



D13 PROTOTYPING + FEEDBACK REPORT

Testing BAMB results through prototyping and Pilot Projects



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 642384.



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Acronyms and abbreviations used

List of project beneficiaries (complete and shortened names)

IBGE-BIM	Brussels Environment
EPEA	EPEA Nederland B.V.
VITO	Vlaamse Instelling Voor Technologisch Onderzoek N.V.
ZUYD	Stichting Hogeschool ZUYD
VUB	Vrije Universiteit Brussel
Ronneby	Ronneby kommun
TUM	Technische Universität München
UTwente	Universiteit Twente
UMinho	Universidade do Minho
SGDF	Sarajevo Green Design Foundation

Pilot Projects

GTB Lab	Green Transformable Building Lab
REM	Reversible Experience Modules ()
GDC	Green Design Centre
CRL	Circular Retrofit Lab

Acronyms

BAMB	Buildings As Material Banks
BIM	Building Information Modelling
D	Deliverable
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCCA	Life Cycle Costing Analysis
MP	Material Passport
MPP	Materials Passports Platform
PCT	Project Coordination Team
SN	Stakeholder Network
WP	Work Package
WP1	Developing a blueprint for dynamic and circular buildings and materials upcycling
WP2	Developing Materials Passports and corresponding database & platform
WP3	Developing Reversible Building Design tools for dynamic and circular buildings
WP5	Facilitating future applications and exploitation of BAMB results



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1 INTRODUCTION

1.1 GENERAL INTRODUCTION BAMB

Within the BAMB Project – Buildings As Material Banks – 16 partners from 7 European countries are working together with one mission-enabling a systemic shift in the building sector by creating circular solutions.

Today, building materials end up as waste when no longer needed, with effects like destroying eco-systems, increasing environmental costs, and creating risks of resource scarcity. To create a sustainable future, the building sector needs to move towards a circular economy.

Whether an industry goes circular or not depends on the value of the materials used – worthless materials are waste, while valuable materials are recycled. Increased value equals less waste, and that is what BAMB is creating – ways to increase the use of valuable building materials and construction systems.

BAMB will enable a systemic shift where dynamically and flexibly designed buildings can be incorporated into a circular economy. Through circular design and value chains, materials in buildings sustain their value. Instead of being to-be waste, buildings will function as banks of valuable materials – slowing down the usage of resources to a rate that meets the capacity of the planet and producing less waste.

In order to maximize the BAMB project's innovation potential, dissemination impact and stakeholder involvement, practical real-life examples are vital to test and demonstrate the project outputs in various settings.



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The reversible building design approach, the implementation of Materials Passports and new business models for circular material value chains developed in BAMB are being tested in **pilot cases within the work package 4 (WP4)**. The pilot cases investigate and demonstrate new design, manufacturing, construction and maintenance approaches for dynamic and circular buildings. The whole pilot development process should raise awareness about the opportunities at hand to capture more value from resources while offering a better, more livable built environment to the users.

The work package 4 “Testing BAMB Results Through Prototyping And Pilot Projects“ foresees a three steps sequence: the pilot projects’ feasibility study, the prototyping and finally, the construction of the pilots (see Figure 1). The results are disseminated in three reports: (1) the feasibility study (D12), (2) **the current report (D13) describing the manufacturing of prototypes and providing feedback**, and (3) the report on the built pilots (D14) which will contain the results of the construction of two pilots.

Prototyping key elements of the pilot projects is an essential first step to materialize, test and improve building elements and systems to maximize impact on the building’s circularity.

The goal is to see how certain building products and systems (existing, improved or newly designed) can be transformed and disassembled with minimum waste production and limited use of natural resources through improved reuse, refurbishment and recycling.

