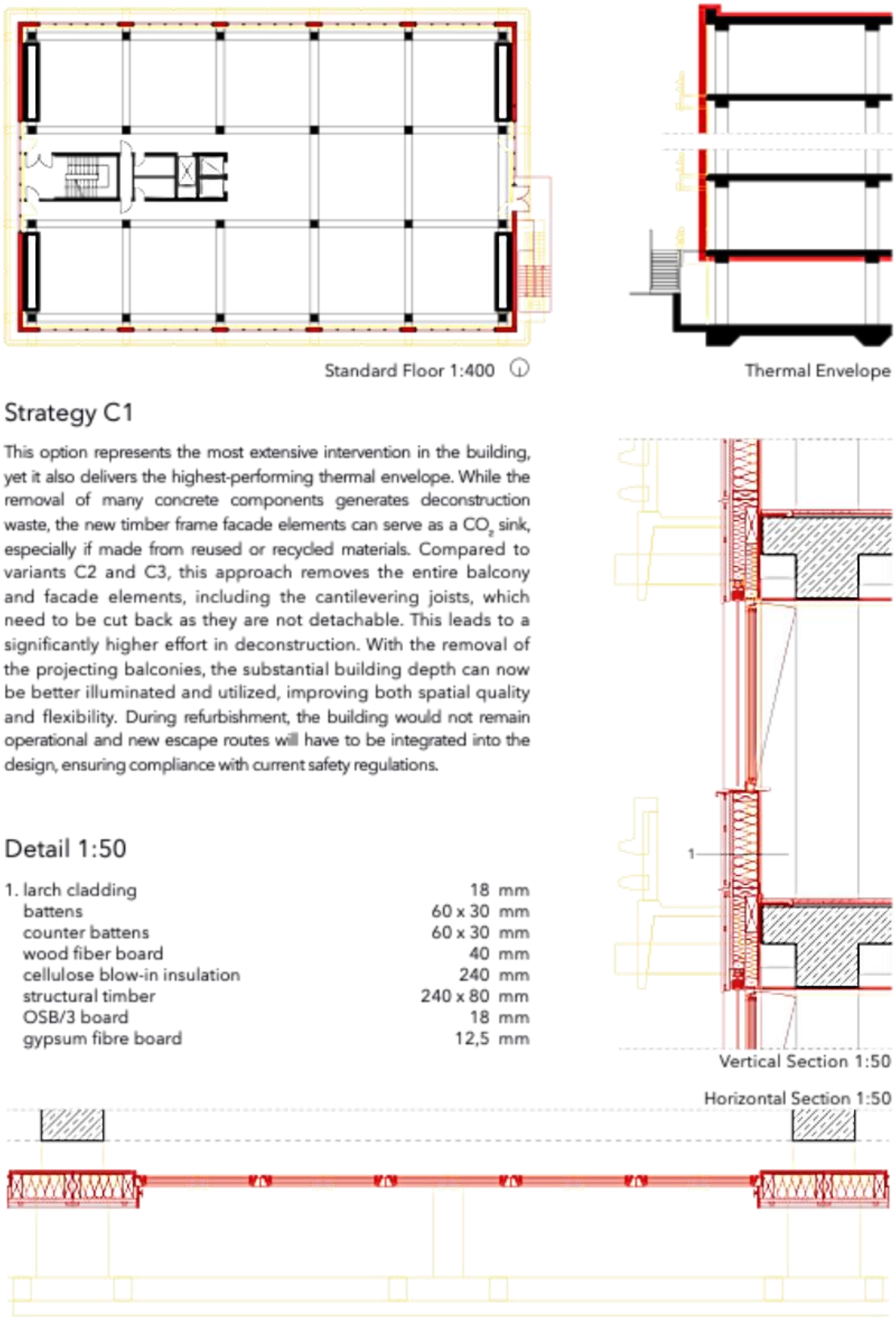
2.2.2.3 Third strategy: Strategy C.1



Strategy C1

This option represents the most extensive intervention in the building, yet it also delivers the highest-performing thermal envelope. While the removal of many concrete components generates deconstruction waste, the new timber frame facade elements can serve as a CO_2 sink, especially if made from reused or recycled materials. Compared to variants C2 and C3, this approach removes the entire balcony and facade elements, including the cantilevering joists, which need to be cut back as they are not detachable. This leads to a significantly higher effort in deconstruction. With the removal of the projecting balconies, the substantial building depth can now be better illuminated and utilized, improving both spatial quality and flexibility. During refurbishment, the building would not remain operational and new escape routes will have to be integrated into the design, ensuring compliance with current safety regulations.

Detail 1:50

1. larch cladding	18 mm
battens	60 x 30 mm
counter battens	60 x 30 mm
wood fiber board	40 mm
cellulose blow-in insulation	240 mm
structural timber	240 x 80 mm
OSB/3 board	18 mm
gypsum fibre board	12,5 mm

Figure 7. Structural drawings for the timber reuse-based retrofitting strategy C.1.

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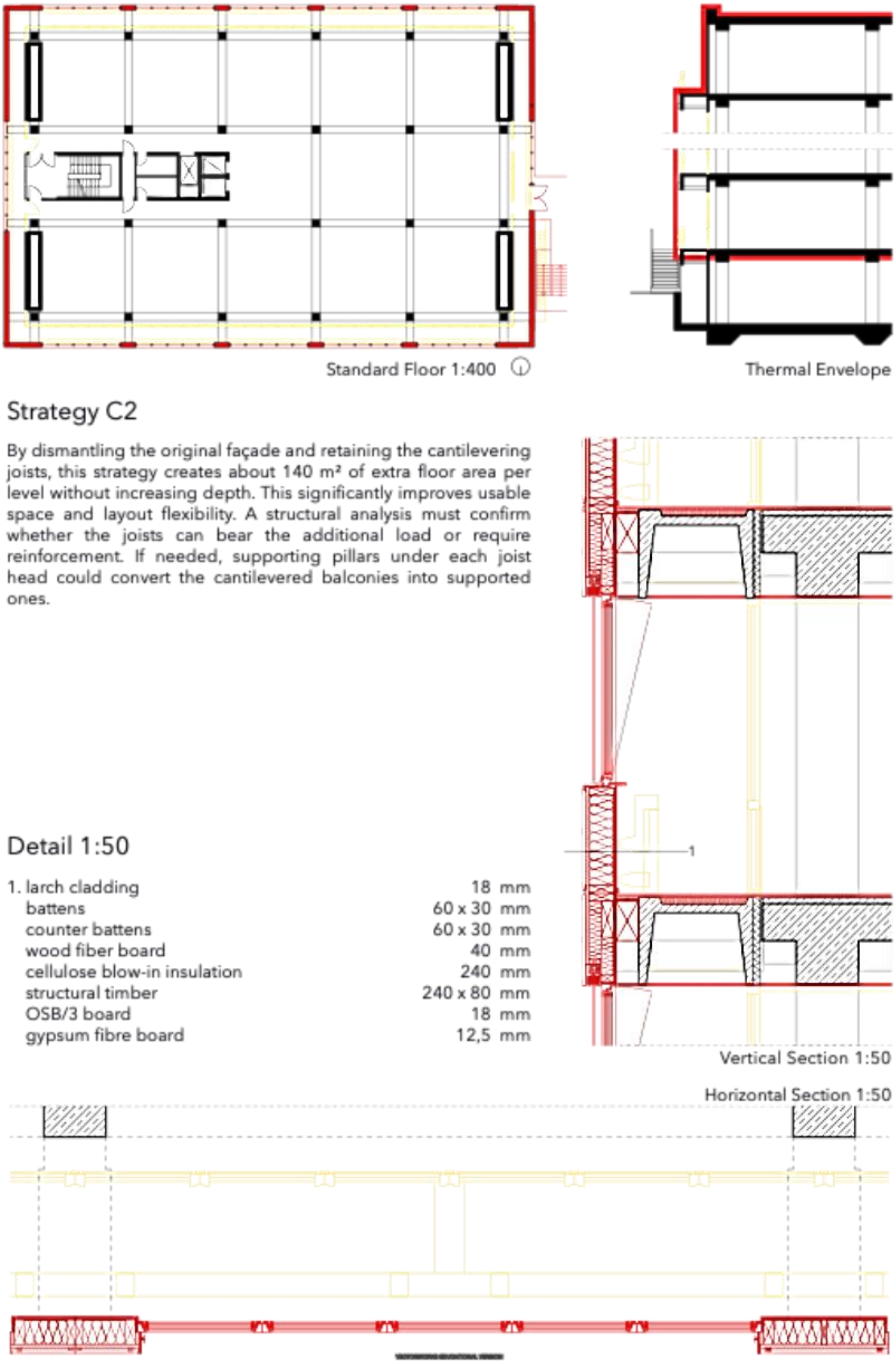
2.2.2.4 Fourth strategy: Strategy C.2



Strategy C2

By dismantling the original façade and retaining the cantilevering joists, this strategy creates about 140 m² of extra floor area per level without increasing depth. This significantly improves usable space and layout flexibility. A structural analysis must confirm whether the joists can bear the additional load or require reinforcement. If needed, supporting pillars under each joist head could convert the cantilevered balconies into supported ones.

Detail 1:50

1. larch cladding	18 mm
battens	60 x 30 mm
counter battens	60 x 30 mm
wood fiber board	40 mm
cellulose blow-in insulation	240 mm
structural timber	240 x 80 mm
OSB/3 board	18 mm
gypsum fibre board	12,5 mm

Figure 8. Structural drawings for the timber reuse-based retrofitting strategy C.2.

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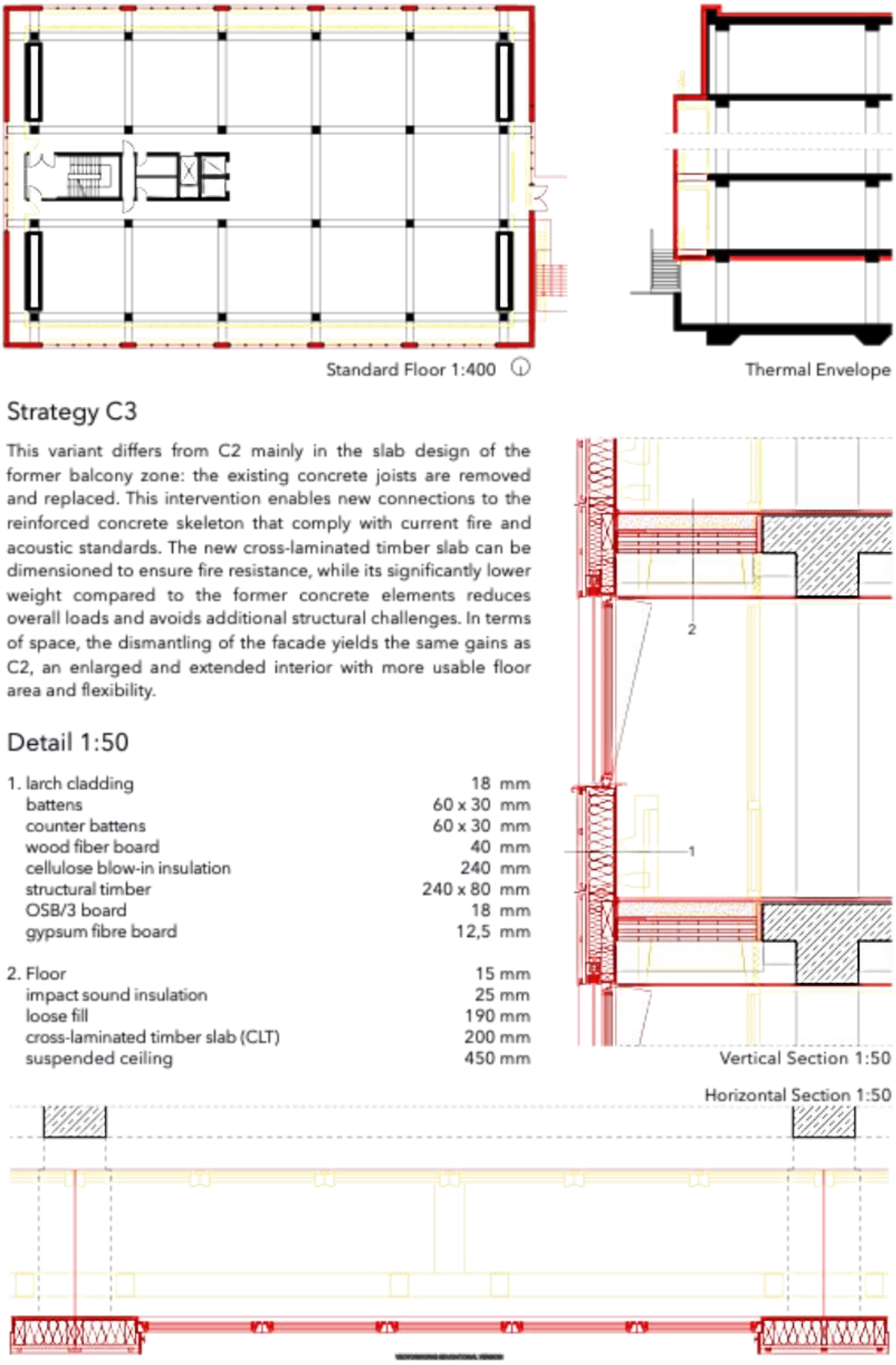
2.2.2.5 Fifth strategy: Strategy C.3



Strategy C3

This variant differs from C2 mainly in the slab design of the former balcony zone: the existing concrete joists are removed and replaced. This intervention enables new connections to the reinforced concrete skeleton that comply with current fire and acoustic standards. The new cross-laminated timber slab can be dimensioned to ensure fire resistance, while its significantly lower weight compared to the former concrete elements reduces overall loads and avoids additional structural challenges. In terms of space, the dismantling of the facade yields the same gains as C2, an enlarged and extended interior with more usable floor area and flexibility.

Detail 1:50

1. larch cladding	18 mm
battens	60 x 30 mm
counter battens	60 x 30 mm
wood fiber board	40 mm
cellulose blow-in insulation	240 mm
structural timber	240 x 80 mm
OSB/3 board	18 mm
gypsum fibre board	12,5 mm
2. Floor	15 mm
impact sound insulation	25 mm
loose fill	190 mm
cross-laminated timber slab (CLT)	200 mm
suspended ceiling	450 mm

Figure 9. Structural drawings for the timber reuse-based retrofitting strategy C.3.

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2.3 Assessment and Validation

2.3.1 Energy performance before and after refurbishment

To verify and quantify the assumptions made during the preliminary design process of the three renovation variants, an environmental assessment is carried out as the basis for final validation. The first part of the assessment investigates the energy demand of the existing building before and after renovation. The renovated state is modelled using the Hottgenroth Software [21] for all three wall-related strategies A, B, and C, which have been introduced in the previous chapter. In addition to the walls, comprehensive measures are also planned to improve the thermal performance of other building components, such as the roof, basement ceiling, and other adjoining elements. Unlike the wall, which is evaluated in three different variants, these other components are assigned one uniform renovation solution. This approach ensures comparability across the wall-retrofitting scenarios, enabling a clear validation of their respective impacts. The objective of this first stage of the assessment is to determine the effect of the renovation about energy savings in the future.

2.3.1.1 Energy performance before renovation: Existing building

To begin with, the existing building in its current state is analyzed as the baseline for comparison. **Table 1** presents the most significant information about the investigated building, which is located in the campus of KIT.

Table 1. Information about the investigated building for the retrofitting strategies.

Information	Details
Building type	University institute building with office space and laboratories
Year of Construction	1970
Heated volume (V_e)	35,855 m^3 (determined in accordance with GEG using external dimensions)
Air volume (V)	28.684 m^3
Net floor area A_{NGF}	7,655 m^2

The demonstrator building, “Materialprüfungs- und Forschungsanstalt Karlsruhe (MPA Karlsruhe)”, is used as a research facility and consists mainly of office spaces, seminar rooms, sanitary facilities, and circulation areas. The technical service rooms are located in the basement and attic, with the basement being unheated. The building is currently supplied with heat via a district heating system, with heat primarily delivered to the rooms through radiators. No cooling system is installed. Domestic hot water heating has been excluded from the scope of this report due to a lack of available information. In the sanitary areas, a period-typical exhaust ventilation system is in place, while the common areas do not have any ventilation system. Lighting mainly relies on fluorescent lamps, with many underutilized areas such as basements and storage rooms lacking occupancy sensors. At present, no regenerative energy systems are in place. Accordingly, no photovoltaic system is installed on the roof, although the roof surface offers substantial potential for solar energy generation.

Figure 10 shows the energy balance of the building in its current state, analyzing heat losses for space heating and heat gains (e.g., solar gains through the windows). Energy losses occur in varying proportions through the building envelope, due to air exchange, and during the generation and supply of the required energy.

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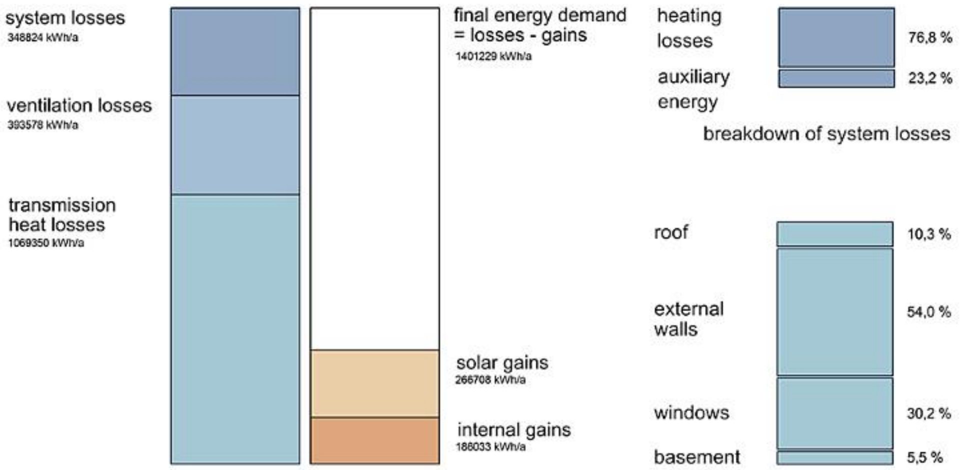

Figure 10. Breakdown of energy losses for space heating (unrenovated state).

As **Figure 10** illustrates, a significant portion of the overall heat loss — 1,069,350 kWh/a out of a total of 1,811,752 kWh/a — is caused by transmission through the building envelope. This is primarily due to the insufficient thermal insulation of the existing structure. Of all envelope-related losses, 84% are attributed to the external walls and windows, while the remaining losses are associated with the roof and basement. A closer examination of the envelope in its current condition reveals that the largest share of the envelope consists of an uninsulated standard wall construction. This construction is made up of 0.8 cm HPL panels, an 8 cm wooden stud frame with uninsulated cavities, and a roughly 1.2 cm thick wood-based panel. The transparent elements are double-glazed timber-frame windows from the 1970s. The exterior walls of the top-floor technical services area are likely concrete with a 1 cm plaster layer. The vertical installation zones are confined by an 18 cm metal stud frame filled with mineral wool and cladded with 1.5 cm plastered gypsum boards. The roof structure is likely concrete with minimal insulation and a bitumen waterproofing layer. The basement is presumably unheated, and its ceiling appears to remain in the original as-built condition.

Table 2 below presents the substandard U-values of the main envelope components of the existing building, as calculated with Hottgenroth Software (left column). These values exceed the maximum allowable limits defined by current regulations (GEG – Building Energy Act, Germany), which are presented in the right column.

Table 2. U-values of the main building envelope elements.

Envelope element	U-value Unrenovated $[W/(m^2K)]$	U-value$_{max}$ GEG $[W/(m^2K)]$
Flat roof	1.22	0.24
Exterior door	3.50	1.80
External wall technical floor (top floor)	3.02	0.24
External wall installation zones	1.60	0.24
External wall façade elements	2.25	0.24
Windows	2.70	1.30
Basement ceiling	1.01	0.30
Secondary facade (strategy B)	-	-

The currently low-performing envelope and outdated building services lead to a high energy demand of the existing building. The energy demand of the building is presented in **Table 3**.

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Table 3. Energy demand of the unrenovated building.

Parameter	Value
Final energy demand [kWh/a]	1,401,229.0
Primary energy demand [kWh/a]	1,862,016.0
Primary energy demand per square meter of usable floor area [kWh/m^{2}a]	243.2

2.3.1.2 Energy performance after renovation

In a second step, the values outlined above are compared with the projected energy demand after renovation to assess its impact. The assumptions for this initial analysis are based on the preliminary design of the renovation scenarios and incorporate generalized estimates where necessary, to provide a consistent assessment and support decision-making at this early stage of the planning process. The renovation comprises the following measures as described in Section 2.2:

Retrofitting of the walls in three variants (Strategies A, B, and C): Three promising wall designs were selected from the preliminary set of variants (see sections 2.2.3, 2.2.4, and 2.2.5). To compare their performance from an energy point of view, each design is modelled as a separate scenario using the Hottgenroth Software.

Retrofitting of the roof: The existing roof, which provides only limited thermal performance, is retrofitted with an extensive green roof on an additional 30 cm thick layer of high-performance, bio-based insulation. This improves the insulating properties of the retrofitted building component significantly, achieving a U-value equal to 0.12 W/m^{2}K. The same measure is applied across all three retrofitting scenarios.

Retrofitting of the basement: Insulation of the basement ceiling has been identified as an economically efficient method to reduce thermal losses. Accordingly, the basement ceiling is insulated to achieve a U-value of 0.28 W/m^{2}K. Again, the same measure applies to all three scenarios.

Revised energy concept: To support the transformation towards ZEB, the building services are retrofitted according to the following in all renovation scenarios. Given the high quality of the building envelope components in all renovation variants, the heating system can be converted to a ground-source heat pump supplying heat via low-temperature radiators. The main distribution system will be insulated. Due to a lack of information, hot water generation has not been considered either in the current state or in the renovation scenarios. The exhaust system in the sanitary areas will be renewed, and the lighting will be reviewed and upgraded to LED technology. In addition, the installation of occupancy sensors in corridors, sanitary, and storage rooms offers the possibility of energy savings through reduced operating times. As the roof offers significant potential for installation of a PV system, PV modules will be mounted as part of the virtual renovation concept to cover the building's electricity demand. The structural capacity of the roof to support the additional load of the PV and the extensive green roof would need to be verified during the detailed planning phase of an actual building project to determine whether any reinforcement measures are required. For the purpose of this virtual demonstration, however, the roof is assumed to have sufficient structural capacity to support the loads of the PV system, based on preliminary estimates.

Table 4 provides an overview of how the main envelope components perform after the renovation (strategies A, B, and C) and compares them to the current maximum values given by the existing law (GEG). As **Table 4** indicates, the solutions developed within the virtual demonstration of the SIRCULAR project substantially enhance the U-values of the main envelope components, thereby reducing thermal losses and contributing to the transformation towards a zero-emission building.

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Table 4. U-values of the main envelope elements according to the retrofitting strategy.

Envelope element	U-value Unrenovated [W/(m²K)]	U-value GEG [W/(m²K)]	U-value Strategy A [W/(m²K)]	U-value Strategy B [W/(m²K)]	U-value Strategy C [W/(m²K)]
Flat roof	1.22	0.24	0.12	0.12	0.12
Exterior door	3.50	1.8	1.30	3.50	1.30
External wall technical floor (top floor)	3.02	0.24	0.13	0.13	0.13
External wall installation zones	1.60	0.24	0.45	1.60	0.45
External wall façade elements	2.25	0.24	0.15	2.25	0.15
Windows	2.70	1.3	0.80	2.70	0.80
Basement ceiling	1.01	0.30	0.28	0.28	0.28
Secondary façade (strategy B)	-	-	-	0.95	-

The previous table, **Table 4**, highlights significant improvements across all three scenarios. As a result of the reduced transmission losses and the updated energy concept, the corresponding final and primary energy demands for the three renovation scenarios are presented in **Table 5** and **Figure 11**, presenting the energy demand according to each strategy and the resulting savings, respectively. The resulting savings are in the range of 91% to 94%, which are very promising. Both final and primary energy savings are key indicators for assessing the effect of the different renovation strategies.

Table 5. Energy demand of the building according the retrofitting strategies.

Parameter	Unrenovated	Strategy A	Strategy B	Strategy C
Final energy demand				
Final energy demand in total [kWh/a]	1,401,229	130,686	150,505	12,014
Final energy covered by PV [kWh/a]	0	- 52,308	- 52,308	- 52,308
Net balance [kWh/a]	1,401,229	78,378	98,197	74,706
Net balance per m² [kWh/m²a]	183	10	11	10
Primary energy demand				
Primary energy demand in total [kWh/a]	1,862,016	235,235	270,909	228,625
Primary energy covered by PV [kWh/a]	0	- 94,154	- 94,154	- 94,154
Net balance [kWh/a]	1,862,016	141,081	176,755	134,471
Net balance per m² [kWh/m²a]	243	18	19	18

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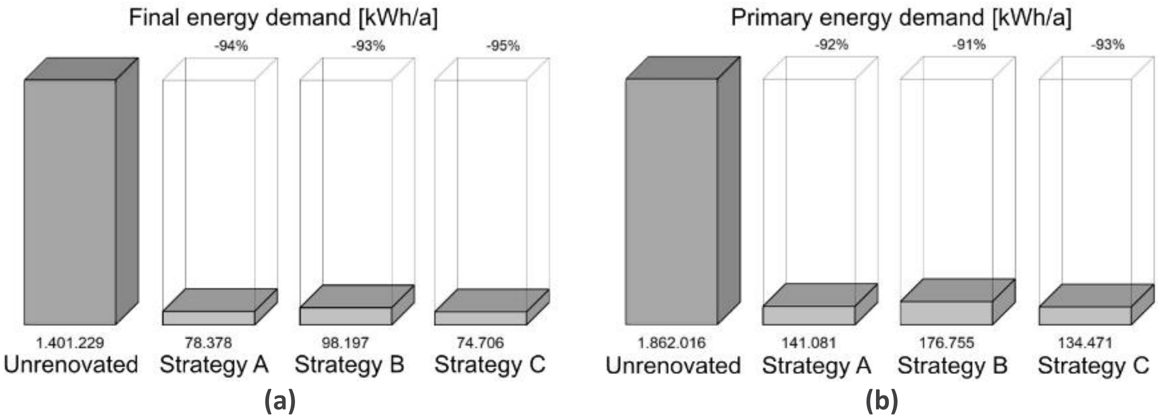

(a) (b)

Figure 11. The energy demand according to each retrofitting strategy. The results (a) for the final energy demand, and (b) for the primary energy demand.

These diagrams show that a substantial reduction in energy demand is achieved across all renovation scenarios, with only minor differences between them. With a slight edge, the most comprehensive measures (Scenario C) deliver the best overall performance. For later comparison of operational energy savings with construction-related embodied energy, the final energy demands calculated above are converted into GHG emissions according to an appendix of the German Energy Law (GEG) [22]. To this end, the energy demand values are multiplied by the respective emission factors defined for each energy carrier (e.g., electricity, natural gas, and district heating). These factors represent the average specific greenhouse gas emissions per unit of delivered energy, expressed as CO_2-equivalents. The resulting values quantify the operational GHG emissions of the existing building in kilograms of CO_2-equivalents per year. The results are presented in **Table 6**.

Table 6. The energy demand converted into GHG emissions according to the German Energy Law.

Parameter	Unrenovated	Strategy A	Strategy B	Strategy C
Final energy demand per year [kWh/a]	1,401,229	78,378	98,197	74,706
Final energy savings per year [kWh/a]	-	1,322,851	1,303,032	1,326,523
GHG emissions per year [t $CO_{2\text{-eq}}$/a]	573.4	43.9	55.0	41.8
GHG emission savings per year [t $CO_{2\text{-eq}}$/a]	-	529.5	518.4	531.6

As a preliminary outcome of the energy assessment, the projected annual final energy savings for the renovations relative to the non-renovated baseline amount to approximately 1.3 million kWh/a and 520 tonnes of greenhouse gases, across all three renovation scenarios. This projection is notably conservative, and the actual CO_2 savings are expected to be higher as the decarbonization of the electricity grid continues. These developments are particularly relevant to the ecological operation of heat pumps, especially in dense inner-city areas where roof space is typically insufficient to fully meet electricity demand, which also applies to the demonstrator project. By 2030, Germany aims to source around 80 percent of its electricity from renewable sources, with steps towards nearly 100 percent renewables in the subsequent decade, significantly improving electricity-operated energy systems [23].

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2.3.2 Life-cycle-Assessment of renovation measures

2.3.2.1 LCA of the three renovation strategies

Following the assessment of operational energy savings, the next section evaluates the renovation strategies in terms of embodied energy resulting from the renovation measures and associated maintenance over a 50-year period. Accordingly, this section aims to determine the environmental footprint of the different renovation strategies, ultimately enabling a comparison of the GHG input required for renovation and the GHG savings due to the lower energy demand. At this stage, it is important to emphasize that the assessment is based on qualified assumptions and estimates, due to the preliminary design status and limited data availability. In the context of the virtual demonstration, opportunities to gather a complete dataset or investigate unknown aspects of the existing structure are inherently limited. Consequently, the assessment should be regarded as a preliminary basis for decision-making.

Figure 12 below illustrates the results of the LCA for all three renovation variants across a 50-year life cycle. The diagram quantifies the Global Warming Potential (GWP) in kg CO_2-eq for the entire building, allowing an assessment of the overall ecological footprint of the renovation. The assessment includes Modules A1–A3, C3, and C4, covering the construction phase and all maintenance or replacement expected over the 50-year period. This analysis does not include the potential recycling of the used materials for the renovation strategies. This potential could further reduce the GWP of the strategies.

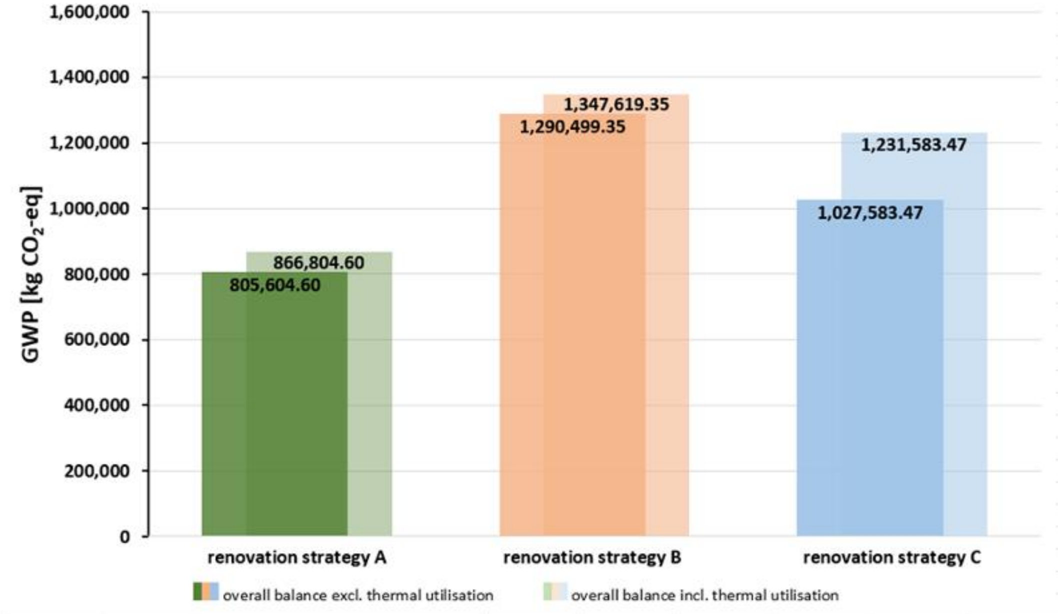

Figure 12. Global warming potential of renovation strategies (over 50 years).

The lighter bars represent the overall balance including thermal utilization, complying with LCA standards. In addition, the darker bars illustrate an alternative outcome in which the carbon stored in the solid timber components remains sequestered, reflecting timber reuse as a future scenario instead of incineration. To this end, Module C3 (Waste Processing) has been determined separately for the solid timber parts of the constructions (see also **Table 7**) and deducted from the overall balance. Doing so leads to a considerably lower GWP — especially in the timber-rich Strategy C — emphasizing the strong climate mitigation potential of reusing building components rather than directing them into the waste stream. The incorporation of additional reused or recycled materials beyond the reclaimed timber components could potentially reduce the GWP of the renovations even further – an aspect not

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yet reflected in the previous figures. This perspective not only highlights the large amounts of embodied energy stored in the existing building stock but also underscores the opportunities arising from keeping this carbon in circulation. By selectively dismantling and reusing components instead of releasing carbon through demolition and incineration, a powerful lever for climate mitigation in the building sector can be activated. The diagram also illustrates how incineration affects the different renovation strategies to varying degrees, particularly to the disadvantage of timber-based constructions. Renovation Strategy B, with its high proportion of carbon-intensive glass surfaces, results in the highest GWP values under both calculation methods, slightly exceeding those of Strategy C. However, this gap widens significantly when incineration is excluded from the end-of-life scenario. In that case, Strategy C — which incorporates the highest share of timber — shows a substantially improved carbon balance. Regardless, Strategy A performs best in both scenarios. As the least intrusive approach, it requires minimal resource input. Moreover, it makes extensive use of existing structures and involves only minor deconstruction work.

In this context, it is important to note that the LCA carried out for this report does not reflect and quantify deconstruction measures. The differences in retained building mass among the renovation strategies are therefore not accounted for. While Strategies A and B both preserve most of the existing structure, Strategy C involves full deconstruction of the envelope and balconies, requiring energy and generating waste. These impacts fall under Modules C1–C4 but are not included in the standardized LCA assessment. Furthermore, the results presented above are based on standard values for timber, which refer to freshly sourced wood. Consequently, this assessment does not take into account that, in the SIRCULAR renovation scenarios, the timber is sourced through urban mining and has been used before. Factoring this into the LCA is challenging and requires a more detailed look. The following section will explore possible approaches to represent and quantify the reuse of timber in the LCA.

2.3.2.2 Opportunities and limits in reflecting reuse and future reusability in the LCA

While it may be a future challenge to ensure that components constructed today are protected from incineration fifty years or more from now, the opportunity to save and reintegrate already available building materials is immediate and actionable. This is the approach taken by the three renovation strategies presented in this deliverable: all of them incorporate reclaimed timber. To determine the positive impact of this design decision on the renovation's environmental footprint, this factor needs to be adequately captured in the LCA. Even if achieving a fully accurate picture is challenging, it can be very valuable to quantify aspects that are important to foster — even though difficult to reflect numerically — such as the reuse of building components. For this purpose, different methods are currently discussed, as analyzed by Allacker et al. [24] and De Wolf et al. [25], based on three different use phases:

- first-time usage with the resource being produced from scratch (e.g., through forestry and production plants),
- mid-phase usage, with the resource being reused (can be repeated several times),
- last-time usage, after which the resource is not reused again (instead, it is utilized, disposed of, or downcycled).

While there are several approaches currently being discussed to reflect reuse in the LCA, one of them is chosen for the scope of this report to show potentials and current limitations. Due to its practical approach, the Cut-Off method [26], as implemented in several frameworks such as ISO 14040 [27], is selected. The Cut-Off method suggests to allocate environmental effects to the phase where they actually occur. Accordingly, the concept implies that the Product Stages A1–A3 are excluded when

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reclaimed material is used, and that the End-of-Life Module C is only considered in the final use cycle. Furthermore, it provides incentives by assigning a reuse credit in Module D ("Benefits and loads beyond the system boundary").

In order to demonstrate the Cut-Off-method and its implications, particularly in relation to reclaimed wood, it will be applied on a material level for the solid timber parts of the three different renovation designs. The resulting GWP balance for the whole building across all three variants is shown in **Table 7**. The procedure will be explained below.

Table 7. CO_2 savings from reuse as reflected under the Cut-Off method.

Parameter	Ökobaudat [28] Data	Strategy A	Strategy B	Strategy C
Amount of solid timber in m^3	1	75	70	250
A1-3 (GWP in kg CO_2-eq.) for timber parts **C3** (GWP in kg CO_2-eq.) for timber parts **D** (GWP in kg CO_2-eq.) for timber parts	-727 816 -12.87	-54,525 61,200 -965	-50,980 57,120 -901	-181,750 204,000 -3,218
Balance of whole building before application of Cut-Off-method for reclaimed timber parts (GWP in kg CO_2-eq., incl. A1-A3, C3-C4)	-	866,805	1,347,619	1,231,583
Balance of whole building after application of Cut-Off-method for reclaimed timber parts (GWP in kg CO_2-eq., incl. A1-3, C3-C4; deduction of A1-A3 and C3 for timber parts, addition of D for timber parts)	-	**859,165**	**1,340,488**	**1,206,115**

According to the phase model, the timber parts in the SIRCULAR renovation strategies can be classified as mid-phase usage, as they originate from prior applications and are expected to be reused in the future. In this case, the Cut-Off-method suggests the omission of the Product Stage Modules A1–A3. The same applies to the End-of-Life Modules C3 and C4, as mid-phase usage implies that the reclaimed materials will be further reused instead of being incinerated. Credits are granted from the Recycling Potential Module D. All these values are determined separately, as shown in **Table 7**, and accounted for in the overall balance.

With this calculation method, the Cut-Off-method aims to reflect the expected environmental burdens and credits of an isolated mid-phase usage life cycle as accurately as possible. Nevertheless, this method remains approximate. For instance, reclaimed timber still requires processing steps and transport similar to fresh wood before it can be reused. These aspects are not accounted for when stages A1–A3 are entirely omitted. To address this distortion, emissions related to processing steps of reclaimed materials could be approximated by using modules C1 and C2 for the mining process and transports, and selected parts of A1–A3 for the processing itself. However, this is not foreseen under the Cut-Off method and must be further investigated.

Another challenge lies in defining the applicable usage phase (first, mid, and last) in the first place, especially with regard to potential life cycles that may or may not follow. Any future reuse remains inherently speculative at the time of design and construction. Moreover, buildings are seldomly designed to enable ease of disassembly and direct reuse. Allowances with regard to future reuse, as suggested in the Cut-Off-method by omission of the End-of-Life scenario (C1–C4), may therefore be viewed critically. As a consequence, it could be reasonable to set the "worst-case scenario" – allocating

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all environmental burdens from Module C – as the default. Any deviation from this, such as omitting Module C, should be subject to specific conditions. For instance, a circularity concept could be provided, showing that the design is suitable for non-destructive deconstruction and reuse in the future, i.e., by planning with reversible connections, avoiding glues, avoiding composite materials, etc. This could prevent the improper omission of environmental burdens associated with the end-of-life stage and further incentivize circular construction. Lastly, while the Cut-Off method is well-suited for estimating the expected environmental effects of a construction measure, it is less suitable for retrospectively assessing the cumulative impact across all life cycles of a material. The reuse credit allocated in Module D during one cycle and the avoided primary production in A1–A3 in the subsequent cycle would result in double-counting.

With the SIRCULAR renovations placing particular emphasis on reclaimed timber, it is important to note that wood, as a renewable building material, behaves differently in CO_2 balances compared to non-renewable materials, due to its inherent carbon storage capacity. For most building materials in mid-phase usage, the Cut-Off-method leads to the omission of environmental burdens from both the Product Stage and the End-of-Life Stage, thereby appropriately rewarding sustainable practices. In the case of timber, however, the Product Stage is associated with a negative total GWP, as the carbon sequestered during the tree's growth significantly outweighs the minor fossil emissions from processing. The stored biogenic carbon is only released at the end of life if the material is incinerated. At that point, the previously negative and the newly positive values roughly cancel each other out. The same balancing effect occurs when both the product and end-of-life stages are omitted, as suggested for a mid-phase life cycle assessment. Theoretically, this could lead to a misleading advantage for first-use timber in the LCA: fresh wood appears particularly beneficial due to its negative GWP in the product stage, while the release of carbon at end-of-life is excluded if reuse is anticipated. This undermines the intention of promoting reuse, as it disincentivizes the integration of reclaimed renewable material.

Two key points must be considered in this context. Firstly, Module D becomes relevant here. It allows the positive effects of reuse to be partially captured. However, it must be acknowledged that Module D reflects future recycling potentials, not the actual use of reclaimed material within the current system. Secondly, it should be further examined whether biogenic carbon is to be included in the total GWP at all. Excluding the carbon stored in the material resource could help prevent distortions in the results caused by varying allocation of carbon release, particularly in timber construction. In this case, the GWP considered in the LCA would reflect only fossil emissions, for instance, those from production processes. The biogenically stored carbon could be reported separately. Such a separation would, in turn, make the omission of these emissions in a reuse scenario both more meaningful and methodologically accurate.

In summary, **Table 7** shows that the CO_2 savings from reuse, as reflected under the Cut-Off method, remain moderate compared to the overall results. Therefore, LCA should not be the sole means of assessing and incentivizing reuse and circular construction. Complementary tools, such as circularity indices (see Section 2.2.4), are essential. Overall, the representation of reuse and reusability in LCAs remains a subject of ongoing discussion and is still evolving toward appropriate methodological treatment. Yet, many of the benefits of reuse lie beyond the scope of current LCA frameworks. Reuse can foster new value chains and economic opportunities, and more broadly, it has the potential to reshape our relationship with material resources. At scale, it may even help reduce land take, preserve natural habitats, lessen reliance on industrial forestry, and contribute meaningfully to addressing the global biodiversity crisis.

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2.3.3 Life-cycle-cost analysis

Life-cycle-cost (LCC) analysis is a well-established method for assessing the comprehensive financial implications of a building or refurbishment project throughout its entire lifespan, encompassing initial investment, component replacements, maintenance, refurbishment, cleaning, and operational expenses. However, conducting an accurate LCC requires detailed and reliable data, which can be challenging to obtain – particularly during the early stages of a project and when renovating existing buildings. Despite these uncertainties related to the preliminary planning phase of the SIRCULAR renovation strategies, cost considerations remain a critical factor in decision-making and are therefore approximated here as accurately as possible.

To support this, the German Sustainable Building Certification System (BNB) offers an LCC-tool, facilitating the standardized assessment of life cycle costs. The LCC-analysis for the SIRCULAR renovation strategies was conducted using the BNB tool tailored for office buildings (BNB_B), providing a comprehensive assessment of the building's performance over a 50-year period [29].

As an initial step, the investment costs of the three different variants were determined based on a detailed cost estimation of the renovation measures, broken down to the level of individual building components. These estimated costs have been derived from multiple sources to ensure accuracy and reliability. Primarily, the "Standardleistungsbuch" [30], a standardized catalogue of construction services widely used in German-speaking countries for pricing and tendering, serves as a reference. Additionally, data from the "Baukosteninformationszentrum Deutscher Architektenkammern" (BKI) [31], which provides comprehensive construction cost information and benchmarks, was used. Finally, practical experience from ongoing building projects was incorporated to complement and validate the figures. Existing building elements have not been included in the costs. The same applies to costs associated with deconstruction measures.

Based on the resulting investment costs for the renovations, replacement costs over a 50-year period were calculated using the BNB tool, which relies on an associated standardized table providing maximum service lives for various building components. In addition to replacement costs, the BNB tool also includes inspection and maintenance, refurbishment, cleaning, and energy costs in its calculations. Although water and sewage costs are typically considered, they were excluded from the overall assessment in this report due to insufficient data. However, these costs would remain constant across all renovation variants and therefore would not affect the comparative evaluation of the building envelope systems.

The energy costs were calculated based on the previously defined energy demands per renovation variant and the predefined energy costs for the respective carrier media in Germany. To account for the total energy expenses over a 50-year period, the BNB tool incorporates an annual price escalation, along with a discount rate to convert the sums into present value. **Figure 13** illustrates the LCC-results for all three renovation strategies.

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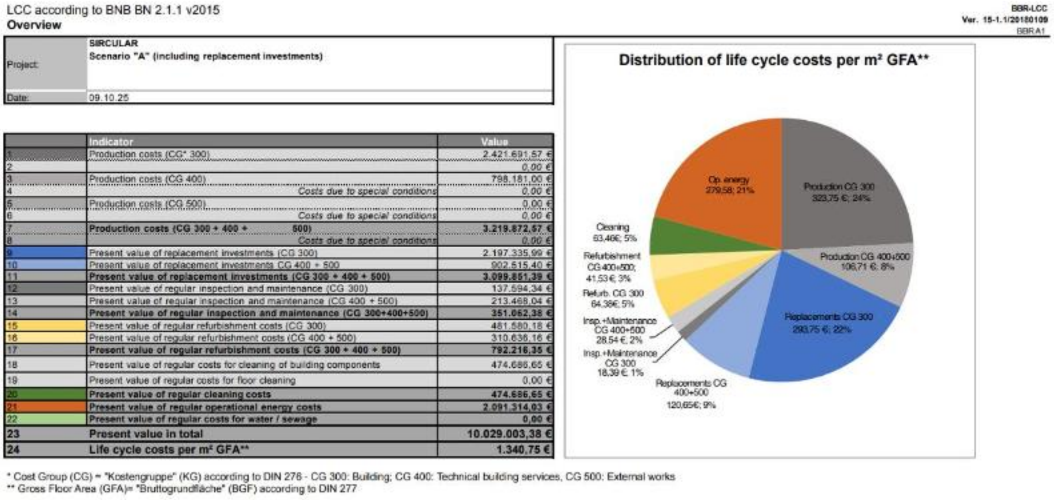


LCC according to BNB BN 2.1.1 v2015
Overview

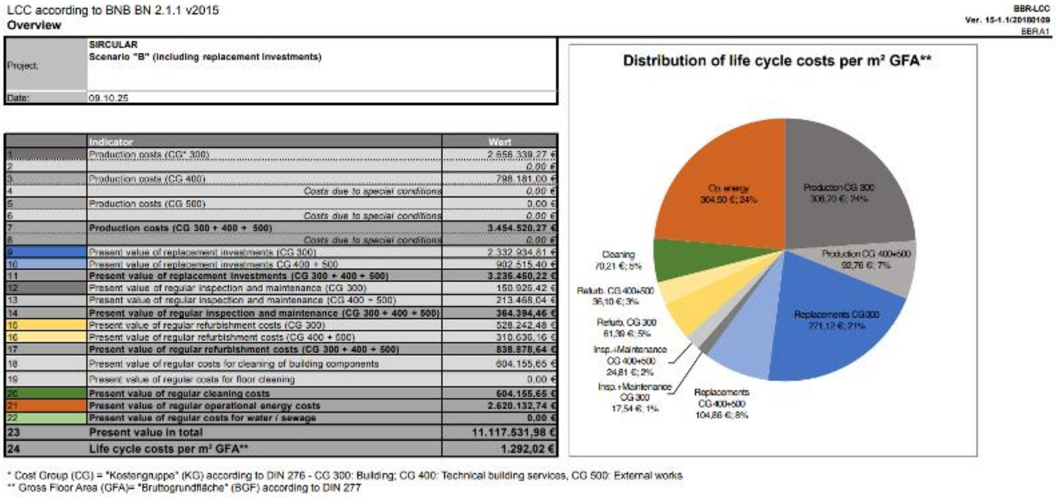
BBR-LCC
Ver. 15-1.1/20180109
BBRA1

Project:	**SIRCULAR** **Scenario "A" (including replacement investments)**
Date:	09.10.25

	Indicator	Value
1	Production costs (CG* 300)	2.421.691,57 €
2		0,00 €
3	Production costs (CG 400)	798.181,00 €
4	*Costs due to special conditions*	0,00 €
5	Production costs (CG 500)	0,00 €
6	*Costs due to special conditions*	0,00 €
7	**Production costs (CG 300 + 400 + 500)**	**3.219.872,57 €**
8	*Costs due to special conditions*	0,00 €
9	Present value of replacement investments (CG 300)	2.197.335,99 €
10	Present value of replacement investments CG 400 + 500	902.515,40 €
11	**Present value of replacement investments (CG 300 + 400 + 500)**	**3.099.851,39 €**
12	Present value of regular inspection and maintenance (CG 300)	137.594,34 €
13	Present value of regular inspection and maintenance (CG 400 + 500)	213.468,04 €
14	**Present value of regular inspection and maintenance (CG 300+400+500)**	**351.062,38 €**
15	Present value of regular refurbishment costs (CG 300)	481.580,18 €
16	Present value of regular refurbishment costs (CG 400 + 500)	310.636,16 €
17	**Present value of regular refurbishment costs (CG 300 + 400 + 500)**	**792.216,35 €**
18	Present value of regular costs for cleaning of building components	474.686,65 €
19	Present value of regular costs for floor cleaning	0,00 €
20	**Present value of regular cleaning costs**	**474.686,65 €**
21	**Present value of regular operational energy costs**	**2.091.314,03 €**
22	**Present value of regular costs for water / sewage**	**0,00 €**
23	**Present value in total**	**10.029.003,38 €**
24	**Life cycle costs per m² GFA****	**1.340,75 €**

* Cost Group (CG) = "Kostengruppe" (KG) according to DIN 276 - CG 300: Building; CG 400: Technical building services, CG 500: External works
** Gross Floor Area (GFA)= "Bruttogrundfläche" (BGF) according to DIN 277

(a)



LCC according to BNB BN 2.1.1 v2015
Overview

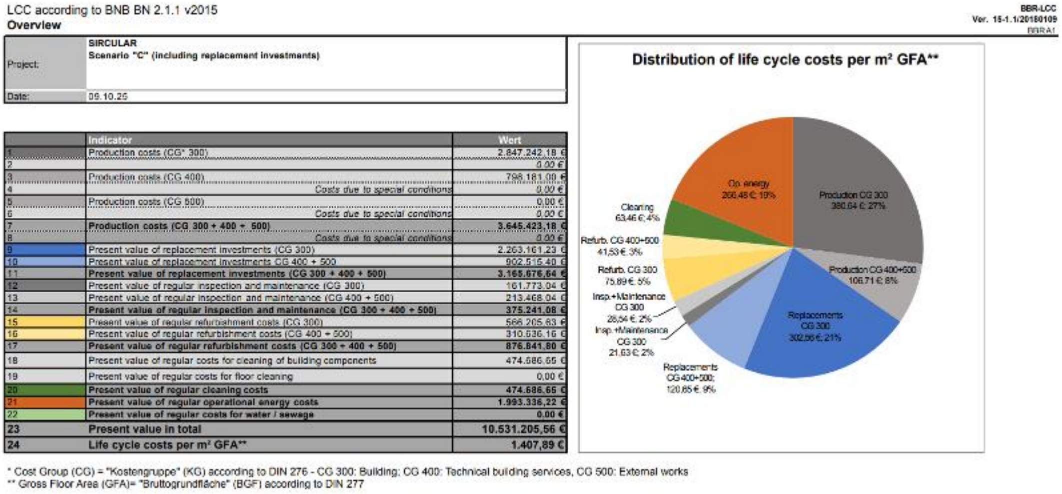
BBR-LCC
Ver. 15-1.1/20180109
BBRA1

Project:	**SIRCULAR** **Scenario "B" (including replacement investments)**
Date:	09.10.25

	Indicator	Wert
1	Production costs (CG* 300)	2.656.339,27 €
2		0,00 €
3	Production costs (CG 400)	798.181,00 €
4	*Costs due to special conditions*	0,00 €
5	Production costs (CG 500)	0,00 €
6	*Costs due to special conditions*	0,00 €
7	**Production costs (CG 300 + 400 + 500)**	**3.454.520,27 €**
8	*Costs due to special conditions*	0,00 €
9	Present value of replacement investments (CG 300)	2.332.934,81 €
10	Present value of replacement investments CG 400 + 500	902.515,40 €
11	**Present value of replacement investments (CG 300 + 400 + 500)**	**3.235.450,22 €**
12	Present value of regular inspection and maintenance (CG 300)	150.925,42 €
13	Present value of regular inspection and maintenance (CG 400 + 500)	213.468,04 €
14	**Present value of regular inspection and maintenance (CG 300 + 400 + 500)**	**364.394,46 €**
15	Present value of regular refurbishment costs (CG 300)	528.242,48 €
16	Present value of regular refurbishment costs (CG 400 + 500)	310.636,16 €
17	**Present value of regular refurbishment costs (CG 300 + 400 + 500)**	**838.878,64 €**
18	Present value of regular costs for cleaning of building components	604.155,65 €
19	Present value of regular costs for floor cleaning	0,00 €
20	**Present value of regular cleaning costs**	**604.155,65 €**
21	**Present value of regular operational energy costs**	**2.620.132,74 €**
22	**Present value of regular costs for water / sewage**	**0,00 €**
23	**Present value in total**	**11.117.531,98 €**
24	**Life cycle costs per m² GFA****	**1.292,02 €**

* Cost Group (CG) = "Kostengruppe" (KG) according to DIN 276 - CG 300: Building; CG 400: Technical building services, CG 500: External works
** Gross Floor Area (GFA)= "Bruttogrundfläche" (BGF) according to DIN 277

(b)



LCC according to BNB BN 2.1.1 v2015
Overview

BBR-LCC
Ver. 15-1.1/20180109
BBRA1

Project:	**SIRCULAR** **Scenario "C" (including replacement investments)**
Date:	09.10.25

	Indicator	Wert
1	Production costs (CG* 300)	2.847.242,18 €
2		0,00 €
3	Production costs (CG 400)	798.181,00 €
4	*Costs due to special conditions*	0,00 €
5	Production costs (CG 500)	0,00 €
6	*Costs due to special conditions*	0,00 €
7	**Production costs (CG 300 + 400 + 500)**	**3.645.423,18 €**
8	*Costs due to special conditions*	0,00 €
9	Present value of replacement investments (CG 300)	2.263.161,23 €
10	Present value of replacement investments CG 400 + 500	902.515,40 €
11	**Present value of replacement investments (CG 300 + 400 + 500)**	**3.165.676,64 €**
12	Present value of regular inspection and maintenance (CG 300)	161.773,04 €
13	Present value of regular inspection and maintenance (CG 400 + 500)	213.468,04 €
14	**Present value of regular inspection and maintenance (CG 300 + 400 + 500)**	**375.241,08 €**
15	Present value of regular refurbishment costs (CG 300)	566.205,83 €
16	Present value of regular refurbishment costs (CG 400 + 500)	310.636,16 €
17	**Present value of regular refurbishment costs (CG 300 + 400 + 500)**	**876.841,80 €**
18	Present value of regular costs for cleaning of building components	474.586,65 €
19	Present value of regular costs for floor cleaning	0,00 €
20	**Present value of regular cleaning costs**	**474.686,65 €**
21	**Present value of regular operational energy costs**	**1.993.336,22 €**
22	**Present value of regular costs for water / sewage**	**0,00 €**
23	**Present value in total**	**10.531.205,56 €**
24	**Life cycle costs per m² GFA****	**1.407,89 €**

* Cost Group (CG) = "Kostengruppe" (KG) according to DIN 276 - CG 300: Building; CG 400: Technical building services, CG 500: External works
** Gross Floor Area (GFA)= "Bruttogrundfläche" (BGF) according to DIN 277

(c)

Figure 13. Life-Cycle-Costs' results according to the retrofitting strategy, for (a) Strategy A, (b) Strategy B (b), and (c) Strategy C.