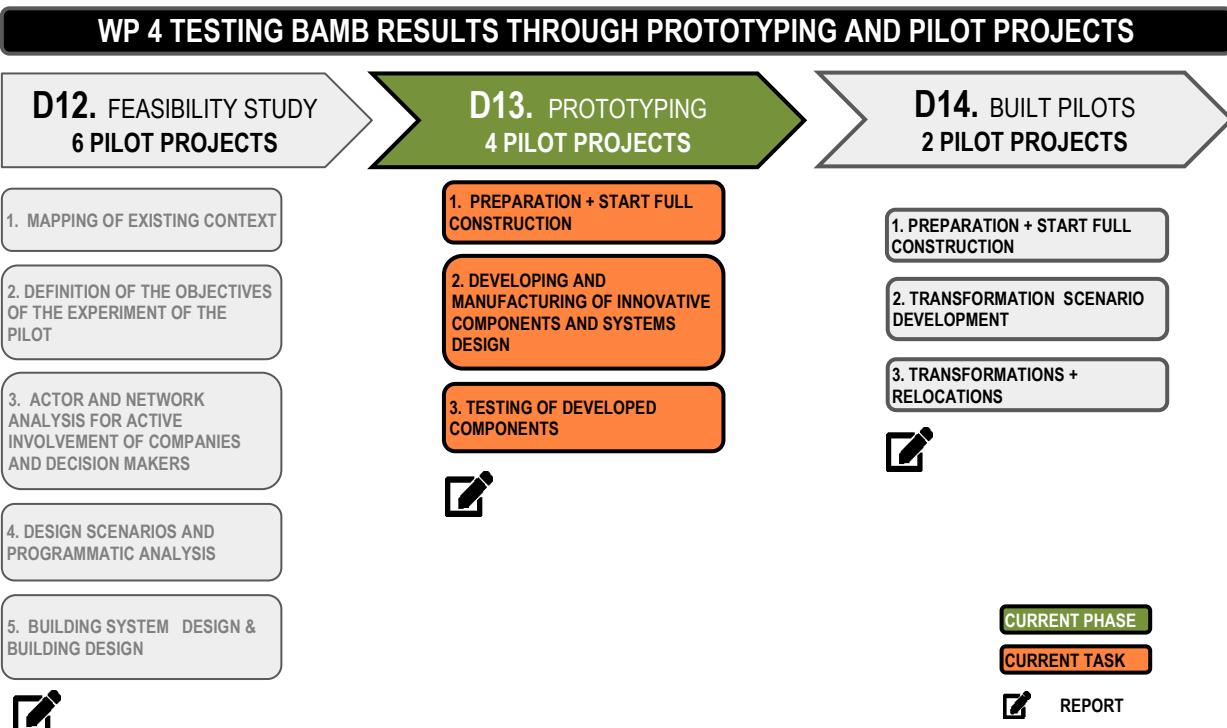


Figure 1: Overview of the pilot projects and prototyping BAMB actions



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1.2 PROTOTYPING AND FEEDBACK REPORT OF PILOT PROJECTS (D13)

The objective of the present **report** is to provide an overview of the essential insights and outcomes of the prototyping development phase. This information is gathered **from the four pilot prototyping studies provided by Pilot Project Leaders**. Conceived as a synthesis, the D13 report focusses on BAMB's essential goals regarding innovations, the identification of lessons learned and recommendations that emerged from the process. This experience will be further built upon for the construction of the pilot projects.

The responsible partner and author of the present report is Brussels Environment. EPEA, Zuyd, VUB and SGDF are involved as partners in charge of the **pilot projects and prototyping studies**. The report is structured around the following chapters:

1. Description of the Pilots and its Prototyping

This chapter provides a short overview of the prototyping **process**, the sequencing of tasks and the way prototyping **studies** were led.

A brief description of each pilot project's purpose helps to present the prototypes in their specific context. Each prototype is identified and briefly introduced. The chapter is accompanied by a synthesis of the selection criteria adopted by each developed product. A detailed description of the pilot project is available in the D12 report “Feasibility Study+ feedback report”, to which we refer the reader for further information.

2. Innovations & Optimization:

This chapter addresses an analysis of the innovative strategies developed by each team. It is followed by a description of technical measures and actions put in place in order to optimize these prototypes. Out of eight prototypes, GTB Lab and CRL (prototype 1) are selected and detailed for their reversibility achievements. GDC will be used to highlight research on materials, whereas REM is the best placed to illustrate material passports development.

3. Stakeholders: An Overview of the Involved Stakeholders and their Contributions

A circular economy involves a process-based approach. The interaction with stakeholders during the development of the prototypes, the co-creative aspects and the upfront intervention of actors traditionally positioned at the end of the value chain are highlighted in this chapter.

4. Environmental and Financial Assessment

Quantitative criteria allow for the continuous evaluation of the achievements related to the initial objectives (e.g. reduction of waste, CO₂ emission, etc.)

5. Business Models Circular Opportunities

6. The chapter highlight important aspects addressed during the prototyping, such as ownership transfer, leasing versus purchasing, and changes in the value chain.

7. Lesson Learned

8. Conclusions



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2 DESCRIPTION OF PILOT PROTOTYPING

Based on the feasibility report (D12), construction components have been selected to be designed and developed for prototyping. The selected construction components were either isolated key construction elements (e.g. structural profiles), building systems (e.g. walls), or a combination of physical and digital systems meant to increase synergies between data interfaces and (re)use opportunities. The scope of prototyping is to test the frameworks and tools investigated in the feasibility report concerning **Material Passports and Reversible Building Design**.