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The results show that renovation Strategy A, as the least intrusive variant, creates the lowest overall costs over a period of 50 years, while Strategy B is expected to be the most expensive variant, with a slightly higher proportion of energy costs compared to investment costs. Strategy C occupies an intermediate position with relatively low energy costs but the highest investment costs.

A critical aspect identified during the LCC assessment is the set of service life assumptions. For instance, components such as wood fibre boards or windows are assigned a maximum service life of 40 years by the BBSR, which automatically triggers a full replacement in the model, looking at a 50-year period. In reality, however, this may not always be necessary. A slight reduction in insulation performance, as may occur with ageing wood fibre insulation, does not inherently justify complete replacement, especially if the material still performs adequately. Nevertheless, the calculations presented above assume full replacements within the predefined timeframes. In this context, the payback periods indicated in sections 2.4.2 and 2.4.3 can be considered conservative, as a significant portion of environmental and financial costs could potentially be avoided if replacements are not required in every case.

The fact that reclaimed timber is used instead of fresh timber has not been factored into the LCC calculations of this deliverable. At present, there is no reliable data on the cost implications of material reuse. Nevertheless, the potential for timber reuse to reduce long-term material acquisition and disposal costs is promising. However, while reuse can offer considerable economic and environmental benefits in the future, it may presently even lead to increased upfront costs. This is largely due to the absence of standardized processes and industrial experience with reclaimed materials, and the additional planning complexity involved often necessitates individual solutions, detailed assessments, or special approvals. As such, the financial impact of reuse remains difficult to quantify at this stage. Nonetheless, as circular construction practices mature and reuse strategies become more widespread, supported by evolving regulatory frameworks and market structures, a reduction in both cost and planning effort is expected in the medium to long term. To accurately capture these dynamics, appropriate methodologies for cost calculation and their integration into LCC assessment tools must be developed and implemented progressively as more experience is gained through pilot projects and living labs.

2.4 Validation of environmental aspects

2.4.1 Achieving ZEB status

For an evaluation of the progress towards ZEB status, the share of non-renewable primary energy demand (PENRT) from the overall primary energy demand is particularly important. Due to the limited roof area available for photovoltaic (PV) installation relative to the large total floor area of the high-rise building, the on-site solar energy generation is insufficient to meet the building's total energy demand for operating the ground-source heat pump, lighting, and all other technical equipment. As shown in **Table 5**, the rooftop PV system can supply 52,308 kWh/a of final energy and 94,154 kWh/a of primary energy. The remaining demand must be covered by electricity purchased from the grid. According to the German Environment Agency (UBA), renewable energy sources accounted for 54.4 % of the electricity sector in 2024 [19].

The non-renewable primary energy demand therefore makes up around half of the total primary energy demand. If the building owner decides to procure electricity exclusively from a renewable provider, the actual share of non-renewable primary energy would be zero. However, even if this is

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the case, purchased electricity does not fall under §23 of the German Buildings Energy Act (GEG) [32], and therefore, cannot be deducted from the primary energy demand. Instead, it must be accounted for in energy balances as the national electricity mix, which includes both renewable and non-renewable sources. This regulation ensures consistency, comparability, and transferability of results.

Strictly speaking, this means that none of the renovation variants achieves a zero non-renewable primary energy balance, not even the most extensive measures implemented in Scenario C. On the one hand, this results from the calculation method prescribed by German energy legislation. On the other hand, it highlights both the challenges of retrofitting this specific building typology and its relevance, given the particularly high energy demand of this type at the current renovation rate. However, achieving ZEB status could become feasible in the future by expanding PV capacity – for instance, by installing PV facade panels on opaque building surfaces or through carport structures with integrated PV modules on the existing parking lot. In practice, procuring renewable-only electricity from an eco-provider could reduce the building's actual non-renewable energy demand to zero at any time, although this is not reflected in the official accounting framework. Additional measures, such as neighborhood-level energy solutions or the application of artificial intelligence, could further optimize energy performance and contribute to reaching net-zero targets.

2.4.2 LCA-related aspects and environmental payback

The determination of the environmental payback builds on the results of the previous assessments: the energy demand evaluation of the unrenovated and renovated building, and the LCA of the renovation measures in terms of GWP. The payback period expresses the time required for the ecological benefits of a refurbishment – namely, the reduction in operational emissions through energy savings – to compensate for the embodied emissions generated during the implementation of the renovation. It is calculated as the ratio of embodied GHG emissions (kg CO_2-eq.) to the annual GHG savings achieved by the measure (kg CO_2-eq./a). In essence, the environmental payback period reflects when the intervention transitions from an ecological debt into a net climate benefit. It can thus be regarded as a simplified ecological cost-benefit calculation, clearly highlighting the balance point between environmental investment and return.

For the purpose of this validation, the reuse-specific aspects discussed in the second part of section 2.3.2 are not considered, as their reflection in the LCA remains experimental and is not compliant with an agreed-on standard. The data used for the determination of the environmental payback-time are therefore taken from the LCA including the Modules A1-A3 and C3-C4. **Figure 14** illustrates the environmental payback period for the different retrofitting strategies.

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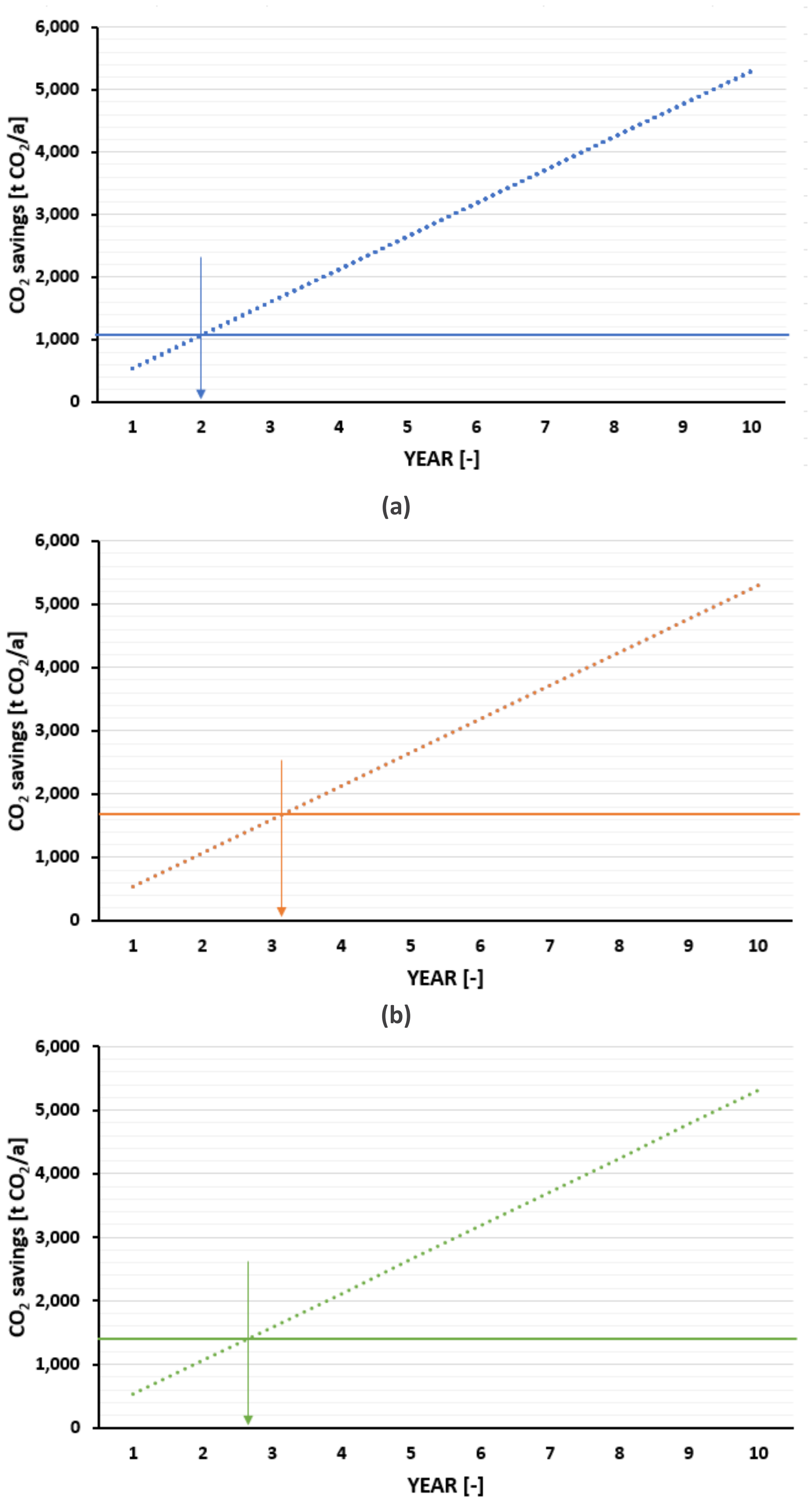

(a)

(b)

(c)

Figure 14. Environmental payback period according to the retrofitting strategy, for (a) Strategy A, (b) Strategy B (b), and (c) Strategy C.

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As can be observed from **Figure 14**, the GHG payback is reached after 1.96 years (Strategy A), 3.11 years (Strategy B), and 2.78 years (Strategy C). After this period, the annual energy savings, shown by the dotted line, surpass the initial GHG emissions invested in the renovation measures, represented by the solid line. Among the three options, Strategy A achieves the most favorable outcome. For all three renovation strategies, these estimates are conservative, as positive effects from reuse and reuse potentials are not considered, and the end-of-life scenario, including thermal utilization, is likewise cautiously assessed.

2.4.3 LCC-related aspects and financial payback

Besides the environmental impact, determining the financial payback period can have a particularly practical purpose with regard to renovations, as it is critical for validating and demonstrating the economic viability of renovation measures to building owners and stakeholders. This, in turn, can encourage increased investment in energy-efficient renovation and help accelerate renovation rates EU-wide. In this deliverable, the financial payback period is defined as the time required to recover the initial renovation investments through projected energy cost savings due to building envelope improvements and retrofitting of renewable energy systems.

In order to enable comparison between the investment costs of the renovation variants, and the corresponding energy savings relative to the unrenovated state, the total energy costs over a period of 50 years are shown in the table below, **Table 8**.

Table 8. Operational energy savings according to strategy.

Parameter	Unrenovated	Strategy A	Strategy B	Strategy C
Specific operational energy costs over 50 years [€/m^2]	1,701	280	305	266
Operational energy costs over 50 years [€]	12,726,280	2,091,314	2,620,133	1,993,336
Operational energy cost savings over 50 years [€]	**-**	**10,634,966**	**10,106,147**	**10,732,944**
Total investment costs for renovation [€]	-	3,219,873	3,454,520	3,645,423
Financial payback times [Years]	-	25	27	27

As shown in **Table 8**, the operational energy savings compared to the unrenovated state are significant. When applying the dynamic pricing model suggested by the BNB-LCC-tool to account for projected energy cost developments, the financial payback of the total investment is reached after approximately 25 years for Strategy A, and 27 years for Strategies B and C.

In this context, it is important to note that this financial outlook is still conservative and rather theoretical, as CO_2 prices are expected to rise substantially over the coming decades, while reliance on fossil-based heating methods will be legally restricted within a relatively short timeframe. The gap in cost savings between the non-renovated and the renovated scenarios would therefore continue to widen if no measures were taken, and investments would become compulsory at some point. This is what the current energy legislation in Germany indicates: a legislative ban on pure fossil-fuel heating systems came into effect in 2024 for new construction, requiring at least 65 percent renewable energy. By 2045, the use of fossil-based heating will no longer be permitted at all [33]. With the projected energy savings shown in **Table 8**, nearly 1 million euros can be recovered within the first 10 years

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following the renovation in all three variants. This clearly demonstrates the significant economic potential of energy-efficient retrofitting, particularly for large buildings with high energy consumption, such as universities or office complexes.

2.4.4 Circularity index

In addition to integrating reclaimed materials into today's construction projects, it is becoming increasingly important to design buildings that are optimized for reuse at the end of their life cycle. Such an approach gradually prepares the building stock for future circular applications by ensuring that structures can be dismantled without demolition, allowing components to re-enter cycles of reuse, recycling, or biodegradation. A useful tool to measure this is the Circularity Index, which evaluates buildings and construction methods based on criteria such as reusability, recyclability, biodegradability, and design strategies for clean material separation across the entire life cycle, from raw material extraction to dismantling and reuse.

The innovative renovation strategies presented above consistently follow the principles of circular construction: materials are applied in a pure and separable form, reversible connections are prioritized, adhesives or irreversible bonds are avoided, and natural, non-toxic materials are used. Within this framework, the three approaches differ in terms of their complexity depending on the level of intervention. Another significant challenge arises with achieving airtightness, which is crucial for improving the building's energy efficiency, as discussed also in Section 3.1.3. Standard materials, such as PE membranes and conventional adhesive tapes, are problematic because they are difficult to separate and are not recyclable. Laminated or permanently bonded products further reduce the potential for clean disassembly. To address this, in the approach, solid wood boards are used, which are connected to the timber studs with wooden nails, minimizing the need for adhesives. Where adhesives are unavoidable, recycling-friendly or removable options are prioritized.

Strategy A uses minimally invasive prefabricated modules with wooden joints, and the screws are needed to secure the clay boards. With only natural materials, all components are reusable, recyclable, or biodegradable. The low-tech approach simplifies both assembly and disassembly. Strategy B uses prefabricated post-and-beam elements from reclaimed timber, combined with mechanically detachable steel parts. Single glazing is chosen to maintain the recyclability of the glass. This system achieves a high level of prefabrication and offers strong disassembly potential. Strategy C relies on prefabricated wall elements mounted onto the existing concrete structure with reversible fixings. Wooden joints and nails are prioritized, while metals are used economically when needed and in such a way that they are easy to disassemble. In this case, triple glazing is required for the facade, to ensure the thermal requirements, which reduces the recyclability of the windows due to the bonded glass layers and air-filled cavities that complicate the separation process.

In summary, all three renovation strategies demonstrate high circularity through reversible connections and material purity, with Strategy A achieving the highest potential for complete biodegradability and excelling through its minimal material consumption, while Strategies B and C balance circularity with structural performance requirements. Overall, these approaches show that circular renovation is technically feasible across different intervention levels, but each strategy requires specific compromises between sustainability goals and building physics requirements.

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2.4.5 Other aspects

2.4.5.1 Usability of spaces during refurbishment

Since building refurbishments usually extend over a longer period, choosing the appropriate strategy is crucial. A central question is whether the building must be closed entirely during the works, or whether a phased refurbishment, for example by floor, by room, or by facade section, is possible. Since this study addresses only the building envelope, it is assumed that the rest of the structure is unaffected.

Strategy A enables room- or floor-wise refurbishment with minimal intervention. The lightweight prefabricated facade elements can be installed without large machinery, reducing noise and construction time while allowing the building to remain largely in use. These critical points are also discussed in Section 3 of this report. Strategy B avoids interventions inside the building but requires scaffolding and crane operations on the facade. The construction time is relatively short due to large, prefabricated elements, though noise and anchoring works may temporarily restrict use. Strategy C involves the complete removal of the existing facade. While the building cannot be used during the works, this approach provides additional usable space, flexible layouts, and opportunities for comprehensive modernization.

In summary, the three refurbishment strategies differ primarily in their level of intervention and impact on building usability. Strategy A enables a low-invasive refurbishment process, allowing the continued occupation of the building with minimal disruption. Strategy B maintains internal operations but requires significant external installation effort, while Strategy C demands full closure during works, albeit offering the most extensive modernization potential. Considering the objectives of minimizing user disruption, maintaining building functionality, and ensuring an efficient refurbishment process, Strategy A is considered the most suitable. Its lightweight prefabricated system provides a balance between construction, efficiency, and spatial usability, making it particularly suitable for occupied buildings and phased renovation approaches.

2.4.5.2 Architectural appearance in renovation strategies

As described in Section 2.2.1, the buildings from the 1960s and 1970s are characterized by a modular grid in reinforced concrete skeleton construction, whose regularity is reflected in the facades with prefabricated concrete elements and continuous balconies. In addition to the structural challenges during renovation, the external appearance and its future management play a significant role. The following strategies adopt three distinct approaches, which are summarized right below.

Strategy A follows a minimally invasive approach: the existing building is largely preserved, maintaining its characteristic appearance. Through the replacement of windows and the renovation and completion of the infill panels, the prominent balcony structure is retained, providing the facade with depth and horizontal articulation. Strategy B also preserves the existing building but significantly alters the external appearance through an additional lightweight facade in a post-and-beam system. This new cladding creates a planar effect, aligning the building more closely with contemporary office architecture. By covering the balconies, the previous facade depth is lost, making the building appear more voluminous. The existing structure is thus effectively "encased" and conserved. Strategy C adopts a highly interventionist approach: the existing building is comprehensively transformed and selectively used for the redesign, while the original appearance is largely abandoned. This allows structural challenges of the construction to be addressed directly. The embodied energy of the concrete structures is preserved, while the facade design can be freely realized. The horizontal

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alignment of the balconies is maintained through parapets, and the use of a timber facade with appropriately scaled windows gives the building a modern appearance. Compared to Strategies C2 and C3, Strategy C1 appears slimmer due to the removal of the balconies.

The three strategies present fundamentally different renovation approaches for 1960s-1970s reinforced concrete structures. Strategy A preserves the original character through minimal interventions, maintaining facade depth and horizontal articulation via retained balconies. Strategy B encapsulates the existing building with a lightweight facade system, creating a contemporary planar aesthetic. Strategy C pursues comprehensive transformation, reimagining the architectural expression through timber cladding and reconfigured fenestration.

From an architectural perspective, Strategy A is recommended as it respects the building's historical identity while achieving necessary technical improvements through window replacement and infill panel renovation. This approach maintains the characteristic three-dimensional facade quality and requires minimal intervention, reducing construction complexity. However, if preservation of the existing aesthetic is not prioritized, Strategy C1 would offer significant advantages. It provides a modern external appearance and addresses structural deficiencies more comprehensively, resolving thermal bridging through balcony removal, and creates a refined volumetric expression with improved energy performance while still retaining the embodied energy of the concrete skeleton.

2.4.5.3 Fire protection considerations

The planned energy-efficient renovation of the demo building, which incorporates renewable materials and reclaimed timber elements, presents a range of specific fire safety challenges. The building is classified as Building Class 5 and designated a special-purpose building. As a high-rise structure (>22 m), it falls under the scope of the Model High-Rise Directive (MHHR). Although this directive is not legally adopted in the building regulations of the federal state of Baden-Württemberg, it serves as a widely recognized reference commonly used by local building authorities to assess compliance with building standards. Specific requirements of high-rise buildings concerning fire protection are typically determined in coordination with the building authorities as part of the fire protection concept and can vary depending on the materials used, building height, and facade system. In any case, the classifications mentioned above impose strict fire safety requirements, particularly concerning the retrofitted wall construction and escape routes.

This creates a significant challenge for the SIRCULAR project, where integrating timber into the wall elements and facade is a core objective. In a high-rise context, the use of timber faces major regulatory hurdles, as the MHHR strictly prohibits combustible materials in the external walls. This includes not only the cladding itself but also substructures, window frames, shading devices, etc. The Model Timber Construction Guideline (MHolzBauRL) [34] provides limited allowances but still requires horizontal fire barriers at each floor level, especially for multi-story timber facades. Moreover, a timber facade is not feasible on the balconies without special approval, as they are legally defined as "open corridors" under the building code, and adjacent building components must have a non-combustible lining, non-combustible cladding, and F90 fire-resistance in accordance with the MHHR. Aside from the challenges associated with the combustibility of timber, another potential key issue of the renovation concept lies in the fact that of the timber is repurposed. The wall element manufacturer might not be willing to confirm compliance with the fire safety certificate if the timber used is not a certified product. Accordingly, a project-specific approval will likely be required in the current legal setting. However, if timber reuse regulations and value chains for quality control and certification of reclaimed timber

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products continue to develop, the need for such approvals could potentially be reduced in the future and improve replicability.

Besides material choices, retrofitting the building will also affect the existing escape concept. Although the building might currently benefit from existing use rights when unaltered, significant changes – such as those anticipated during the SIRCULAR renovation – can revoke this status. Any alterations that affect the fire safety performance or require a new building permit may trigger the need to comply with current regulations and elaborate on a revised fire safety and evacuation concept. The existing concept includes escape balconies and stairs as a secondary means of egress. However, the MHHR mandates a minimum clear width of 1.20 m for all parts of escape routes. This requirement is not met by the current balconies, and adding external insulation as part of the energy retrofit would further reduce the usable width. If the renovation measurements resulted in the loss of existing use rights, which would most likely be the case, new escape routes would be necessary. Only Strategy A offers a slightly higher chance of retaining the protection status for both balconies and stairs and thus their functionality as escape routes, since the building envelope is only partially replaced in this variant.

However, retaining the balconies poses other challenges, as they significantly compromise the accessibility for the installation of prefabricated facade systems and the building's energy performance due to the thermal bridges. On the other hand, the escape balconies are a defining architectural feature and contribute significantly to the building's identity. They also help prevent vertical fire spread due to the concrete cantilevers. These different pros and cons are reflected in the different renovation approaches, including options for both retention and removal. In response to the aspects concerning fire protection, new escape routes are created in all three renovation scenarios by constructing fire-rated corridors on each floor leading to an external escape stair, providing a safer and regulation-compliant solution. Based on a preliminary examination, the building's structure and floor plan appear generally suitable for this adaptation. However, since the precise measures required to meet regulations depend on case-specific decisions by the building authorities and require comprehensive planning, the revised fire protection concept has only been incorporated to a limited extent in the assessments of this report. Specifically, a new external staircase has been included in renovation Strategies B and C, where existing usage rights are likely to be lost due to the extent of the renovation, serving as a placeholder for the concrete measures to be defined at a later stage of the planning process.

Despite the challenges, innovation and the use of renewable materials can become viable if mitigation strategies are implemented that safeguard the fire protection objectives. In order to reconcile the architectural and sustainability goals with fire safety requirements, the following aspects can become relevant in coordination with the building authorities:

- Non-combustible insulation between the studs in sensitive areas.
- Coverage of combustible materials with fire-resistant linings. Clay boards are increasingly available for fire-protection applications and are gradually being recognized in regulatory frameworks.
- Horizontal fire stops between floors to prevent vertical fire spread; these can be metal sheets. In scenario B, the retained concrete balconies are also well-suited for fulfilling this function.
- Non-combustible external surfaces, such as plaster.

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- Integration of advanced fire protection technologies, such as sprinkler systems or water mist systems, which can potentially allow for relaxations in material requirements or compartmentation, subject to approval by the building authorities.
- Fire simulation studies in accordance with DIN 18009-1 [35] to validate the proposed design during the detailed planning phase.

Through intelligent system design, the use of non-combustible layers, and careful planning in coordination with building authorities, a compliant and still sustainable solution is achievable. Early coordination with the relevant building inspection authority is essential to assess acceptable deviations or project-specific approvals.

3. Prefabricated Circular Renovation Component

The main objective for designing prefabricated circular renovation components is to provide an extra solution towards decarbonization of the building sector. Prefabricated components are one-stop-shop (OSS) solutions towards achieving the status of Positive Energy Buildings (PEBs). The design of these components focuses on providing a simplistic solution, emphasizing the geometry, the assembly, and the ease of installation and deconstruction on the external building envelope. Also, the provided solutions have the potential for future integration with Building Information Modeling (BIM) and 3D printing.

The prefabricated solution targets some severe problems that constitute a significant obstacle to the decarbonization of the building sector. First of all, there is a lack of technicians and the workforce to renovate the current building stock. This means that there is a need for industrialized solutions. Also, there is a lack of deep quality renovation, mainly due to the difference between the modeling and the practical implementation. Thus, new solutions that minimize the possibility of wrong, inefficient, or even incomplete implementation are required. Finally, there is a lack of time to reach the EU goals for decarbonization until 2050, since with the existing solutions and renovation rate, the engineers and technicians will not be able to renovate the existing building stock of the EU. These problems highlight the necessity for prefabricated solutions as a reliable and valuable strategy to tackle all these issues.

In this section, a prefabricated component is introduced as possible retrofitting solution. To begin with, the main design considerations for prefabricated components are described. Also, detailed mathematical, construction, deconstruction, and installation methodologies are presented for both solutions. Finally, all the elements that comprise this component are illustrated, and component-level and system-level simulations support the results for the thermal efficiency and the total thermal transmittance (U-values).

3.1 Description of the Prefabricated Component

This section focuses on the main considerations when designing prefabricated renovation units. First of all, the materials selected for the frame and the insulation are discussed. Such specifications are the selected materials, the integration with windows, the airtightness assurance, the water and vapor resistance, and the integration of ventilation systems. Also, similar products on the market are briefly discussed.

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3.1.1 Selection of the Appropriate Materials

The selection of the appropriate materials is a crucial factor for both the design methodology and the construction of the prefabricated components. The required materials can be categorized into two types. The first category regards the materials required for the frame, and the second category the materials for the encapsulated insulation. Also, for more complicated prefabricated components, a third category of materials could be introduced. This category could include materials for ventilation or windows integrated into the components.

3.1.1.1 Framing materials

Framing is critical for the prefabrication components, regardless of the thermal and physical properties of the insulation material that will be selected. The main reason is that the frame could introduce thermal bridges to the component. Tackling thermal bridges is a very important design parameter since they introduce thermal losses and are a significant factor for possible condensation, which could lead to future moisture or mold spots.

The materials used for the framing of such components can vary. The most important indices to consider when selecting them are their thermophysical properties, mechanical strength, and other aspects such as yield, recyclability level, corrosion due to external moisture, and material ageing. There is a wide range of materials used for the framing of windows, which could also be examined as possible candidates for the prefabrication components, from metals such as steel or aluminium to wood or plastic. Each of the available materials on the market presents advantages and disadvantages. A wooden frame would provide higher thermal resistance compared to a steel or an aluminum frame, but at the same time, less structural strength, which would possibly lead to some limitations regarding the size of the module. Additionally, wood may not be an easy solution for some southern European countries for various reasons, such as the lack of special forest area cultivations for wood production, and other environmental matters. These aspects can make wood harvesting inefficient, expensive, or even unsustainable. Such a country is Greece. However, Greece has a large aluminium industry that facilitates wider availability and lower costs, while also having technical expertise in aluminium profile processing. Furthermore, aluminium is a fully recyclable material, and there is plenty of knowledge and expertise in this field, thus making aluminium a suitable candidate. It is important to mention that aluminium can be recycled without degradation of its mechanical properties [36]. Moreover, the energy demand is reduced by approximately 95% compared to the aluminium production by raw bauxite [37]. Another possible candidate is PVC, which is a solution based on plastics. This solution provides the advantage of a lower total weight for the produced component. However, from the environmental point of view, it has a different behavior compared to aluminium since after some recycling cycles its properties degrade [38]. **Table 9** presents the basic thermal properties of the most commonly used framing materials [8,9].

Table 9. Basic thermal properties of common framing materials.

Material	Thermal conductivity [W/(mK)]	Density [kg/m^3]	Specific heat capacity [J/(kgK)]
Aluminum	237.0	2702.0	903.0
316 Stainless steel	13.4	8238.0	468.0
Plastic (PVC)	0.19	1470.0	840.0
Wood (Oak)	0.17	545.0	2385.0

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The previous analysis highlights a critical issue: the trade-off between thermal efficiency and structural composition. Multiple simulations were required to identify an optimal solution, since improvements in structural integrity often led to a decline in thermal efficiency, and vice versa. The framing material of the proposed prefabrication component in this project is chosen to be aluminium.

3.1.1.2 Insulation materials

The most important material for the prefabricated component is the insulation material. There are plenty of insulation material solutions that could be integrated into the proposed solution. Each of these offers some advantages depending on the construction sequence and structural considerations. There are two different construction methodologies that could be used for the prefabrication module. The first one concerns the installation of the insulation material after installing other elements of the module, and the second one concerns the installation of the insulation material before installing them. These elements are ventilation ducts, electrical wires, plumbing conduits, and others. Furthermore, insulation must be used as a thermal break in the frame profile.

In the first case, where the insulation material is installed subsequently to the other selected elements, the non-rigid insulation materials seem to be the most ideal solution. Non-rigid insulation materials effectively conform to the irregularities that exist due to the variable geometries and constraints of the module. The most commonly used non-rigid insulation materials are mineral wool, stone wool, and fiberglass wool. These fibrous materials present high thermal resistance and very good acoustic properties and thus are effective solutions for noise insulation in buildings [41]. However, to exploit these characteristics, proper installation is vital since their efficiency strongly depends on gaps or voids that may occur due to insufficient filling. This could lead to major problems such as thermal losses, thermal bridges, and condensation issues. An alternative solution is polyurethane (PU) foam. This foam can be injected or sprayed into the module. After injecting it, the foam expands, thus filling any cavities, ensuring uniform distribution of the insulation material, which leads to enhanced thermal and acoustic performance. To achieve this, pre-drilled access points have to be considered prior to designing the module. Also, PU foam provides improvement regarding the moisture resistance due to the structure of the material cells [42]. In addition, the insulation material waste is limited while constructing the prefabricated components. Finally, because of the low density of these materials, the constructed components will be lighter. This will result in simplifying both the installation and transportation of the prefabricated components.

In the second case, where the insulation material is installed prior to other elements, the best choice seems to be rigid insulation materials. In this approach, the insulation material is installed in the component, and then precise cuts are made to install the other required elements, such as tubes. This methodology presents a critical advantage over the previous one since it provides more flexibility regarding the construction of tailor-made systems. The most representative rigid insulation materials are expanded polystyrene (EPS), extruded polystyrene (XPS), and polyisocyanurate (PIR). Rigid insulation materials present higher thermal resistance compared to the non-rigid ones [43]. Moreover, by using rigid insulation materials, the structural integrity of the prefabricated component is enhanced, providing greater dimensional stability and mechanical strength. Furthermore, rigid insulation materials, such as cellulose and cork, combine high efficiency and low embodied carbon emissions. In general, there are plenty of rigid biobased insulation materials, thus making them an ideal solution to further reduce the environmental impact of the element and increase its circularity. Their main drawback is their higher density, leading to a more difficult installation and transportation.

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Many insulation materials were considered emphasizing on bio-derived materials with a lower carbon footprint. Research for the insulation material included consideration of their thermal and mechanical properties, as well as weight, cost, and environmental impact. Based on all these factors, final testing showed that the most suitable insulation material is XPS due to its excellent thermal resistance, adequate mechanical properties, and very low weight. In environmental terms, XPS is not the most appropriate solution since it is made of petrochemical products, mainly benzene and ethylene. The petroleum-based products are not recyclable, and a significant amount of greenhouse gases are emitted during their production. However, the main reason for selecting XPS is to set the baseline scenario for the development of such products based on the worst-case scenario in environmental terms. Furthermore, as already mentioned, there are plenty of other materials which could be implemented. Both rigid and non-rigid insulation materials already available on the market could be tested in future research activities to provide a greater variety of prefabricated solutions. **Table 10** presents the basic thermal properties of the most commonly used insulation materials [8,9]. These are representative values since the actual values can vary in a broad spectrum, and the actual values must be taken as appropriate.

Table 10. Basic thermal properties of common insulation materials.

Material	Thermal conductivity [W/(mK)]	Density [kg/m^3]	Specific heat capacity [J/(kgK)]
XPS	0.027 – 0.035	25 – 45	1200 – 1500
EPS	0.032 – 0.040	10 – 35	1200 – 1500
Mineral wool	0.030 – 0.046	30 – 200	700 – 850
Cellulose	0.038 – 0.045	40 – 80	1300 – 1600
Rockwool	0.033 – 0.046	40 – 200	750 – 840

3.1.2 Windows integration

Windows are fundamental parts of the building envelope since they enable natural sunlight to enter the interior of the building while simultaneously blocking unwanted environmental elements such as pollutants, dust, water, or even noise. Also, if it is needed or wanted, windows provide the opportunity for natural ventilation. Moreover, windows provide some psychological benefits to the building users that cannot be neglected since they negate the effects of being confined in a space by allowing a view of the external environment [44]. A windowless interior space would be very uncomfortable either for living or working. Considering these reasons, windows are crucial parts of the building envelope, and fenestration is a necessary aspect for buildings that cannot and should not be neglected. In this study, the solution is of low Technology Readiness Level (TRL), and windows are not implemented. However, a brief discussion on this matter was considered necessary for providing some guidelines for future research studies.

Besides the aesthetic and psychological value of windows, in terms of a building's energy efficiency, windows are mostly the weakest elements of the building envelope. Thus, it is essential that they are carefully and in detail designed to achieve optimal thermal performance. The most important issues are the performance of the window and its proper installation to eliminate thermal bridges. A window frame with an excellent thermal design, including thermal breaks, is required, along with multiple glass panes separated by plastic spacers. Usually, two or even three separate glass panes are used. [14,15] A proper selection of the frame also leads to avoiding condensation and mold, and a proper connection between the frame and the glass panes minimizes thermal bridges. Except for the U-value, another significant parameter is the g-value. A window system's g-value determines how much of the

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solar energy incident on the window is allowed to pass to the interior of the building. The selection of a window's g-value cannot be specified at random or based on experience, since it is one of the values that can only be determined as a result of an energy study for a building.

In this work, windows are not examined as part of the prefabricated component. This means that the proposed solution must be installed around the existing windows on a building facade. In the future, dedicated prefabricated components that will have specific openings and provisions for integrating with the existing windows should be investigated. The most critical point will be to ensure a perfect connection to minimize thermal bridging and moisture effects. **Figure 15** illustrates a prefabricated unit that incorporates specific openings for windows.

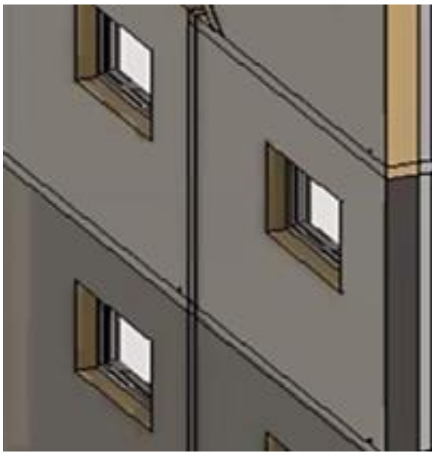

Figure 15. Prefabricated components that incorporate dedicated openings for windows.

3.1.3 Airtightness Assurance

Airtightness is the building's ability to resist unintentional and uncontrolled air infiltration from existing gaps on its envelope [47]. Also, it is a key factor in thermal loss reduction, both in construction and renovation processes. Additionally, it is considered one of the most cost-effective interventions on the building envelope during renovation procedures. The pressure difference between the interior and exterior environment of the building, caused by temperature differences and wind loads, leads to uncontrolled air infiltration or exfiltration through any existing gaps. As a result, despite the absence of any visible gaps on the exterior of the building, the existence of small gaps allows hot or cold air to enter the interior of the building during summer and winter respectively, thus increasing the heating and cooling demand. Some of the main reasons for the existence of such gaps are improper installation of windows and insufficient sealings in the building's envelope due to intervention activities such as the installation of heat pumps. It has to be mentioned that airtightness issues can always be tackled by exploiting membranes and solutions on the interior wall surface of the building.

A prefabricated component can easily achieve an excellent level of airtightness with a detailed design and controlled manufacturing conditions since it fully covers the building envelope and seals any unwanted gaps. A significant point to consider is the spots where the prefabricated components are joined together. Also, airtightness needs to be ensured by eliminating the gaps between the prefabricated facade and the external wall of the building. Specifically designed airtightness tapes or membranes can be utilized to achieve this. In this direction, the proper attachment between the prefabricated components and the external walls is a key design point. Also, the necessary bolts, nuts, and washers that are going to be used, along with the necessary preparations on the external wall, such as drilling the necessary holes, are considered important design parameters for the unit.

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Furthermore, airtightness is linked with the integration of the prefabricated components with windows. When the old windows are removed, the new windows have to be secured properly to ensure structural integrity, and then it has to be airtightly sealed together with the prefabricated components using appropriate airtightness tapes on the entire perimeter of the window frame. Windows must be able to reach air permeability class "4" in order to achieve an excellent performance under any weather conditions, maintaining structural integrity and airtightness.

After the installation of the windows and the sealing of any breaches on the envelope, the building has to reach less than one Air Change per Hour (ACH) at 50 Pa according to ISO 9972:2015 to achieve the level of airtightness that can allow excellent energy efficiency [48]. Any holes that exist on the building envelope have to be repaired and closed, after which they will be sealed by the prefabricated components, which will have the airtightness membrane applied on their external side to ensure no air leaks.

3.1.4 Wind Resistance and Vapor Control

Wind resistance in buildings is one of the fundamental design aspects for structural reasons. Mainly, wind resistance in buildings is about the height of the building. In this direction, the EU has published the Eurocode EN 1991-1-4, providing guidance on dealing with the wind for building construction. Furthermore, the ISO 4354:2009 is dedicated to the necessary wind actions on structures [49]. The structures should be able to endure in specific wind conditions, including the endurance regarding the environmental pressure and wind loads. On the other hand, water and vapor control is crucial for the energy efficiency of the building, the indoor air quality, and thermal comfort. Unfortunately, water and vapor resistance are considered lower-priority interventions during building construction or renovation [50]. Trapped vapor inside the materials or the interior of the building leads to moisture development.

The prefabricated component must comply with the EU legislation regarding the wind resistance to secure the structural integrity of the building. Thus, the proposed prefabricated component is designed to endure the wind loads and environmental pressure as the Eurocode suggests. For the water and vapor resistance, the developed component must address these issues in two different ways. The first one regards the resistance of the component, while the second one regards the resistance due to the proper attachment of the component and the exterior wall surface. To address these issues, the proper materials are selected both for the frames and for the insulation. Also, the design and construction methodologies emphasize on the creation of compact components that do not have any gaps to allow water or vapor from outdoor air to penetrate the components or the building. Finally, after deploying the component, necessary minor interventions or works will secure both the airtightness and vapor resistance of the building.

3.1.5 Mechanical Ventilation with Heat Recovery

Airtightness plays a critical role in the energy efficiency of the building. However, in the attempt to create an airtight building, the significant problem of poor indoor air quality arises due to the lack of natural ventilation. This is likely to cause the appearance of condensation and mold. To avoid health issues for the users and to achieve a healthy indoor air quality, fresh air needs to enter the interior of the building and at the same time stale air needs to be removed. To achieve air infiltration in airtight buildings, MVHR is introduced. However, in the case of retrofits installation of an MVHR system can be problematic, especially due to the network of airducts that have to be installed in all living and

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utility spaces. Structural elements like beams and columns or installations like electrical wiring and plumbing can make interior building spaces inaccessible and hinder the routing from the MVHR unit. In addition to these technical constraints, the installation of such a system creates disturbance to the occupants of the building, since it creates noise and pollutants like dust from drilling, making living spaces uninhabitable.

To solve the previously mentioned problems, the ventilation unit can be installed outside of the building, for example, on its roof. **Figure 16** illustrates a building model that includes an installed MVHR system. By installing the MVHR system outside the building, the ductwork can be installed inside the prefabricated components through predesigned openings existing in the insulation element of the component.

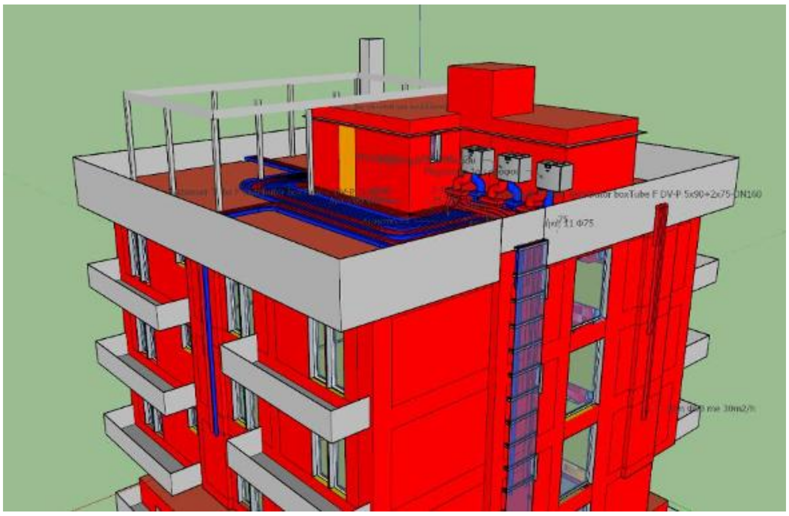

Figure 16. A building model which includes an installed MVHR system on the roof.

3.1.6 Similar products on the market

In the market, there are currently several commercial products of prefabricated components [19-22]. The existing components integrate insulation materials in a prefabricated system solution. However, there are no existing solutions considering a holistic prefabricated component construction approach that combines not only insulation, but also other important energy retrofitting elements such as ventilation ducts, plumbing pipes, windows, or even MVHR provisions. Most of the commercially available prefabricated products consist of a simple design approach, where two structural layers support an insulation layer in between them. The main goal of the existing systems is to reduce the on-site construction time. Also, the existing products consider aesthetic versatility by implementing external architectural textures. In addition, very few products incorporate vapor control systems, while also very few target renovations since many of them act as structural systems for the creation of new prefabricated homes, which also ignores third sector buildings. These products generally lack energy efficiency, solutions to tackle moisture issues, and mechanical strength. As a result, new prefabricated components should be designed and constructed to expand the available solutions on the market by providing holistic energy retrofitting solutions that combine energy efficiency, low embodied carbon, and mechanical strength.

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3.2 Methodology

In this section, the methodology to design, construct, and install the prefabricated component is presented. The design methodology follows the design principles and restrictions to propose a product that potentially should be constructed and released into the market. The proposed component is low TRL solutions but present a great potential to be developed into a real product. In addition, specific instructions for the installation of the component is presented in detail.

3.2.1 Mathematical Background

The main goals of the simulations are to calculate the U-value, to identify thermal bridges, and to calculate the annual energy savings when implementing these components on existing buildings. In this direction, the simulations are completed in two different levels: a component-level and a system-level. These different simulation strategies will reveal the U-value of the prefabricated component and also how this component affect the energy consumption of a building.

In this deliverable, two different simulation environments are used. For the component-level simulations, the SolidWorks Simulation studio, and the SolidWorks Flow Simulation studio are used [55]. The main goal is to calculate the heat flow through the component, aiming to determine the U-value. SolidWorks has been utilized in various design and simulation applications since it presents the advantage of both design and simulation environments. On the other hand, for the system-level simulations, IDA ICE simulation software is utilized [56]. IDA ICE is a well-known simulation software for buildings, especially in the region of northern Europe, and has been used for numerous building applications.

The SolidWorks design environment is used for designing mechanical and other components for structures or machinery. However, SolidWorks also provides the possibility of conducting both structural and thermal simulations in steady-state and transient conditions based on the finite element analysis and computational fluid dynamics by solving the Navier-Stokes equations. These analyses are conducted in the “Simulation” and “Flow Simulation” plug-ins of the software.

IDA ICE uses the calculation methods as described by the standards of the International Organization for Standards (ISO) and European Norms (ENs). This approach makes IDA ICE a trustworthy and useful simulation tool. The first ISO utilized by the software is ISO 521000-1:2017 [57], “Energy performance of buildings – Overarching EPB assessment”, which establishes a systematic, comprehensive, and modular structure for assessing the Energy Performance of new and existing Buildings (EPB) in a holistic way. Also, the software makes use of the ISO 52022-3:2017 [58], “Energy performance of buildings – Thermal, solar and daylight properties of building components and elements” which specifies a detailed method based on spectral data of the transmittance and reflectance of the constituent materials to determine the total solar energy transmittance, the total light transmittance and other relevant solar-optical data of the combination. Moreover, the software uses ISO 15099:2003 [59], “Thermal performance of windows, doors and shading devices – Detailed calculations” which specifies detailed calculation procedures for determining the thermal and optical transmission properties of window and door systems based on the most up-to-date algorithms and methods, and the relevant solar and thermal properties of all components. Finally, it utilizes EN 410:2011 [60], “Glass in building – Determination of luminous and solar characteristics of glazing”, which specifies methods of determining the luminous and solar characteristics of glazing in buildings.

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The main goal of the mathematical modeling and simulations is to determine the U-value (U) and the heat flux of the component. Firstly, this value is calculated based on Eq. (1) in W/m^{2}K, where (h_{out}) is the heat convection coefficient between the outer surface of the component and the exterior environment, (h_{in}) is the heat convection coefficient of the inner surface of the component or the wall and the interior environment, (d_i) is the thickness of each specific element, and (k_i) is the thermal conductivity of each element. The total number of elements (n) depends on the structure of the component and the outer wall. The indoor and outdoor conditions are selected based on the ISO 6946:2017, with temperature values of 20°C and 0°C respectively, and heat convection coefficient values of 20 W/m^{2}K and 5 W/m^{2}K [61].

$$\mathrm{U} = \frac{1}{\frac{1}{\mathrm{h_{out}}} + \sum_{i=1}^{n} \frac{d_i}{k_i} + \frac{1}{\mathrm{h_{in}}}} \tag{1}$$

In the case where the enclosed air in the component is not considered static, then the relevant thermal resistance is the convection one and not the conduction. This issue may occur when there are spaces with enclosed air inside the components that are big enough to allow air circulation when the air temperature rises. This incident occurs in the case of the small-scale prefabricated component. Thus, for the thermal analysis of the component, the convection coefficient in these gaps is equal to 3.5 W/m^{2}K.

The U-value (U) can also be calculated using the value of the heat flow rate (q), which can be calculated via the simulations conducted in the SolidWorks software. Eq. (2) can then be used to calculate the U-value based on the simulation results, where (T_{out}) is the temperature of the exterior environment of the component, and (T_{in}) is the temperature of the interior environment of the component or the wall to which this component is attached. The two calculated U-values must be equal.

$$\mathrm{q} = \mathrm{U} \cdot (\mathrm{T_{out}} - \mathrm{T_{in}}) \tag{2}$$

3.2.2 Design Methodology

To design a prefabrication component for energy retrofitting, several design parameters have to be considered. In this section, the main design stages and the main criteria for the design of such a unit are described. **Figure 17** summarizes the steps for designing prefabricated components in a schematic diagram.

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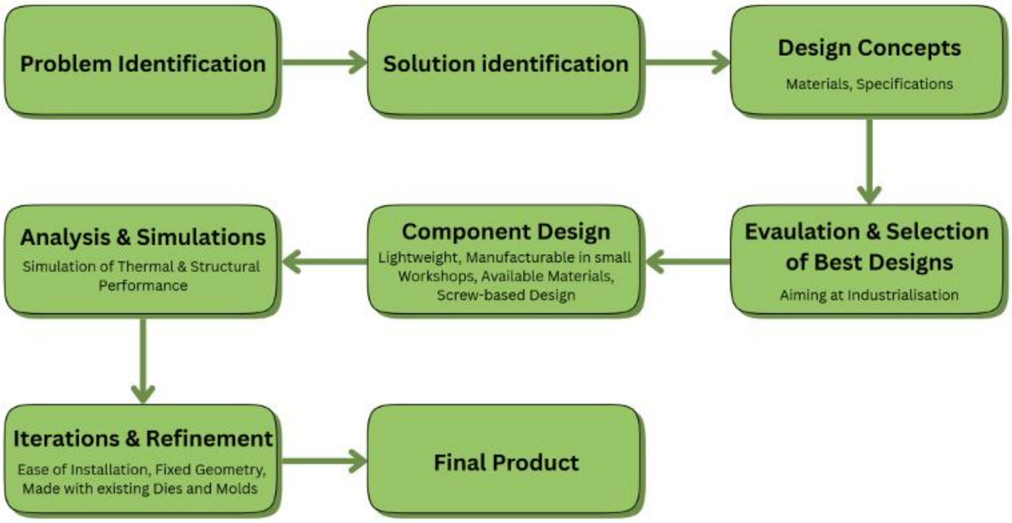

Figure 17. Schematic diagram of the design stages for prefabricated components.

When designing such a product, multiple design criteria and restrictions should be considered, such as mechanical strength, thermal efficiency, construction cost, maintenance, life-time, construction and deconstruction, and others. Also, the aesthetic of the product is considered an important factor. In this case, the sizing and weight of the product are also fundamental design criteria to support the One-Stop-Shop (OSS) solution. For example, the component has to be easily transportable by a single person, which introduces a limit on the total weight of the component. Furthermore, since the prefabrication components are going to be installed on the outer surface of the building, they must endure in corrosion. One of the most important design parameters is the attachment of the components to the wall. Specific elements must be designed and constructed to ensure proper support of the component using screws. Moreover, the proper connection between the components is fundamental to seal all the gaps and avoid thermal bridges, but also to distribute the loads of the whole structure. Thus, specific plastic elements are designed to ensure proper connection between the components.

Considering these design specifications and restrictions, the materials and the individual elements of the component have to be designed. The first element to be selected is the framing element. The framing elements are not designed in-house, but existing aluminium profiles are selected. Then, these profiles undergo some processes, such as cutting, based on the required size of each profile. Then, the rest of the framing is designed, including the thermal break element, which should have some specific design details based on the selected profile to perfectly adjust and couple. These four framing sides position the main insulation element. The thickness of this element is also a design parameter that will strongly affect the thermal efficiency and the U-value of the component. Also, insulation material needs to fill the void of the thermal break to reduce thermal bridges and the overall U-value. The insulation material can be either a rigid or a non-rigid element. The proposed component is fully adaptable to any change in the insulation material. After these stages, the necessary covers are designed to fit the existing framing. Then, the connection elements that connect two consecutive components are designed to fit on the external geometry of the component. For connecting the component with the wall, specific brackets that will be fastened on the wall using screws are designed. Finally, the handle needs to be ergonomic, especially for the such a small component to be easily carried and transported.

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3.2.3 Construction and Assembly Methodology

The previous analysis regarding the design methodology indicates the key points for the construction methodology. It is important to highlight that the component was designed with ease of construction, simplicity, and the ability to disassemble the unit when required. Most of the elements needed will not be constructed in-house, but already existing products in the market will be used. Additionally, when possible, fastening methods that can be undone and redone endlessly, like screws and bolts, are chosen over methods like glueing, which prevents material waste and promotes a longer lifecycle for the prefabricated components. In the future, when this technology is mature enough and of a high TRL, it should be possible for a company to construct all of the elements in-house. In this section, the construction methodology for the component is described. Then, in Section 3.3, the assembling methodology is illustrated, including all the intermediate steps.

The aluminium profile is designed in-house and can be constructed by an aluminium industry that is equipped with the appropriate machinery. Then, two of these profiles are joined together with the thermal break material and insulation material to form the one of the four in total sides of the component. To connect these four sides, special connection elements are used to link them together, enclosing the main insulation element. To ensure that friction forces between the elements in touch are minimized, special gaskets are used. These gaskets also increase the airtightness and prevent moisture from entering. After assembling the main body of the component, two covers are joined together with it. The covers are created from cutting and bending aluminium sheets. After these steps, the brackets, the plastic connections for connecting two consecutive components, the metal connections for mounting the components on the wall, and the handle are placed on the component's main body, thus finalizing the construction phase of the prefabricated component. In Section 3.3, detailed figures present the assembling process of this component step-by-step.

All these construction steps ensure that the unit enables easy assembly, fast and safe transportation, along with reduced renovation times due to simpler installation with low risks. Furthermore, both assembling and disassembling processes ensure limited waste since emphasis is given on using bolts and screws rather than glue. The design and construction of the component is very simple, which showcases the proposed solution as an excellent OSS for building retrofitting.

3.2.4 Installation and Deconstruction Methodology

The small-scale component can be easily transferred by the technicians or even the owner of the building himself or herself. This is expected to rapidly increase the energy retrofitting processes in the EU. To optimize the installation process and renovation time plan, the components should be transported on-site before the scheduled installation process. The components can be easily transported from the manufacturing facility using a simple transportation vehicle, since during the design phase, transportation and installation were considered as design parameters. To install the component, some preparatory works on the external wall surface have to be completed before the actual installation process begins. More specifically, the spots where the components will be attached to the wall must be clearly marked. Then, the necessary holes will be drilled so that, with the use of the necessary bolts and screws, the component will be perfectly attached to the wall. Drilling the holes appropriately is crucial for the whole installation process to achieve the perfect cooperation between the components, thus minimizing thermal bridges and improving airtightness. After installing the first component, the holes for the neighbor component will be drilled, and the next component will be

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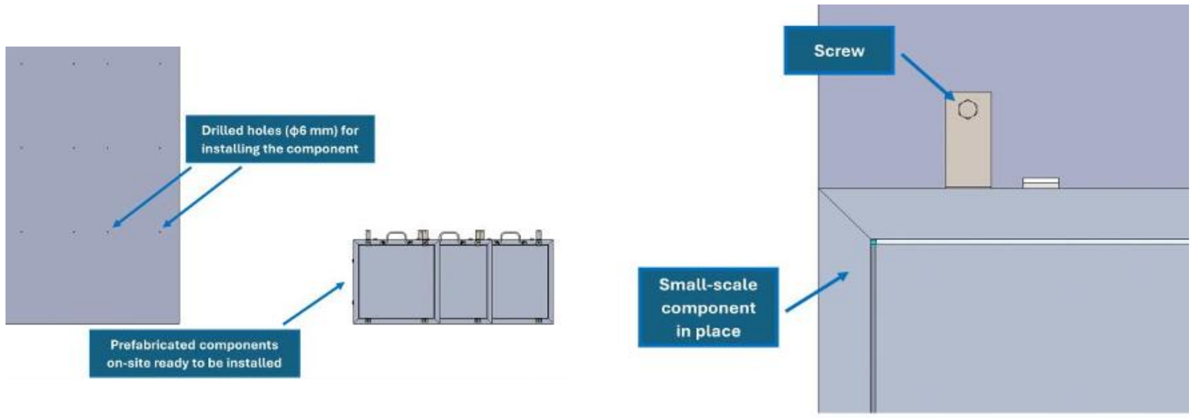
installed, securing also the proper fitting between the two components. When the installation of the components is completed, some extra work may be needed to ensure that no voids or gaps remain.

Figure 18 depicts the necessary procurements for the installation of the first prefabrication component, and how this component is attached to the wall using screws. For installing the component, very few tools are required. A crane is not required since this component is light and can be easily carried and installed by hand. The first unit is then placed on the wall. The brackets can revolve, allowing for convenience while drilling. This was also a design parameter for the components. Then, the mounting brackets are bolted in place, and the next unit can be placed right next to it by repeating the same sequence. The installation process begins from a chosen corner of the building's wall. After installing the first component, the others will follow accordingly.



(a) (b)

Figure 18. Installation process for the prefabricated component. (a) Drilled holes and on-site components ready to be installed, and (b) installation of a component.

Figure 19 illustrates the components located on-site, where some of these components are already installed on the outer wall. The consecutive components are well attached due to the existence of specific plastics that are installed directly on the frame of the component. To join together the components, one "male" and one "female" version would normally have to be created and placed on the unit alternatively. However, in this case, there is no need for the fabrication of extra elements to distinguish two separate units since "male" elements are created by installing plastic clips on their side that grab onto the next unit. Basically, the components have these pins only on two of their sites, which allows the connection with the near components using their sites that do not have the pins. Thus, by alternating units with and without clips, they can be connected easily.

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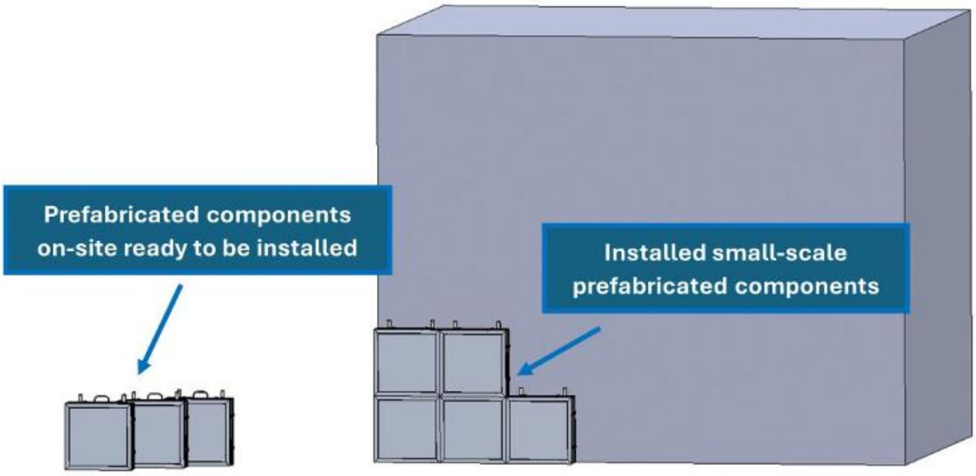

Figure 19. Installed small-scale prefabricated components, and components on-site ready for installation.

One of the main advantages that the prefabricated component offer is the reduced energy-based renovation time due to the simplicity in their design, assembly, and installation. However, another important design parameter is the ease of uninstalling this component. The main reason is that gluing is avoided, and the attachment process of screwing is preferred. This increases the recyclability of the products, which means that the lifecycle of the sub-elements can be extended, thus reducing the carbon footprint of the component. The disassembled materials can then be utilized for creating new prefabricated components or other useful components for the energy retrofitting of buildings. Besides disassembling, the ease in uninstalling these components is also crucial. For example, at any time, the installed components can be uninstalled simply by removing the washers and nuts that mount them on the external wall and then be replaced with another prefabricated component with the same design but with different thermal or construction properties, thus further reducing the U-value of the building envelope and increasing the thermal comfort. This makes the buildings more resilient and adjustable to several changes, such as climate change or perhaps a change in the use of the building. By considering both the disassembly and installation processes as design parameters, future renovated buildings become more sustainable and resilient.

3.3 Design and Simulation Results

In this section of the deliverable, the prefabricated component is presented in detail. The elements required to assemble this unit are listed in bills of materials, which include their description, mass, and quantity. Furthermore, a step-by-step approach is used to show the exact methodology for assembling the system using schematic diagrams to be as easy to understand as possible. After presenting the unit, component-level and system-level simulations are conducted. The component-level simulations calculate numerically the U-value of the component, verify this with the analytical solution, and present the temperature distribution throughout its structure. The system-level simulations indicate the energy savings and thermal comfort improvement by utilizing this component on a virtual demo site of an existing building that is fully uninsulated.

The prefabricated component proposed in this deliverable is a small, flexible, and easy-to-transport and install unit. **Figure 20** illustrates the prefabricated component. To conclude at its final design, a lot of criteria, limitations, and goals were considered to optimize the component. The first class of criteria regards its mechanical properties. More specifically, aspects such as the mechanical strength and water resistance are considered. Another important class refers to the construction and assembly

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process of the component, which directly affects some critical parameters such as the total construction cost and the installation process. Finally, another class refers to the thermal properties of the component, expressed mainly by the thermal transmittance coefficient (U), also known as the U-value.

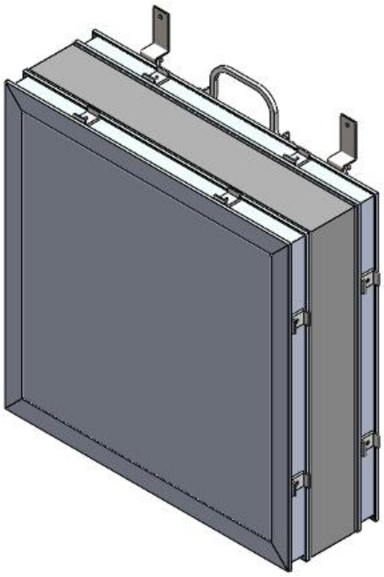

Figure 20. The proposed prefabricated component.

The prefabricated component consists of various elements that are joined together to form the final assembly. The main elements are the frame and the insulation material which is enclosed inside the component. The main frame is made of aluminium, which is a fully recyclable material. The aluminium profiles designed to form the main frame should be fabricated using the extrusion process. The selected insulation material is XPS, which is an ideal material due to its mechanical properties, its low coefficient of thermal conductivity, and its high vapor resistance due to its crystalline structure. Of course, other insulation materials could be used equally well, where each one introduces its own advantages and drawbacks. In addition to these two main construction elements, several other elements are of high importance for the thermal resistance of the component and the installation process. An important element is the thermal break since aluminum is a highly conductive material. Otherwise, the effect of thermal bridges would significantly affect the overall performance of the component, leading to higher U-values and thermal losses. The material for the thermal break is polyamide (PA), which is also known as nylon. This material presents high thermal stability in the temperature range in which the ambient temperature lies, and abrasion resistance [20]. Another essential part is the aluminium cover to seal the insulation material inside the component. Both the front and back covers should be made of aluminium sheets. following both cutting and bending processes to form their final shape. Finally, four specific link elements to assemble the frame are required. These are crimp corner clits. **Figure 21** illustrates the most significant sub-components that comprise the frame and the insulation of the component.

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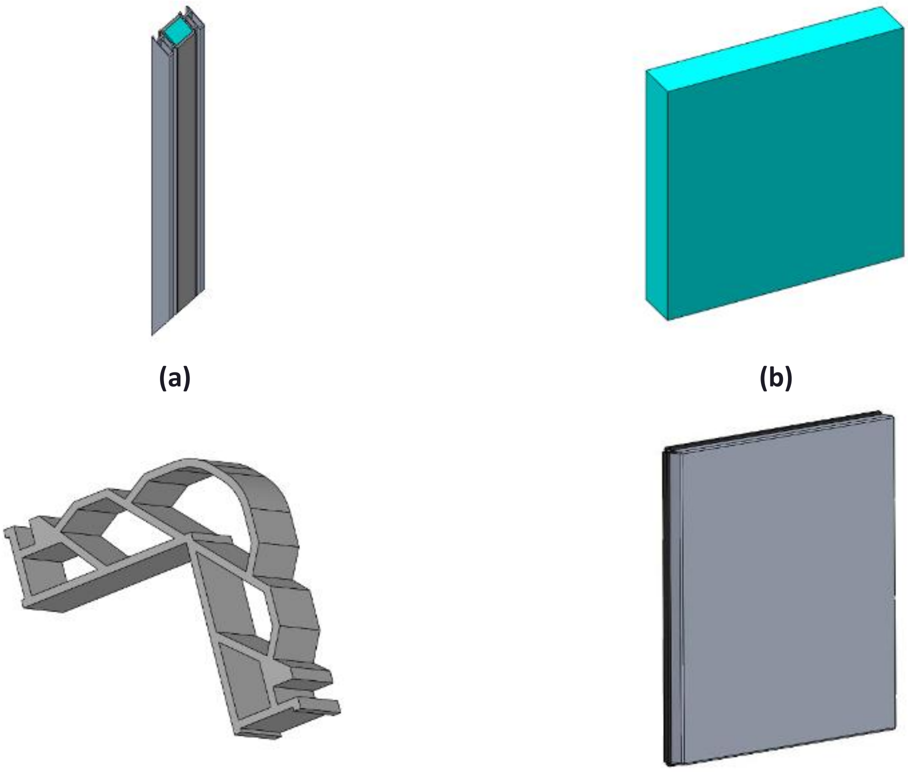
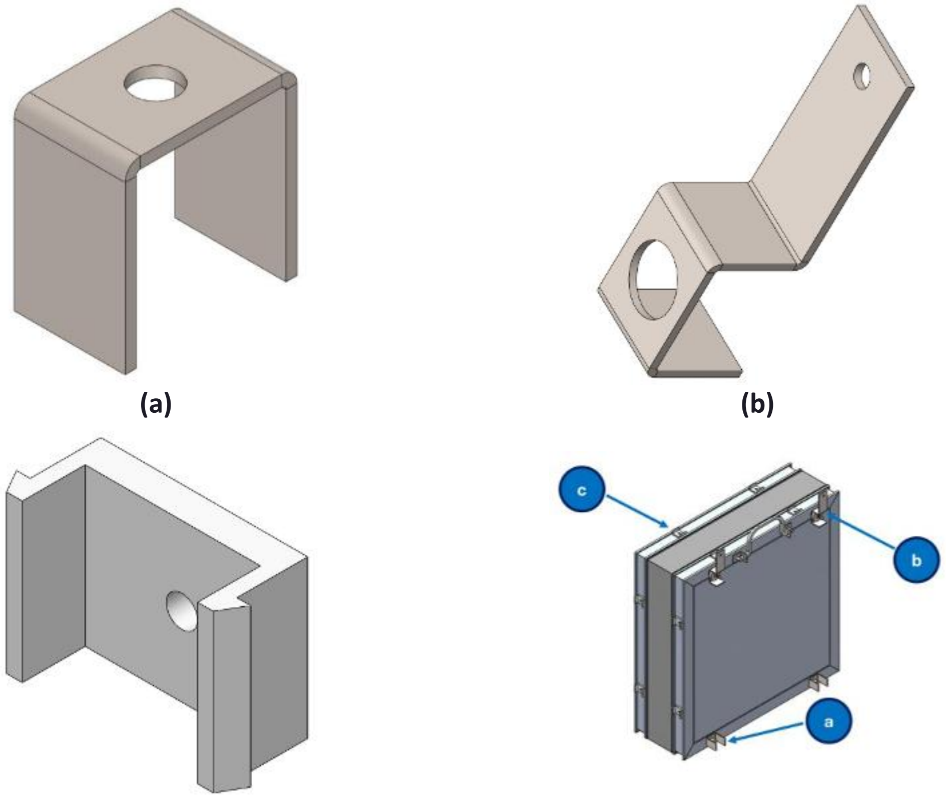


(a) (b)

(c) (d)

Figure 21. The main specific elements that comprise the frame and the insulation of the prefabricated component. (a) Aluminium sub-assembly profile with thermal break and insulation, (b) main insulation element, (c) crimp corner clits for the peripheral frame sub-assemblies, and (d) cover of the prefabricated component.

The prefabricated components need to be fully and well attached to the wall. Thus, during the design phase, some extra elements need to be considered. To attach the component to the wall, two identical specific elements made of steel are designed. The required processes to design these elements are cutting, bending, and finally drilling. The main reason for selecting steel is its mechanical strength. Furthermore, an element is also required to secure the connection between two consecutive installed prefabricated components. This is a crucial aspect to avoid thermal bridges and ensure that every possible void is completely sealed. These connection elements are made of polylactic acid (PLA) via 3D printing. Additionally, special plastic elements should be used to reduce the abrasion between the components. Thus, special plastic gaskets are used, which also prevent water or vapor from entering the component's interior. **Figure 22** illustrates the elements used to ensure the proper connection of the component and the external wall, as well as between two consecutive components.

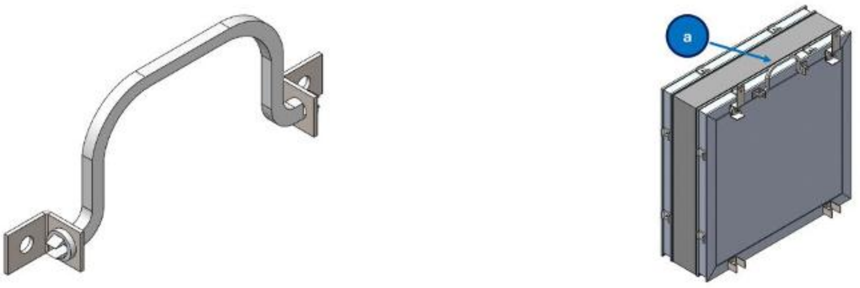


(a) (b)

(c) (d)

Figure 22. The specific elements used for the connection of the prefabricated component. (a) Supportive link between the component and the external wall, (b) connection link between the component and the external wall, (c) connection link between two consecutive components, and (d) their place on the component.

The prefabricated component was designed so that it is easy to transport and install. Thus, a handle is designed and attached to the component. The designed handle consists of two different sub-elements, the base and grip, which are made of PLA and steel, respectively. Also, the attachment of the handle on the component must ensure the smooth coupling of the components when installed. **Figure 23** illustrates the handle of the component.



(a) (b)

Figure 23. The handle of the prefabricated component. (a) Handle assembly, and (b) handle as part of the general component.

The overall weight of the prefabricated component is 8.64 kg, and its overall volume is 0.02 m^3. The wall surface that one component covers when attached on to a building is equal to 0.25 m^2. The small weight and size are critical advantages of this component. Additionally, this component can easily be transferred from the construction factory to the renovation site, and then it can easily be installed without the need for a crane if the construction guidelines are followed by the technicians. The component comprises of many individual elements, such as insulation, frame, thermal break, bolts, and other supportive plastic or metal elements. **Figure 24** depicts the exploded view of the prefabricated component. **Table 11** is an extended form of the bill of materials for this component, where useful information about the individual elements is presented. Finally, **Figure 25** indicates the parts listed in **Table 11** for the convenience of the reader.

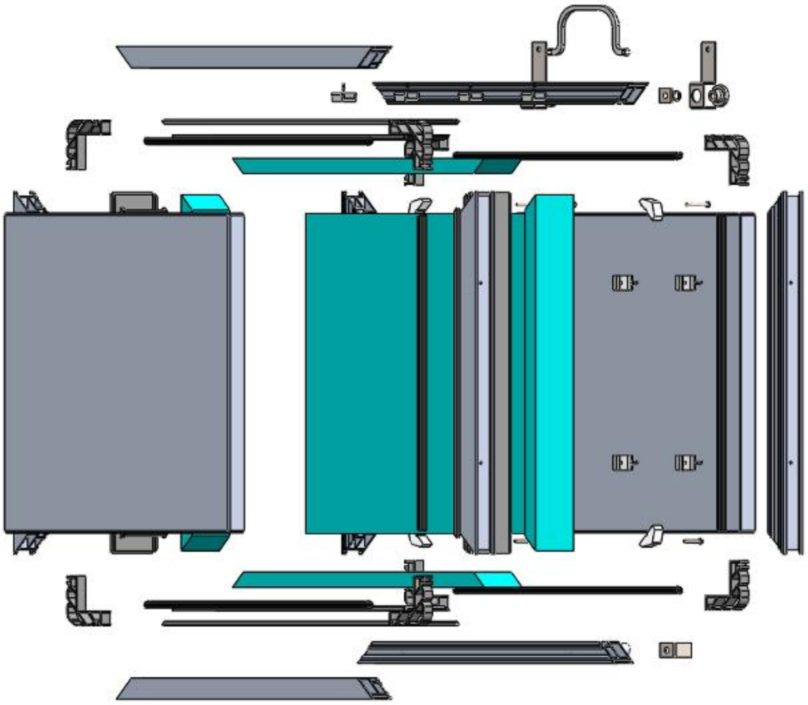


Figure 24. Exploded view of the prefabricated component.

Table 11. An extended bill of materials for the prefabricated component.

No.	Part name	Material	Mass	Quantity
1	Main insulation element	XPS	448.8 g	1
2	External aluminium frame	Aluminium	436.8 g	8
3	Thermal break element	PA	323.3 g	4
4	Insulation for thermal break	XPS	23.37 g	4
5	Crimp corner cleat (Alumil EX-1131917000)	Aluminium	13.91 g	8
6	Component cover	Aluminium	1305.7 g	2
7	Sealing gasket (BMP: 1089-99-18)	PVC	56.53 g	8
8	Metal cavity anchor HM 4x32 S (fisher)	Stainless steel	12.01 g	4
9	Metal cavity anchor HM 4x45 SB (fisher)	Stainless steel	24.86 g	2
10	Wall supportive element	Stainless steel	27.61 g	2
11	Wall mounting element	Stainless steel	50.35 g	2
12	Knurled nuts (DIN 466 – high type)	Stainless steel	42.58 g	2
13	Handle	PLA	21.33 g	1
14	Handle brackets	Stainless steel	11.81 g	2
15	Handle support	PLA	0.500 g	2
16	Connection plastic element	PLA	6.150 g	8
17	Connection plastic pin	PLA	0.060 g	8
18	Hexagon bolt (ISO 4014 – M4 x 30 x 30-N)	Stainless steel	0.493 g	4
19	Hexagon bolt (ISO 4015 – M4 x 40 x 40-S)	Stainless steel	0.549 g	2

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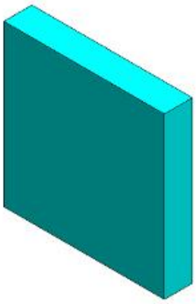


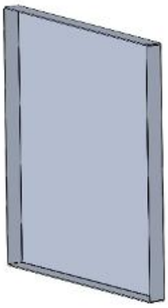
(1)

(2)

(3)

(4)

(5)



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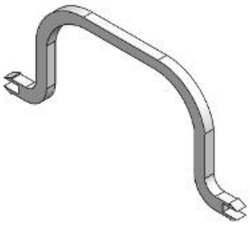
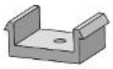


(13)

(14)

(15)



(16)

(17)

Figure 25. Illustration of the elements listed in the previous table, Table 11.

Assembling the prefabricated component must be an easy and straightforward process. Thus, this parameter has been selected as a design parameter for the component. **Figure 26** presents a step-by-step process on how this component is assembled using the elements that have already been presented in this section. In each sub-figure, the assembly process, as well as the intermediate stage that the component is in, is illustrated. **Figure 26.a** presents the first step for assembling the component, which refers to the assembly of the component's frame. After cutting the edges of the elements at a 45° angle, the aluminium frames slide into the grooves of the thermal break element.

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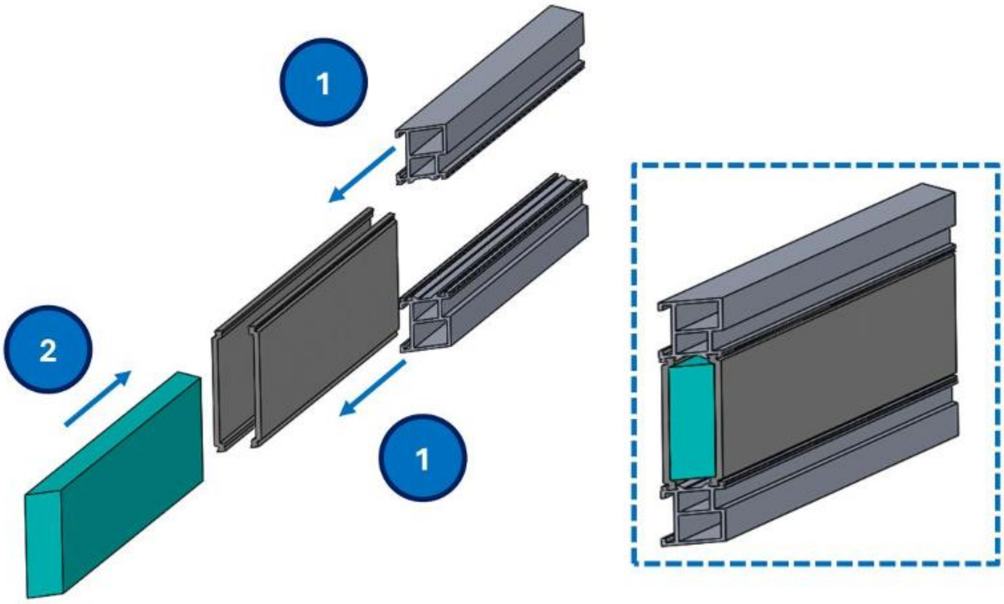
Then, the insulation element used as a thermal break is placed inside the frame to create the final component's frame. The same procedure is followed to create four identical profile sub-components. The second step is to assemble the component's frame profile, as depicted in **Figure 26.b**. To do so, the crimp corner clits (Alumil EX-1131917000) are placed in two of the four identical profile sub-components assembled in the previous step. Then, the next step is to connect all four sub-elements of the component's profile, enclosing at the same time the main insulation element, as **Figure 26.c** suggests. The fourth step is to adjust the two covers on the main body of the component. First, specialized plastic gaskets made of PVC are placed on the two aluminium covers to form two cover sub-assemblies, one for each side of the component. Then, these are wedged together with the main component. The fourth step is depicted in detail in **Figure 26.d**. Afterwards, all the necessary holes are drilled, and the connection plastic elements along with their pins, as well as the supporting brackets, which enable fastening and stabilization of the component onto the wall, are placed. This procedure is depicted in **Figure 26.e**. Finally, **Figure 26.f** presents the procedure for assembling the handle and placing it onto the main body of the component to finalize the assembly procedure. These very simple steps indicate the ease of assembly as one of the advantages of the prefabrication retrofitting process.



(a)

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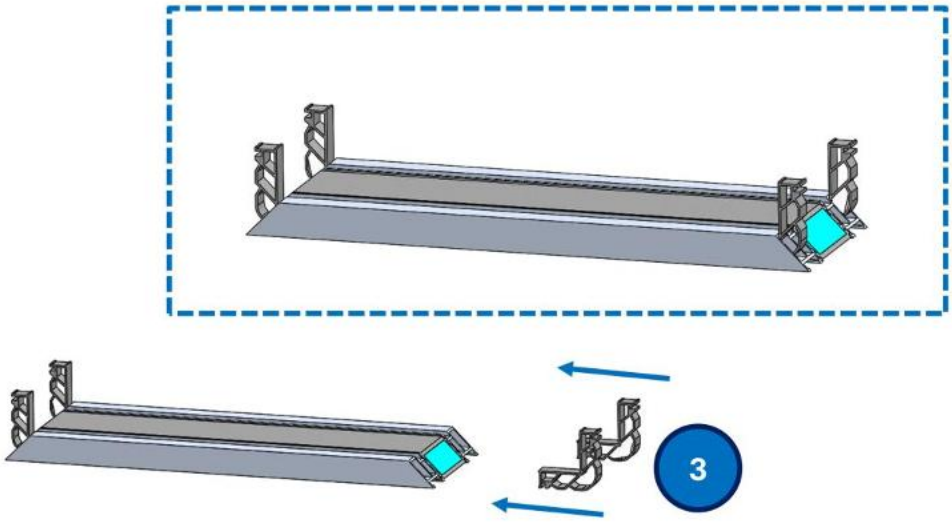
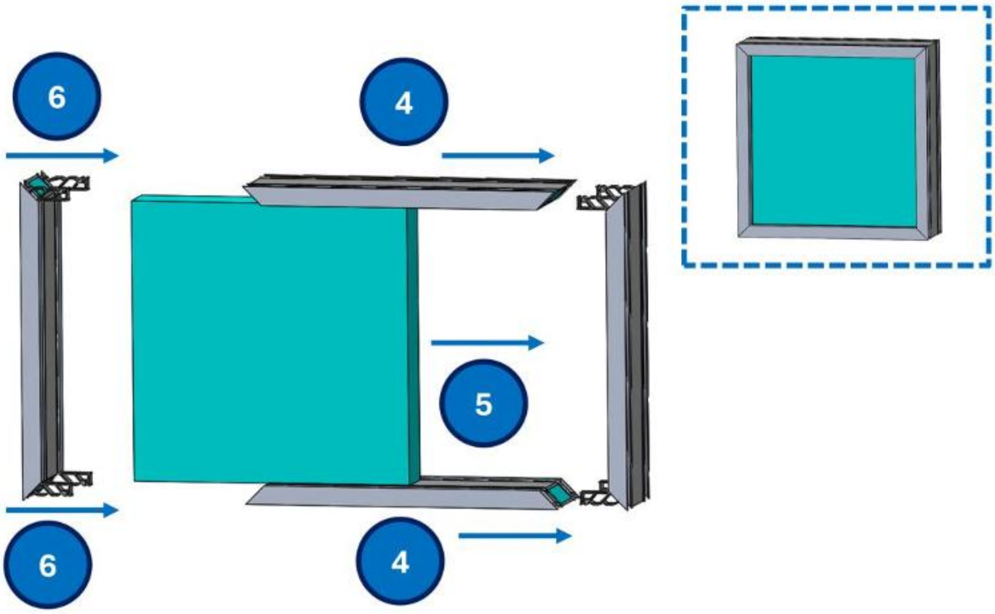


(b)



(c)

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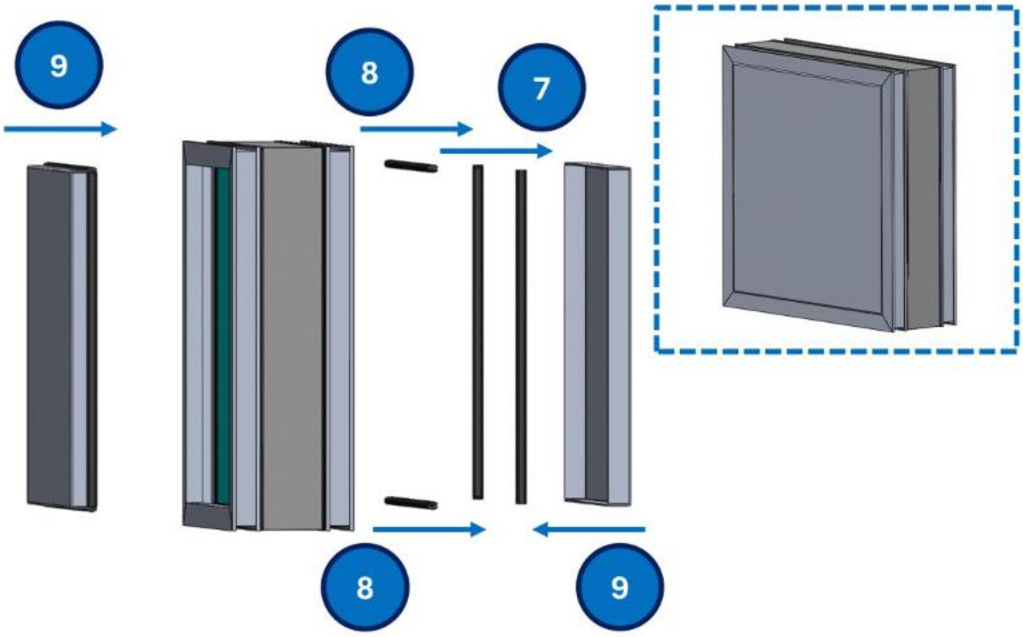
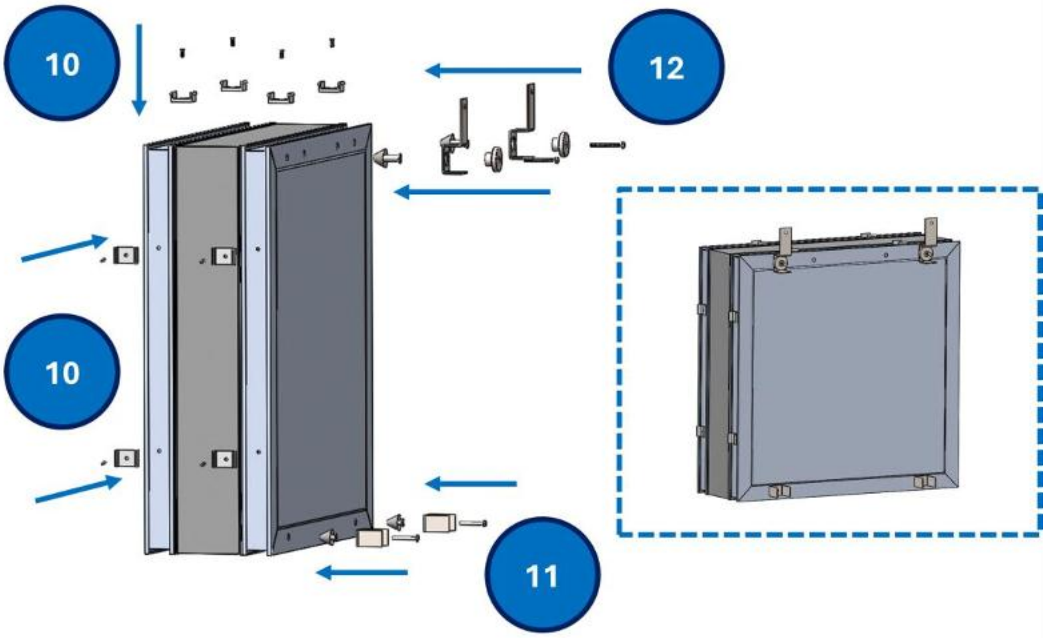


(d)



(e)

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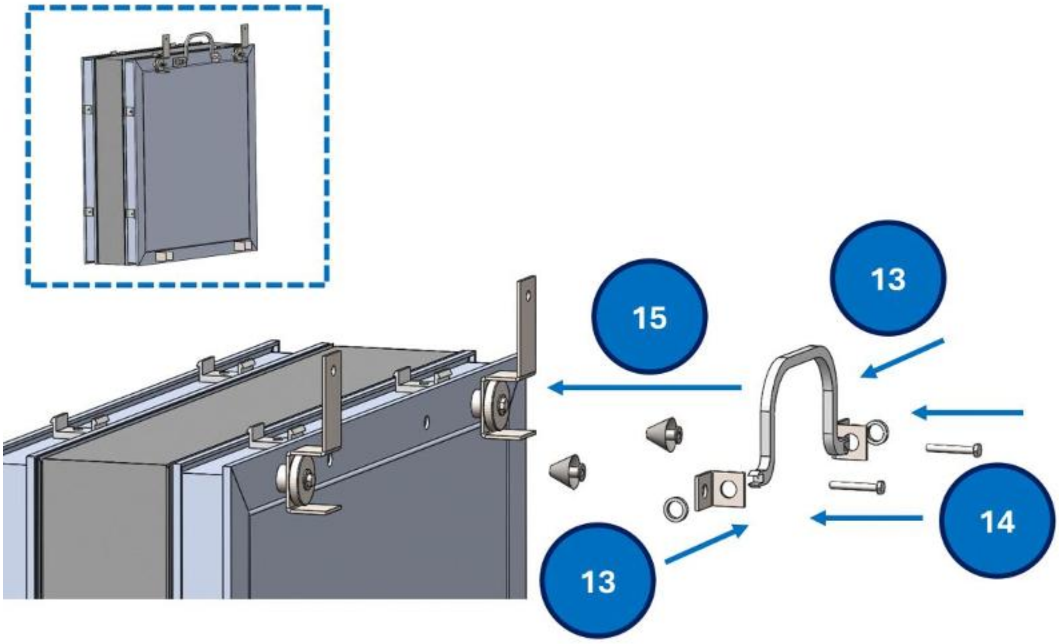

(f)

Figure 26. The step-by-step assembly process for the small-scale prefabricated component.

3.3.1 Component-level Simulation Results

The simulations are conducted on two different levels, on a component level and on a system level. The component-level simulation results are important to determine the U-value of the component. Also, the temperature distribution within the component reveals some critical points where thermal bridging may occur. In this deliverable, the SolidWorks Flow Simulation studio is used to calculate the heat flux, which will then be used to calculate the U-value [63]. To calculate the U-value, the software is used to calculate the heat flow in W/m^2, and then, this value is divided by the temperature difference of the boundary conditions to ultimately determine the U-value of the component. The required input data for the simulations are the material's thermal properties and the boundary conditions. **Table 12** present the thickness and thermal conductivity values used for the numerical calculations of the U-value. These layers are depicted in **Figure 27**. The air gap in the prefabricated component is considered as a convective thermal resistance as discusses in Section 3.2.1.

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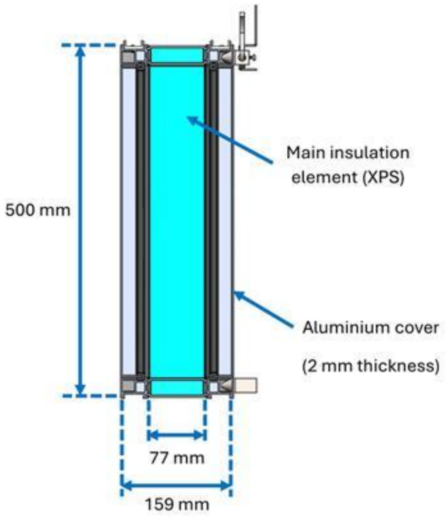


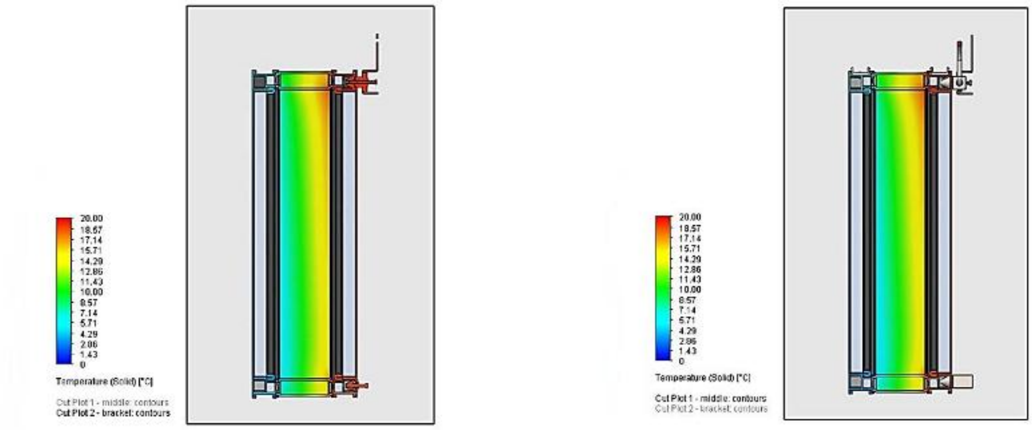
Figure 27. Material layers for the numerical calculations of the U-values.

Table 12. Thermal properties of the materials used for the numerical calculation of the U-values for the prefabricated component.

Material	Thickness [mm]	Density [kg/m^3]	Thermal conductivity [W/(mK)]	Specific heat capacity [J/(kgK)]
Aluminium (x2)	2.00	2702.0	237.0	903.0
XPS	77.0	35.0	0.024	1380.0

3.3.3.1 Small-scale component-level simulation results

The calculated U-value of the component is equal to 0.333 W/m^{2}K. This value meets the requirements for a house in all the climate changes in Greece, based on the relevant regulations [64]. **Figure 28** illustrates the temperature distribution inside the component for the boundary conditions presented in the previous section. **Figure 28.a** clearly indicates that thermal bridges occur due to the material of the connection elements, which is Stainless Steel (SS). However, this material cannot be replaced with plastic because this would result in structural strength issues when the component is fixed on the external wall surface.



(a) **(b)**

Figure 28. Temperature distribution for the prefabricated component for (a) a cross-section on the wall mounting element plane, and (b) a cross-section on the middle plane of the component.

3.3.2 System-level Simulation Results

The aim of the system-level simulations is to quantify the improvement in energy efficiency. The building used for the simulations is the Greek virtual pilot, which is the “Lela Karagianni” primary school building in the city center of Athens, Greece (latitude 38.00°, longitude 23.73°). The building envelope is representative for the buildings constructed in the 1980s, consisting of concrete and bricks, and it is fully uninsulated. The school includes two buildings, and the newer one was used, as the older building is considered a historic building and its facade cannot be altered. The cases that are compared are the existing building, which is completely uninsulated, and the complete retrofitting with the prefabricated components. The complete retrofit of the building aims at achieving the Passivhaus standard, because it offers a great reduction of energy demands for heating and cooling, while at the same time achieving optimal thermal comfort. The renovation includes the installation of the prefabricated elements along with the resulting improvement of thermal bridges, installation of energy-efficient windows, improvement of the airtightness of the building envelope, the introduction of a MVHR system, as well as the addition of shading elements on the glazing surfaces. All these energy saving measures improve the energy efficiency of the building by introducing significant energy savings, while in parallel, interior thermal comfort levels are greatly improved. **Figure 29** depicts the installation process of the prefabricated components on the virtual building.

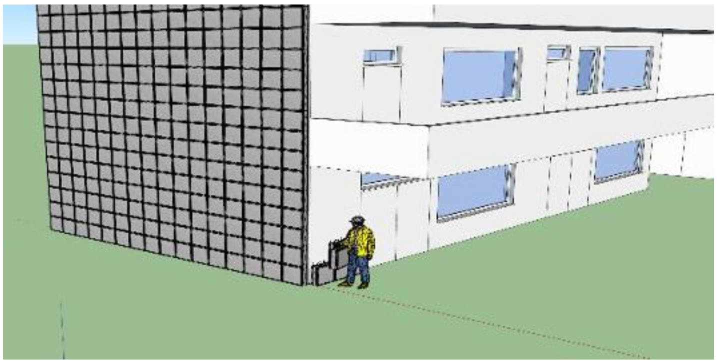


Figure 29. Installation process of the prefabricated components on the virtual building.

The existing building requires 31,334 kWh annually for heating and cooling based on the results of dynamic simulations for the baseline scenario. It is important to note here that the school is not equipped with active cooling systems. This directly affects thermal comfort during the warm Greek months. Without the use of a cooling system, the building requires 23,408 kWh annually for heating. The reason the cooling system is added is to compare the effect of the prefabricated element on an equivalent basis. However, the actual case of the building was also considered and evaluated. **Figure 30** illustrates the mean air temperature variation of the building (blue line). Additionally, the holiday periods of the school’s schedules are noted on the diagram: the summer holiday period (green lines), the Easter holiday period (red lines), and the Christmas holiday period (orange lines). Also, the range of thermal comfort according to the Greek building code (grey lines), which lies in the range of 20-26°C is also presented. It is evident that the existing building suffers greatly from the fluctuations of external temperatures. The heating system shuts down after managing to reach 20°C momentarily, and the building is unable to maintain the heat, which is evident because during the heating period, the temperatures are always equal to or less than the 20°C threshold. The night fluctuations when the energy systems are turned off are also visible, as well as the weekend fluctuations when the energy systems are also deactivated, and temperatures can drop as low as 10°C. The weekend periods can be seen as the periodic dips that appear at a rate of 5 every 1000 hours (approximately 5 weekends over a period of roughly 6 weeks). Moreover, during the winter break, the temperature stagnates at around 10°C. During the Easter holiday break, the temperature seems to drop significantly since the heating load inside the building decreases as the building is unoccupied. As the Easter break period ends, the temperatures appear to increase rapidly, with the cooling system struggling to maintain temperatures below the level of 26°C. As the summer break starts, the temperature increases further until a peak of approximately 37°C. By the end of the summer break and the activation of the cooling systems, the temperatures are declining, which continues until the end of the year, and the cycle repeats.

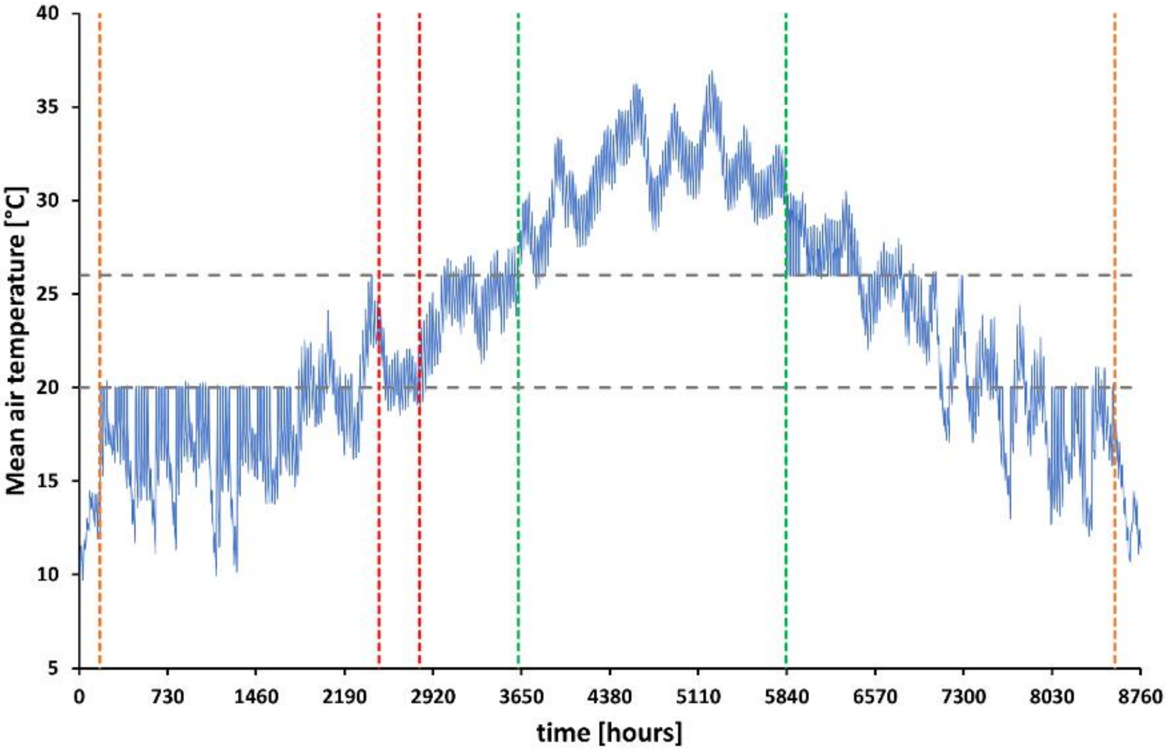


Figure 30. The mean air temperature variation of the building.

It is obvious that the time period in which the temperature levels are within the optimum range of 20-26°C is limited. This indicates the necessity for building retrofitting. Renovation processes in school units must be completed within the summer break period, which is approximately 3 months. This is a very challenging target, and conventional retrofitting techniques seem to struggle. Thus, prefabricated solutions seem to be ideal for these case studies. The calculated annual energy demand for heating and cooling is found to be equal to 10,297 kWh, which corresponds to a 67% percentage reduction compared to the baseline scenario, which includes the cooling systems. The annual cooling demand was calculated at 4,479 kWh, while the annual heating demand was calculated at 5,818 kWh. **Figure 31** depicts the mean air temperature variation of the building when the prefabricated component is utilized. **Figure 32** summarizes and compares the mean air temperature fluctuations before and after the energy retrofitting using the prefabricated components. **Table 13** summarizes the annual heating and cooling demand after the installation of the prefabricated components, and the total energy savings.

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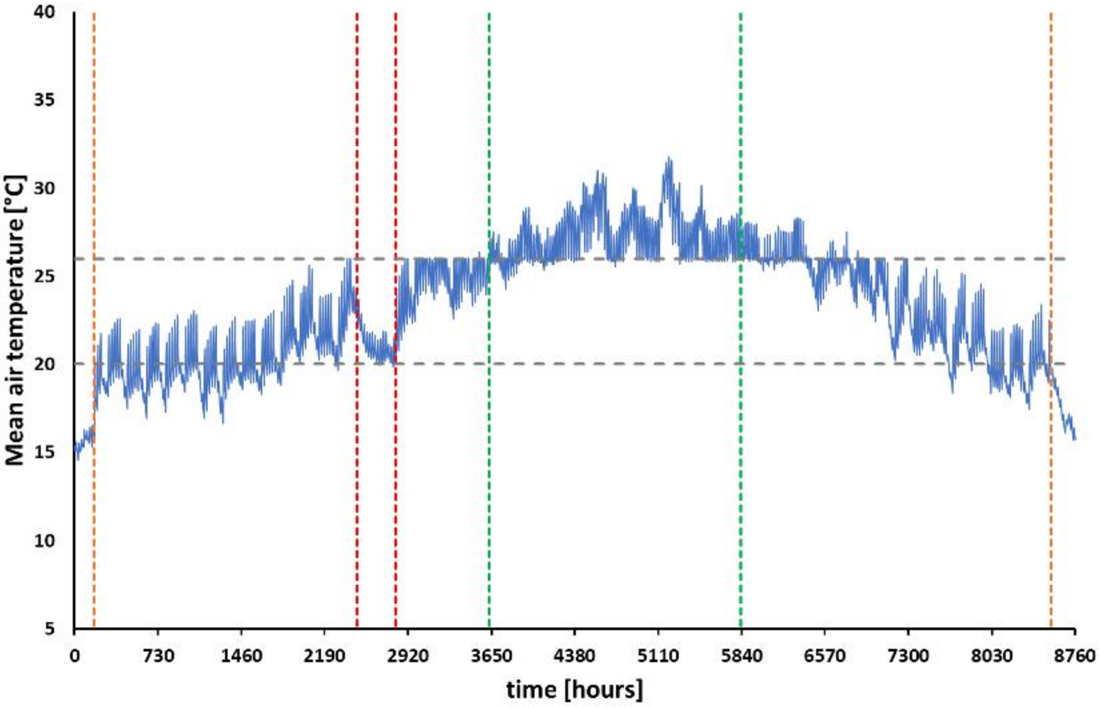

Figure 31. The mean air temperature variation of the building after the retrofitting process using the prefabricated component.

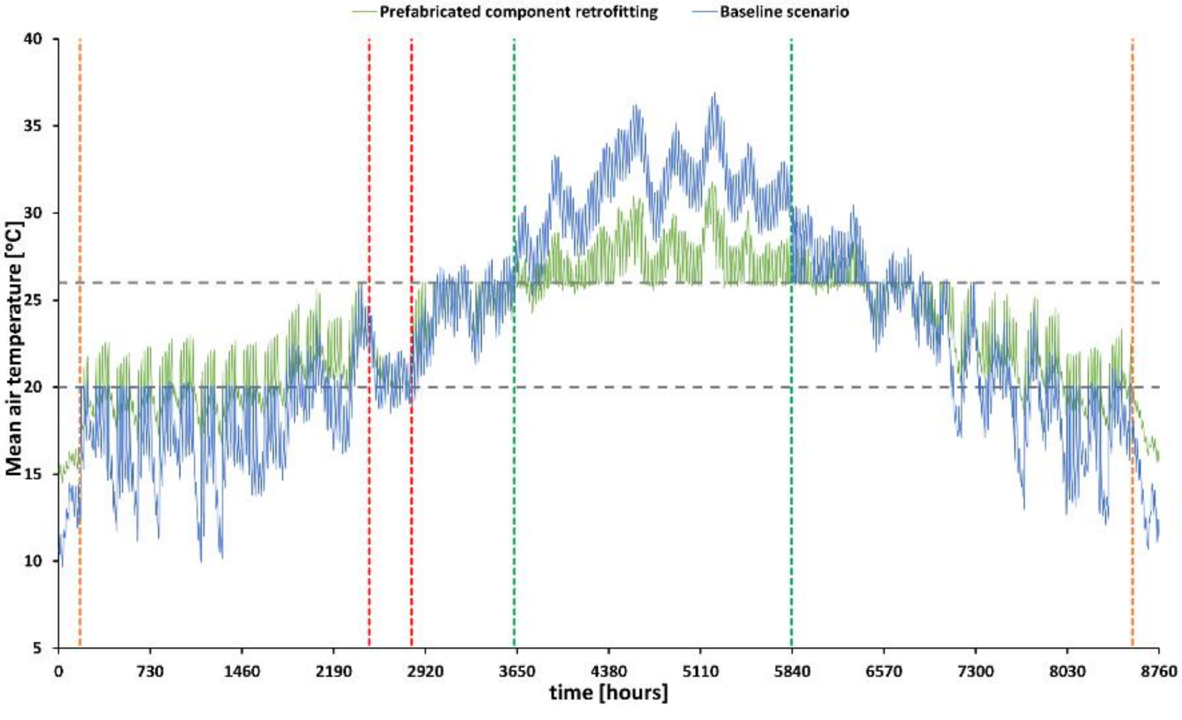

Figure 32. The mean air temperature variation of the building before and after the retrofitting process using prefabricated components.

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Table 13. System-level simulation results for the prefabricated component.

Parameter	Value
Existing building energy consumption – Baseline scenario	31,334 kWh
Annual cooling demand when installing the component	4,479 kWh
Annual heating demand when installing the component	5,818 kWh
Annual energy savings percentage when installing the component	67.1%

3.3.3 Environmental Footprint and Construction Cost

This section discusses some preliminary estimations about the construction cost, and the carbon footprint of the proposed prefabricated component. This indicator must be compared both in absolute cost value (€), but also in cost expressed in units of square meters (€/m^2) for the wall surface that each component can cover. The mean value from the range values of each element has been considered in these calculations. The average cost for aluminium it can range from 2.3 €/kg to 3.0 €/kg [65]. The most expensive element is the insulation one. For XPS, this cost can range from 1.5 to 3.0 €/kg [66]. Stainless steel is used for the construction of the supportive brackets and elements, especially for the smaller unit, but also for the construction of all the necessary anchoring bolts and screws. The cost of stainless steel, including chromium for properties reinforcement, is estimated in the range of 2.2 to 4.8 €/kg [67], while for an alloy steel this value is in the range of 0.33 €/kg to 0.85 €/kg [68]. The estimated construction cost for the component is equal to 19.5 €, while the estimated construction cost per square meter of surface area is equal to 78.0 €/m^2. To be more accurate in the cost prediction, two more things must be taken into consideration, which are the assembly and the installation on-site. Construction cost is always dependent on the location, the scale of the project, and the quantity of materials which will be ordered.

The equivalent carbon dioxide ($CO_{2\text{-eq}}$) emissions for the construction of the component are used as the main indicator for the environmental footprint analysis. According to the international aluminium organization, the carbon footprint of aluminium is equal to 14.8 kg_{CO2_eq}/kg_{Al} if the aluminium is produced by raw bauxite [69]. However, if recycled aluminium is used, this value is equal to 0.52 kg_{CO2_eq}/kg_{Al} [70]. In this study, recycled aluminium is used for the calculations. For the insulation material, the material utilized is XPS. However, the component was designed so that a great variety of insulation materials could be used. The carbon footprint of XPS is estimated at 85.8 kg_{CO2_eq}/kg_{XPS} [71]. For the sealing gaskets of the small-scale component, the material used is PA, and its equivalent emissions are equal to 9.1 kg_{CO2_eq}/kg_{PA} [72]. However, for the biobased PA, which is used in this study, the carbon footprint is significantly reduced to 1.7 kg_{CO2_eq}/kg_{PA} [72]. Finaly, stainless steel is utilized for the construction of the necessary bolts and screws. Despite the probability of in-house construction of these screws is very low, their footprint is calculated as well, and its equivalent footprint equals to 5.3 kg_{CO2_eq}/kg_{SS} or to 1.6 kg_{CO2_eq}/kg_{SS} if the stainless steel was fully recycled [73]. Given that the surface area for the proposed prefabricated component is equal to 0.25 m^2, its specific equivalent carbon footprint is equal to 224.4 kg_{CO2_eq}/m^2. The main reason for these high value is the selection of XPS as the insulation element, which has been done in purpose to set the environmentally worst-case scenario as the baseline.

3.3.4 Overall Benefits of the Prefabricated Components Exploitation

The advantages that prefabricated components can provide to all the stakeholders involved in a retrofit are evident. First and foremost, the necessary energy efficiency of the building stock can be achieved by enabling deep energy retrofits for the vast majority of aging buildings that would

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otherwise not be able to achieve significant energy savings with the required internal thermal conditions. This improvement in energy efficiency can allow for thermal comfort and a sustainable future. Additionally, such an innovative product will bring more know-how towards energy-saving measures that will push the industry towards the EU's goals. Also, buildings that will undergo renovations with the use of prefabricated units will achieve optimal thermal comfort in their interior, which is very often neglected when it comes to energy efficiency in buildings, since the main focus is on energy consumption and not occupant well-being. While it achieves this improvement in thermal comfort, it does so by greatly reducing occupant hassle during the retrofitting process. Furthermore, there is a significant economic relief that such a unit can provide, since renovation times and costs are being pushed down, thus reducing capital costs, while also reducing energy bills, leading to larger disposable income for building occupants due to lower operational costs. These prefabricated elements also have a positive effect on the lifecycle of a building. Since thermal insulation and minimization of thermal bridging eliminated problems like moisture building up in structural elements, problems like rusting of the reinforcement and deterioration of the structural elements are prevented, and consequently, the building's lifetime is extended, thus reducing the building's yearly carbon footprint, considering the embodied carbon in its construction materials. Last but not least, the environmental footprint of the element is designed in such a way to strike a perfect balance between performance and recyclability, since the entire frame material is recyclable, while the insulation material, despite being a petroleum product, can also be recycled.

3.3.5 Potential Usage in the Market

The introduction of a prefabricated component that aids the retrofitting process by integrating multiple energy-saving measures demonstrates significant potential for market utilization, addressing a critical need in both the domestic and global construction sectors. While prefabricated insulating units exist worldwide, very few combine a comprehensive set of energy efficiency features into a single, ready-to-install solution. Most current units focus primarily on insulation and are commonly constructed with timber frames. Although timber offers certain advantages, as presented in Section 2 of this deliverable, its large-scale use in the Greek market is not feasible due to limited forest resources and smaller supply chains. These limitations lead to longer construction timelines, higher material costs, and a greater environmental footprint. All the aforementioned factors highlight a gap in the market that a prefabricated component, such as the proposed ones, comes to fill. It is an innovative product for the global market since, unlike conventional units, it integrates a multitude of energy efficiency-improving features in its design, enabling adherence to the Passivhaus standard. The Passivhaus standard provides a way to achieve very low energy demands along with excellent thermal comfort through a holistic building design approach, due to its basic principles, which are thermal insulation, minimized thermal bridges, improved window performance, airtightness, MVHR, and shading, especially for climate zones closer to the equator. All these principles are incorporated into the prefabricated component. The result is that this component enables retrofits in aging buildings that otherwise would not be feasible, both in the public and private sectors, due to large capital costs, extensive renovation times, and feasibility concerns. Last but certainly not least are its lifecycle advantages. Not only does it extend the lifecycle of existing buildings, with high embodied carbon by eliminating corrosive moisture in structural elements and enabling them to be used for longer with comfortable interior conditions, but it also provides a form of circularity due to its highly recyclable nature. Countries with demo sites will also benefit from such a product.

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4. Conclusions

This deliverable emphasizes on two renovation strategies for the existing building stock, timber reuse and prefabrication. Both solutions present some advantages and disadvantages. However, they seem to be possible candidate solutions towards renovating the EU's building stock which is mandatory to achieve the EU sustainable goals for 2050.

4.1 Conclusions and Further Considerations: Design Studies on Timber Reuse

Based on the comprehensive analysis conducted through the virtual demonstrator in Germany, Strategy A is recommended as the optimal approach for deep energy renovation of the existing building stock using reclaimed timber. This recommendation is grounded in Strategy A's strongest performance across most key evaluation criteria.

Strategy A, the least invasive approach, delivers the best overall environmental and economic performance. The results demonstrate that this strategy achieves environmental payback within the shortest period while maintaining the highest degree of structural preservation. Its advantages in terms of resource efficiency, cost-effectiveness, and minimal intervention requirements make it the most suitable solution for widespread implementation in renovation projects. Strategy A combines technical feasibility with environmental benefits and economic viability over building lifecycles, positioning it as the clear frontrunner among the evaluated approaches.

Building on these promising results, Strategy A must be subjected to more rigorous technical evaluation in follow-up investigations, including in-depth analysis of structural performance, thermal bridging, hygrothermal behavior, and detailed connection design to fully validate its implementation feasibility.

While all three strategies presented in this study represent realistic approaches to renovation, their suitability depends on which aspects (environmental performance, economic viability, or preservation of existing structures) are prioritized. In practice, such decisions are often influenced by multiple stakeholders, regulatory frameworks, and funding conditions. However, when evaluated holistically, Strategy A emerges as the most balanced and effective solution.

Realizing the full potential of circular timber construction requires concerted action across multiple domains:

- development of enabling regulations and standards
- maturation of circular value chains
- advancement of digital tools and assessment methodologies
- innovation in reversible connection systems
- cultivation of social acceptance among designers, builders, and clients

The transformation from linear to circular construction practices demands systemic change, but the demonstrator project provides evidence that this transition is both necessary and achievable.

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4.2 Conclusions and Further Considerations: Prefabricated Circular Renovation Component

Prefabrication in renovation is a mandatory process to accelerate building decarbonization, improve thermal comfort, and create affordable solutions. At the same time, prefabricated elements that can use recycled and biobased materials provide a holistic approach to the solution. NTUA's solutions throughout the SIRCULAR project are aiming to raise awareness for prefabricated components by designing simplified and easy-to-construct solutions on a small scale, giving the opportunity to local enterprises to invest in innovative solutions.

Regarding materials, XPS is used as one of the most well-known materials in the market as an example. This solution indicates the worst-case scenario in environmental terms as the baseline design scenario. The proposed prefabricated element can use every available material in the market, prioritizing biobased or recycled materials with lower embodied energy. The advantages of prefabrication in renovation are the following:

- Reduce construction time: Industrialization is one of the few ways to accelerate building renovation in comparison to conventional techniques. This is happening by crafting 90% of the final wall of the construction site. It is important not only for the building but also for the surrounding area.
- Improve the quality of renovation: Deep energy renovations rely on engineers, technicians, and market products, where there is a huge variety in all of these. Prefabrication in renovation offers an OSS solution, incorporating different building components (insulation, windows, etc.) in one final product designed only for deep energy renovations.
- Avoid human errors through industrialized products: Similar to above, the quality of the renovation often requires specialized technicians and time, which they don't have. These lead to significant errors (for example, thermal bridging) despite utilizing very good products. Industrialization lacks customization but offers safety and quality assurance.
- Address the lack of technical workforce: Building renovations require a dedicated technical workforce, which nowadays is a huge issue for Europe. It is very difficult to create that working force, and this is why prefabrication will play a crucial role in our society.
- Reduce construction cost: Prefabrication is still a bit more expensive in comparison to a typical renovation. The designed solution has taken into consideration the cost, using conventional materials and simplified geometry to enable mass production and cost minimization.
- Reduce the disturbance to the residents who will be able to live in their buildings during the renovation process: Exterior insulation requires a scaffold, MVHR, and HVAC systems require working from the interior, and the same for windows. The OSS prefabrication solution that is designed has taken into consideration the disturbance, which has been minimized as much as possible through penetrations in the exterior wall.

During the development of the prefabricated component there were some issues that emerged and deserve attention in future research to further develop these solutions to higher TRL levels. The main consideration issues are listed below:

- Specific prefabricated component sizes: The proposed component has a specific size. This leads to the problem of covering the entire outer wall, since most probably, the existing wall size will not perfectly fit on an integer number of components. Thus, specific treatment will be necessary to cover the gaps that will remain. However, considering that there are many

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neighborhoods with a lot of identical buildings in many EU countries, tailor-made components could be designed for each purpose based on the strategy and analysis presented.

- Prefabricated components for the roof: The developed solutions were examined only for the installation on vertical outer wall surfaces. However, prefabrication could also be used for roof insulation. Specific criteria should be added when designing such components since some issues are more critical for the roof insulation, such as wind and vapor resistance.
- Possible flaws during installation due to human errors: The installation process is semi-automated. Thus, human intervention is limited but cannot be entirely avoided. Thus, human errors may exist during the installation process, resulting in thermal bridges and airtightness issues. Specific treatment with further insulation foam addition may be required.

5. Appendix

In the Appendix, figures and tables that provide further illustration and clarifications regarding the reported data and results are presented.

Figure A1. Pictures of the existing building under investigation for the timber-reuse retrofitting.

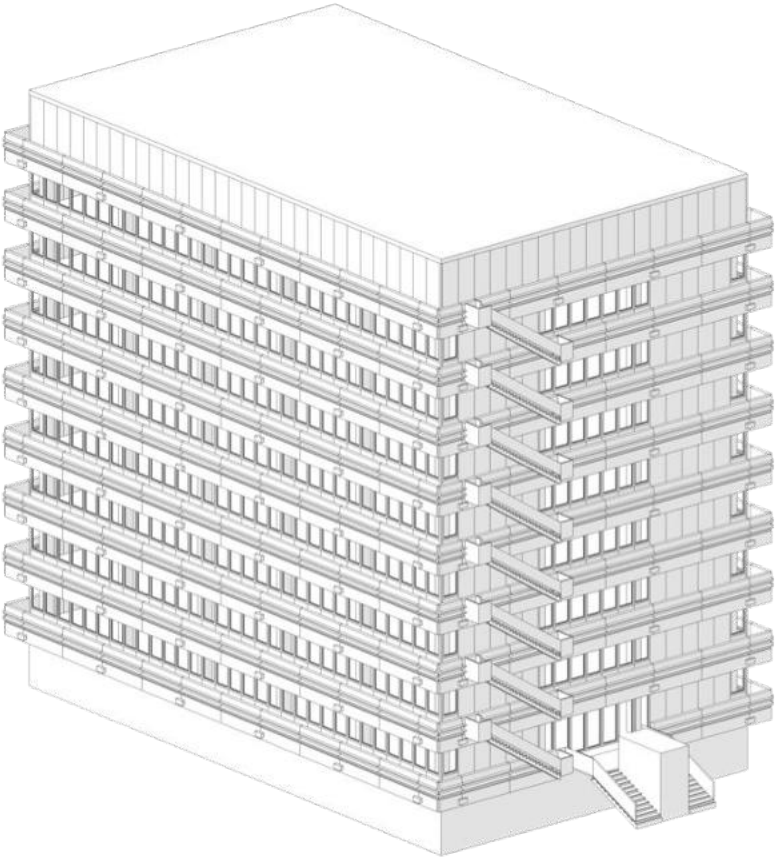

Figure A2. Axonometric drawing of the existing building under investigation for the timber-reuse retrofitting.

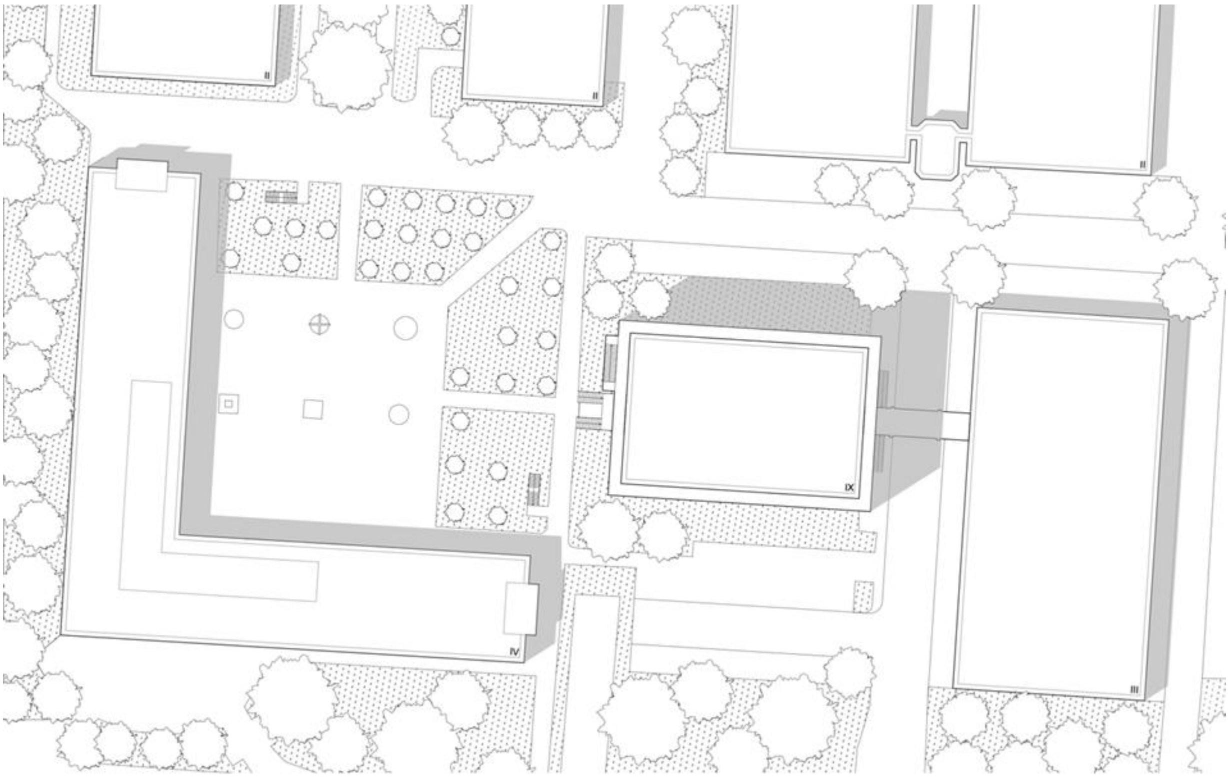

Figure A3. Site plan of the existing building under investigation for the timber-reuse retrofitting.

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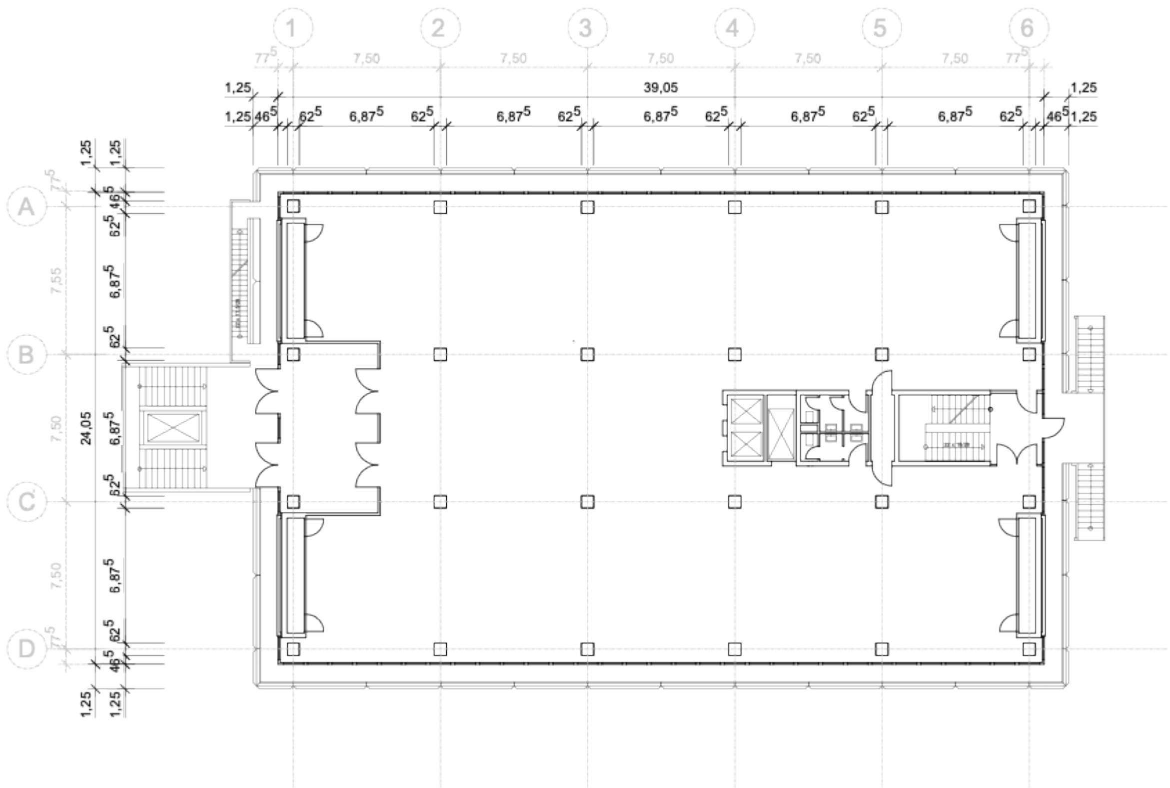

Figure A4. Ground floor of the existing building under investigation for the timber-reuse retrofitting.

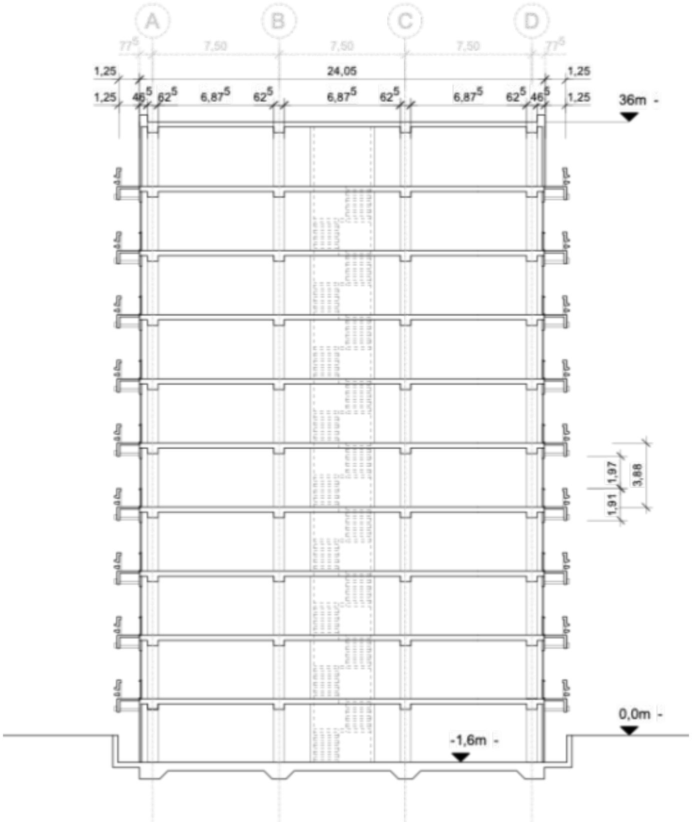

Figure A5. Section AA of the existing building under investigation for the timber-reuse retrofitting.

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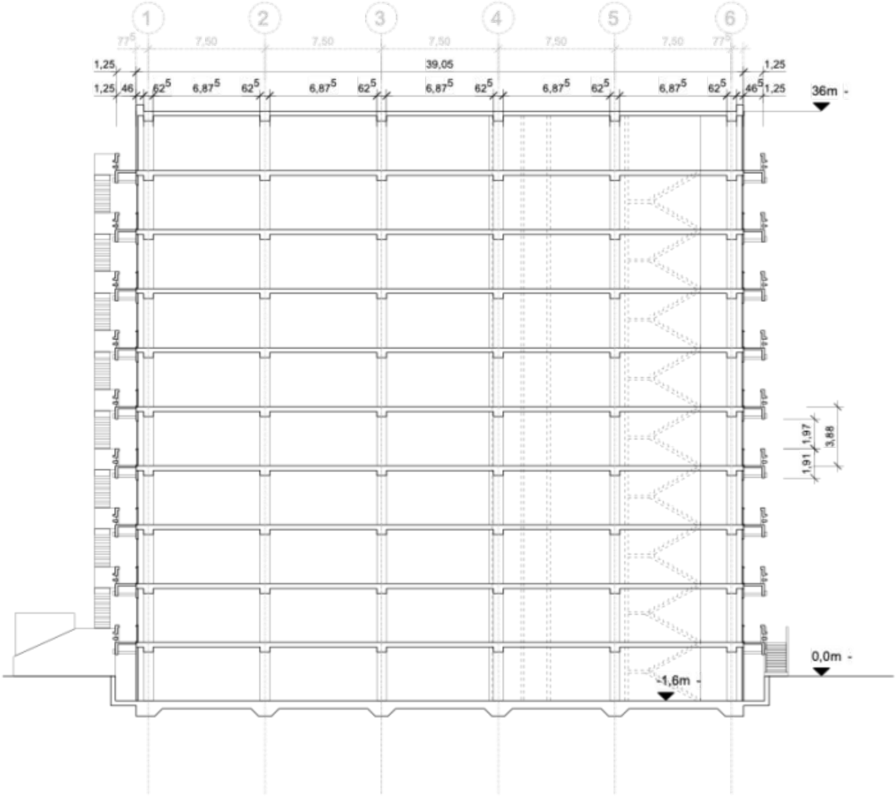

Figure A6. Section BB of the existing building under investigation for the timber-reuse retrofitting.

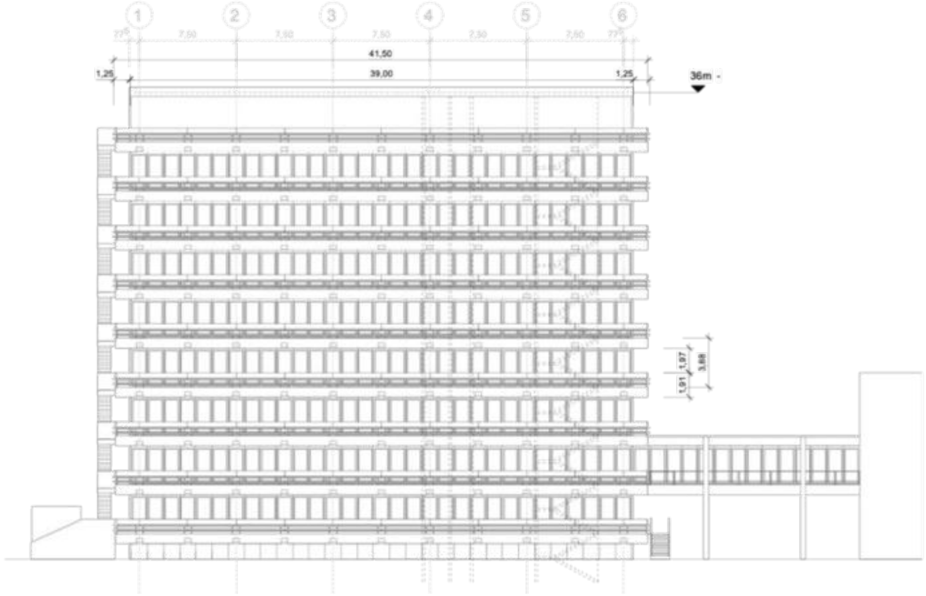

Figure A7. Elevation south side of the existing building under investigation for the timber-reuse retrofitting.

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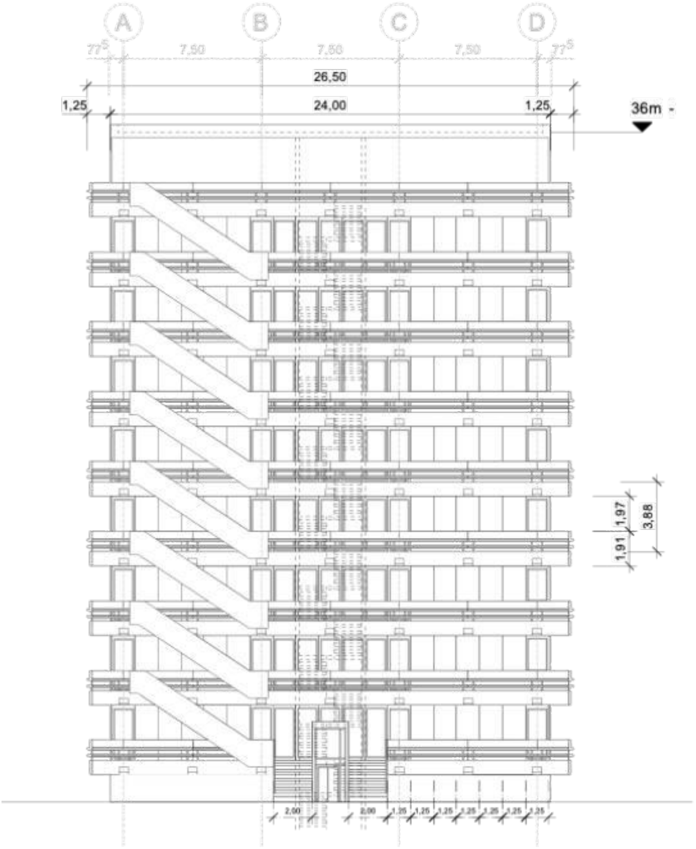
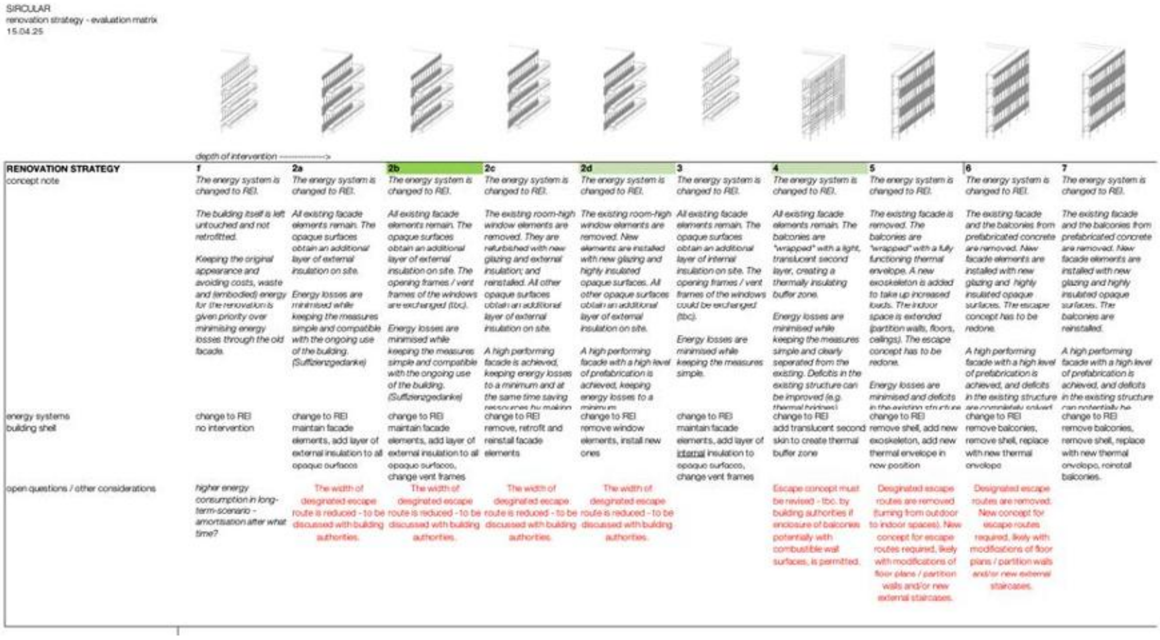


Figure A8. Elevation on west side of the existing building under investigation for the timber-reuse retrofitting.

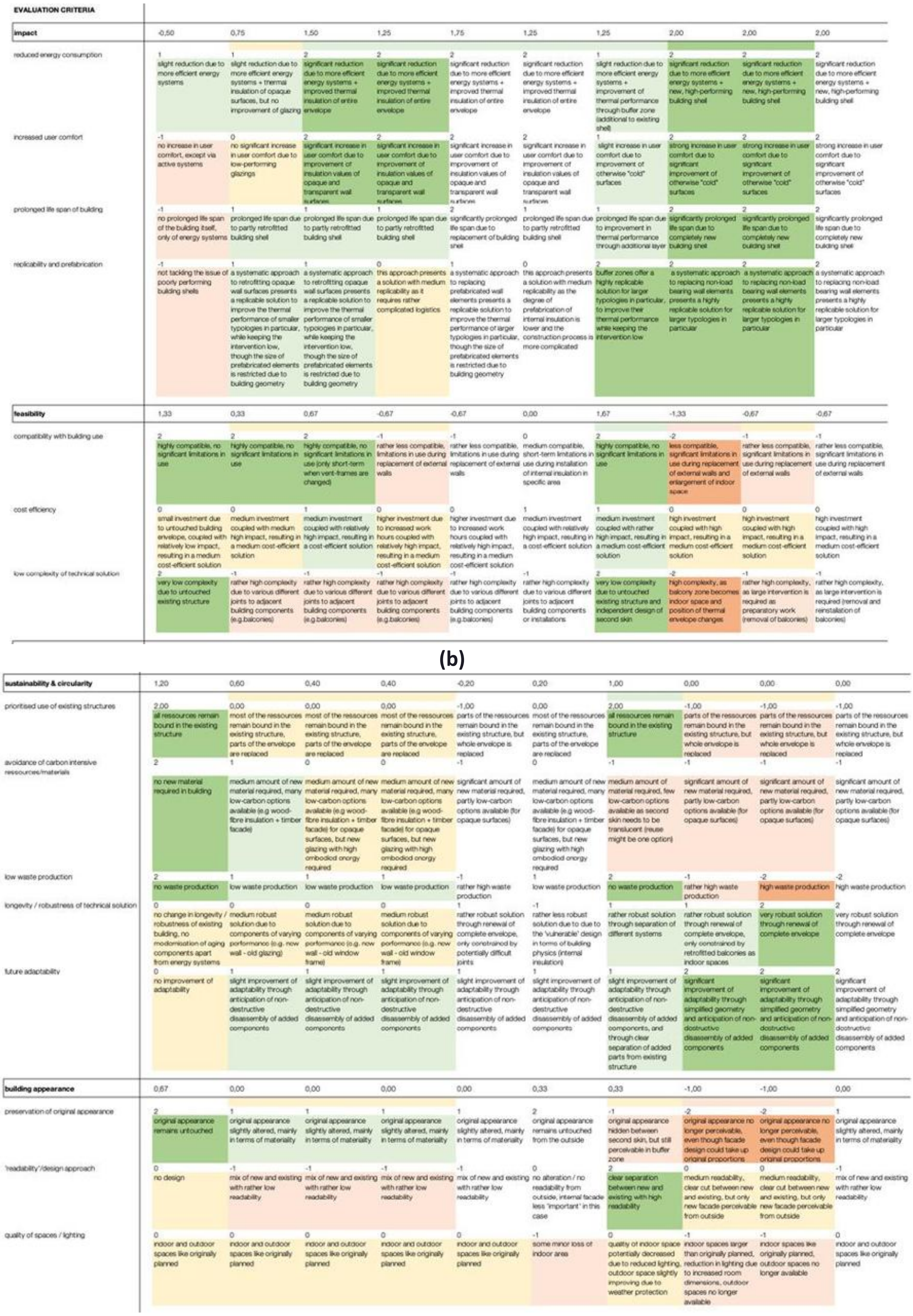


SIRCULAR
renovation strategy - evaluation matrix
15.04.25

depth of intervention ------------->

RENOVATION STRATEGY	1	2a	2b	2c	2d	3	4	5	6	7
concept note	*The energy system is changed to REI.* *The building itself is left untouched and not retrofitted.* *Keeping the original appearance and avoiding costs, waste and (embodied) energy for the renovation is given priority over minimising energy losses through the old facade.*	*The energy system is changed to REI.* *All existing facade elements remain. The opaque surfaces obtain an additional layer of external insulation on site.* *Energy losses are minimised while keeping the measures simple and compatible with the ongoing use of the building. (Suffizienzgedanke)*	*The energy system is changed to REI.* *All existing facade elements remain. The opaque surfaces obtain an additional layer of external insulation on site. The opening frames / vent frames of the windows are exchanged (tbc).* *Energy losses are minimised while keeping the measures simple and compatible with the ongoing use of the building. (Suffizienzgedanke)*	*The energy system is changed to REI.* *The existing room-high window elements are removed. They are refurbished with new glazing and external insulation; and reinstalled. All other opaque surfaces obtain an additional layer of external insulation on site.* *A high performing facade is achieved, keeping energy losses to a minimum and at the same time saving ressources by making*	*The energy system is changed to REI.* *The existing room-high window elements are removed. New elements are installed with new glazing and highly insulated opaque surfaces. All other opaque surfaces obtain an additional layer of external insulation on site.* *A high performing facade with a high level of prefabrication is achieved, keeping energy losses to a minimum*	*The energy system is changed to REI.* *All existing facade elements remain. The opaque surfaces obtain an additional layer of internal insulation on site. The opening frames / vent frames of the windows could be exchanged (tbc).* *Energy losses are minimised while keeping the measures simple.*	*The energy system is changed to REI.* *All existing facade elements remain. The balconies are "wrapped" with a light, translucent second layer, creating a thermally insulating buffer zone.* *Energy losses are minimised while keeping the measures simple and clearly seperated from the existing. Deficits in the existing structure can be improved (e.g. thermal bridges)*	*The energy system is changed to REI.* *The existing facade is removed. The balconies are "wrapped" with a fully functioning thermal envelope. A new exoskeleton is added to take up increased loads. The indoor space is extended (partition walls, floors, ceilings). The escape concept has to be redone.* *Energy losses are minimised and deficits in the existing structure*	*The energy system is changed to REI.* *The existing facade and the balconies from prefabricated concrete are removed. New facade elements are installed with new glazing and highly insulated opaque surfaces. The escape concept has to be redone.* *A high performing facade with a high level of prefabrication is achieved, and deficits in the existing structure are completely solved*	*The energy system is changed to REI.* *The existing facade and the balconies from prefabricated concrete are removed. New facade elements are installed with new glazing and highly insulated opaque surfaces. The balconies are reinstalled.* *A high performing facade with a high level of prefabrication is achieved, and deficits in the existing structure can potentially be*
energy systems building shell	change to REI no intervention	change to REI maintain facade elements, add layer of external insulation to all opaque surfaces	change to REI maintain facade elements, add layer of external insulation to all opaque surfaces, change vent frames	change to REI remove, retrofit and reinstall facade elements	change to REI remove window elements, install new ones	change to REI maintain facade elements, add layer of internal insulation to opaque surfaces, change vent frames	change to REI add translucent second skin to create thermal buffer zone	change to REI remove shell, add new exoskeleton, add new thermal envelope in new position	change to REI remove balconies, remove shell, replace with new thermal envelope	change to REI remove balconies, remove shell, replace with new thermal envelope, reinstall balconies.
open questions / other considerations	*higher energy consumption in long-term-scenario - amortisation after what time?*	The width of designated escape route is reduced - to be discussed with building authorities.	The width of designated escape route is reduced - to be discussed with building authorities.	The width of designated escape route is reduced - to be discussed with building authorities.	The width of designated escape route is reduced - to be discussed with building authorities.		Escape concept must be revised - tbc. by building authorities if enclosure of balconies potentially with combustible wall surfaces, is permitted.	Designated escape routes are removed (turning from outdoor to indoor spaces). New concept for escape routes required, likely with modifications of floor plans / partition walls and/or new external staircases.	Designated escape routes are removed. New concept for escape routes required, likely with modifications of floor plans / partition walls and/or new external staircases.	

(a)



EVALUATION CRITERIA										
impact	-0,50	0,75	1,50	1,25	1,75	1,25	1,25	2,00	2,00	2,00
reduced energy consumption	1 slight reduction due to more efficient energy systems	1 slight reduction due to more efficient energy systems + thermal insulation of opaque surfaces, but no improvement of glazing	2 significant reduction due to more efficient energy systems + improved thermal insulation of entire envelope	2 significant reduction due to more efficient energy systems + improved thermal insulation of entire envelope	2 significant reduction due to more efficient energy systems + improved thermal insulation of entire envelope	2 significant reduction due to more efficient energy systems + improved thermal insulation of entire envelope	1 slight reduction due to more efficient energy systems + improvement of thermal performance through buffer zone (additional to existing shell)	2 significant reduction due to more efficient energy systems + new, high-performing building shell	2 significant reduction due to more efficient energy systems + new, high-performing building shell	2 significant reduction due to more efficient energy systems + new, high-performing building shell
increased user comfort	-1 no increase in user comfort, except via active systems	0 no significant increase in user comfort due to low-performing glazings	2 significant increase in user comfort due to improvement of insulation values of opaque and transparent wall surfaces	2 significant increase in user comfort due to improvement of insulation values of opaque and transparent wall surfaces	2 significant increase in user comfort due to improvement of insulation values of opaque and transparent wall surfaces	2 significant increase in user comfort due to improvement of insulation values of opaque and transparent wall surfaces	1 slight increase in user comfort due to improvement of otherwise "cold" surfaces	2 strong increase in user comfort due to significant improvement of otherwise "cold" surfaces	2 strong increase in user comfort due to significant improvement of otherwise "cold" surfaces	2 strong increase in user comfort due to significant improvement of otherwise "cold" surfaces
prolonged life span of building	-1 no prolonged life span of the building itself, only of energy systems	1 prolonged life span due to partly retrofitted building shell	1 prolonged life span due to partly retrofitted building shell	1 prolonged life span due to partly retrofitted building shell	2 significantly prolonged life span due to replacement of building shell	1 prolonged life span due to partly retrofitted building shell	1 prolonged life span due to improvement in thermal performance through additional layer	2 significantly prolonged life span due to completely new building shell	2 significantly prolonged life span due to completely new building shell	2 significantly prolonged life span due to completely new building shell
replicability and prefabrication	-1 not tackling the issue of poorly performing building shells	1 a systematic approach to retrofitting opaque wall surfaces presents a replicable solution to improve the thermal performance of smaller typologies in particular, while keeping the intervention low, though the size of prefabricated elements is restricted due to building geometry	1 a systematic approach to retrofitting opaque wall surfaces presents a replicable solution to improve the thermal performance of smaller typologies in particular, while keeping the intervention low, though the size of prefabricated elements is restricted due to building geometry	0 this approach presents a solution with medium replicability as it requires rather complicated logistics	1 a systematic approach to replacing prefabricated wall elements presents a replicable solution to improve the thermal performance of larger typologies in particular, though the size of prefabricated elements is restricted due to building geometry	0 this approach presents a solution with medium replicability as the degree of prefabrication of internal insulation is lower and the construction process is more complicated	2 buffer zones offer a highly replicable solution for larger typologies in particular, to improve their thermal performance while keeping the intervention low	2 a systematic approach to replacing non-load bearing wall elements presents a highly replicable solution for larger typologies in particular	2 a systematic approach to replacing non-load bearing wall elements presents a highly replicable solution for larger typologies in particular	2 a systematic approach to replacing non-load bearing wall elements presents a highly replicable solution for larger typologies in particular
feasibility	1,33	0,33	0,67	-0,67	-0,67	0,00	1,67	-1,33	-0,67	-0,67
compatibility with building use	2 highly compatible, no significant limitations in use	2 highly compatible, no significant limitations in use	2 highly compatible, no significant limitations in use (only short-term when vent-frames are changed)	-1 rather less compatible, limitations in use during replacement of external walls	-1 rather less compatible, limitations in use during replacement of external walls	0 medium compatible, short-term limitations in use during installation of internal insulation in specific area	2 highly compatible, no significant limitations in use	-2 less compatible, significant limitations in use during replacement of external walls and enlargement of indoor space	-1 rather less compatible, significant limitations in use during replacement of external walls	-1 rather less compatible, significant limitations in use during replacement of external walls
cost efficiency	0 small investment due to untouched building envelope, coupled with relatively low impact, resulting in a medium cost-efficient solution	0 medium investment coupled with medium high impact, resulting in a medium cost-efficient solution	1 medium investment coupled with relatively high impact, resulting in a cost-efficient solution	0 higher investment due to increased work hours coupled with relatively high impact, resulting in a medium cost-efficient solution	0 higher investment due to increased work hours coupled with relatively high impact, resulting in a medium cost-efficient solution	1 medium investment coupled with relatively high impact, resulting in a cost-efficient solution	1 medium investment coupled with rather high impact, resulting in a medium cost-efficient solution	0 high investment coupled with high impact, resulting in a medium cost-efficient solution	0 high investment coupled with high impact, resulting in a medium cost-efficient solution	0 high investment coupled with high impact, resulting in a medium cost-efficient solution
low complexity of technical solution	2 very low complexity due to untouched existing structure	-1 rather high complexity due to various different joints to adjacent building components (e.g.balconies)	-1 rather high complexity due to various different joints to adjacent building components (e.g.balconies)	-1 rather high complexity due to various different joints to adjacent building components (e.g.balconies)	-1 rather high complexity due to various different joints to adjacent building components (e.g.balconies)	-1 rather high complexity due to various different joints to adjacent building components or installations	2 very low complexity due to untouched existing structure and independent design of second skin	-2 high complexity, as balcony zone becomes indoor space and position of thermal envelope changes	-1 rather high complexity, as large intervention is required as preparatory work (removal of balconies)	-1 rather high complexity, as large intervention is required (removal and reinstallation of balconies)

(b)

sustainability & circularity	1,20	0,60	0,40	0,40	-0,20	0,20	1,00	0,00	0,00	0,00
prioritised use of existing structures	2,00 all ressources remain bound in the existing structure	0,00 most of the ressources remain bound in the existing structure, parts of the envelope are replaced	0,00 most of the ressources remain bound in the existing structure, parts of the envelope are replaced	0,00 most of the ressources remain bound in the existing structure, parts of the envelope are replaced	-1,00 parts of the ressources remain bound in the existing structure, but whole envelope is replaced	0,00 most of the ressources remain bound in the existing structure, parts of the envelope are replaced	2,00 all ressources remain bound in the existing structure	-1,00 parts of the ressources remain bound in the existing structure, but whole envelope is replaced	-1,00 parts of the ressources remain bound in the existing structure, but whole envelope is replaced	-1,00 parts of the ressources remain bound in the existing structure, but whole envelope is replaced
avoidance of carbon intensive ressources/materials	2 no new material required in building	1 medium amount of new material required, many low-carbon options available (e.g wood-fibre insulation + timber facade)	0 medium amount of new material required, many low-carbon options available (e.g wood-fibre insulation + timber facade) for opaque surfaces, but new glazing with high embodied energy required	0 medium amount of new material required, many low-carbon options available (e.g wood-fibre insulation + timber facade) for opaque surfaces, but new glazing with high embodied energy required	-1 significant amount of new material required, partly low-carbon options available (for opaque surfaces)	0 medium amount of new material required, many low-carbon options available (e.g wood-fibre insulation + timber facade) for opaque surfaces, but new glazing with high embodied energy required	-1 medium amount of material required, few low-carbon options available as second skin needs to be translucent (reuse might be one option)	-1 significant amount of new material required, partly low-carbon options available (for opaque surfaces)	-1 significant amount of new material required, partly low-carbon options available (for opaque surfaces)	-1 significant amount of new material required, partly low-carbon options available (for opaque surfaces)
low waste production	2 no waste production	1 low waste production	1 low waste production	1 low waste production	-1 rather high waste production	1 low waste production	2 no waste production	-1 rather high waste production	-2 high waste production	-2 high waste production
longevity / robustness of technical solution	0 no change in longevity / robustness of existing building, no modernisation of aging components apart from energy systems	0 medium robust solution due to components of varying performance (e.g. new wall - old glazing)	0 medium robust solution due to components of varying performance (e.g. new wall - old window frame)	0 medium robust solution due to components of varying performance (e.g. new wall - old window frame)	1 rather robust solution through renewal of complete envelope, only constrained by potentially difficult joints	-1 rather less robust solution due to due to the 'vulnerable' design in terms of building physics (internal insulation)	1 rather robust solution through separation of different systems	1 rather robust solution through renewal of complete envelope, only constrained by retrofitted balconies as indoor spaces	2 very robust solution through renewal of complete envelope	2 very robust solution through renewal of complete envelope
future adaptability	0 no improvement of adaptability	1 slight improvement of adaptability through anticipation of non-destructive disassembly of added components	1 slight improvement of adaptability through anticipation of non-destructive disassembly of added components	1 slight improvement of adaptability through anticipation of non-destructive disassembly of added components	1 slight improvement of adaptability through anticipation of non-destructive disassembly of added components	1 slight improvement of adaptability through anticipation of non-destructive disassembly of added components	1 slight improvement of adaptability through anticipation of non-destructive disassembly of added components, and through clear separation of added parts from existing structure	2 significant improvement of adaptability through simplified geometry and anticipation of non-destructive disassembly of added components	2 significant improvement of adaptability through simplified geometry and anticipation of non-destructive disassembly of added components	2 significant improvement of adaptability through simplified geometry and anticipation of non-destructive disassembly of added components
building appearance	0,67	0,00	0,00	0,00	0,00	0,33	0,33	-1,00	-1,00	0,00
preservation of original appearance	2 original appearance remains untouched	1 original appearance slightly altered, mainly in terms of materiality	1 original appearance slightly altered, mainly in terms of materiality	1 original appearance slightly altered, mainly in terms of materiality	1 original appearance slightly altered, mainly in terms of materiality	2 original appearance remains untouched from the outside	-1 original appearance hidden between second skin, but still perceivable in buffer zone	-2 original appearance no longer perceivable, even though facade design could take up original proportions	-2 original appearance no longer perceivable, even though facade design could take up original proportions	1 original appearance slightly altered, mainly in terms of materiality
'readability'/design approach	0 no design	-1 mix of new and existing with rather low readability	-1 mix of new and existing with rather low readability	-1 mix of new and existing with rather low readability	-1 mix of new and existing with rather low readability	0 no alteration / no readability from outside, internal facade less 'important' in this case	2 clear separation between new and existing with high readability	0 medium readability, clear cut between new and existing, but only new facade perceivable from outside	0 medium readability, clear cut between new and existing, but only new facade perceivable from outside	-1 mix of new and existing with rather low readability
quality of spaces / lighting	0 indoor and outdoor spaces like originally planned	0 indoor and outdoor spaces like originally planned	0 indoor and outdoor spaces like originally planned	0 indoor and outdoor spaces like originally planned	0 indoor and outdoor spaces like originally planned	-1 some minor loss of indoor area	0 quality of indoor space potentially decreased due to reduced lighting, outdoor space slightly improving due to weather protection	-1 indoor spaces larger than originally planned, reduction in lighting due to increased room dimensions, outdoor spaces no longer available	-1 indoor spaces like originally planned, outdoor spaces no longer available	0 indoor and outdoor spaces like originally planned

(c)

Figure A9. Evaluation matrix for the timber-reuse retrofitting scenarios.

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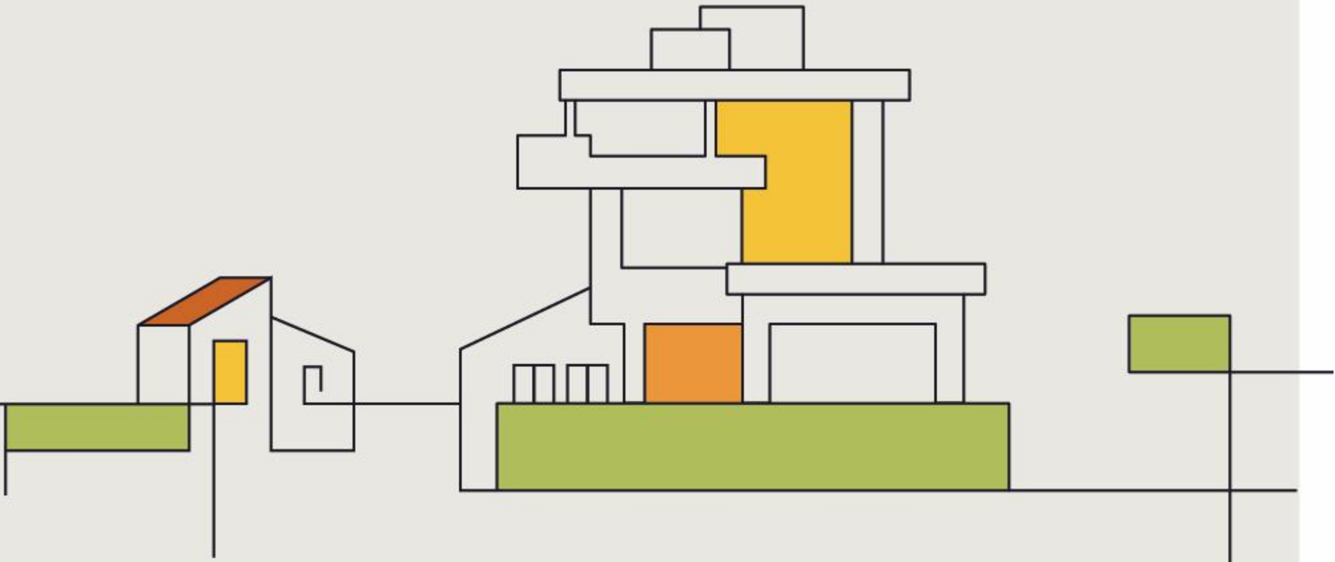

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