This prototyping phase concerns four of the six pilot projects (see table 1). A prototyping study and a feedback report have been submitted to Brussels Environment (WP4 leader) by:

Pilot	Leading Partner	Action code	Deliverable code
Green Transformable Building Lab (GTB Lab)	ZUYD	A1	D13.1
Reversible Experience Modules (REM)	EPEA	A2	D13.2
Green Design Centre (GDC)	SGDF	A3	D13.3
Circular Retrofit Lab (CRL)	VUB	A4	D13.4

Table 1: An overview of the prototyping pilot projects

The prototyping studies made by each team specify the sequencing of the tasks and process needed for the development. Each team had to pre-define and select the prototypes, provide design concepts and technical details, manufacture the prototypes, evaluate, give feedback and optimize the prototypes.

Moreover, the studies highlight the evolution associated with the previous deliverable D12 “Feasibility Study + feedback report”. They highlight the development of design plans for prototyping and the integration of conclusions issued during technical preparations.

Each team developed detailed plans for the execution of the prototypes and provided an explanation of the processes related to the manufacturing. The assessment of the manufacturing process is an integral part of prototyping, and allows for redesign and improvements.

In order to ensure coherency throughout the BAMB project and alignment with the circularity vision and objectives, the feedback report provides important takeaways related to lessons learned, process analysis, waste and environmental assessments. It also provides feedback on specific aspects regarding materials passports, reversible building design, and future applications of BAMB tools, such as the circular building assessment tool.



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Figure 2: Location of the pilot projects

- 1 GTB Lab, Green Transformable Building Lab, Heerlen, The Netherlands
- 2 REMs, Reversible Experience Modules, prototype realized in Eindhoven, The Netherlands,
REMs pilot traveling exhibition module
- 3 CRL, Circular Retrofit Lab – Brussels, Belgium
- 4 GDC ,Green Design Center – Mostar, Bosnia Herzegovina



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PILOT PROJECT		PILOT PROTOTYPE (S)				
1 GTB Lab 	GTB Lab Profile PROTOTYPE 1 					
2 REMs  <div style="border: 1px solid green; padding: 5px; width: fit-content; margin-left: auto; margin-right: 0;">REM MODULE PILOT PROJECT</div>	PROTOTYPE 1 MODULE REMs  <div style="border: 1px solid green; padding: 5px; width: fit-content; margin-left: 20px;">OCTANORM STRUCTURE</div> <div style="border: 1px solid green; padding: 5px; width: fit-content; margin-left: 20px;">HUNTER DOUGLAS PANELS / CEILING</div> <div style="border: 1px solid green; padding: 5px; width: fit-content; margin-left: 20px;">FABER EXPOSE PRINT PANELS</div> <div style="border: 1px solid green; padding: 5px; width: fit-content; margin-left: 20px;">DESSO CARPET</div> <div style="border: 1px solid green; padding: 5px; width: fit-content; margin-left: 20px;">BSW LIFT OFF HINGE</div> <div style="border: 1px solid green; padding: 5px; width: fit-content; margin-left: 20px;">AMI DOOR HANDLE</div>      					
3 CRL 	GEBERIT PROTOTYPE 1  SAINt GOBAIN PROTOTyPES 2,3  Wall inQ PROTOTYPE 4  SYSTIMBER PROTOTYPE 5 					
4 GDC 	WALL PROTOTYPE 1   					

Figure 3: An overview of the pilot projects and their associated prototype products



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2.1 GREEN TRANSFORMABLE BUILDING LAB (GTB Lab)

2.1.1 Pilot concept

The Green Transformable Building Lab (GTB Lab) is an innovation center for dynamic and circular buildings; a testing and demonstration place in Heerlen, the Netherlands. The GTB Lab is foreseen as a flexible and evolving structure organized around a steel frame structural grid. The construction will be transformed once a year.

2.1. Green Transformable Building Lab (GTB Lab)

- Focus:
- Reversible Building Design supporting the transformation in shape, size and function.
 - Investigation of business model needs and requirements of the local stakeholders

Type: New Construction

Size: minimum size: 150 m²; maximum size: 1200 m²

Function: Initial: multifunctional space that can adjust to changing daily activities from work lounge to meeting space and lecture hall, and 1 housing unit.

After the 1st transformation: Offices and housing

Country: The Netherlands

Location: IBA2020, Heerlen NL

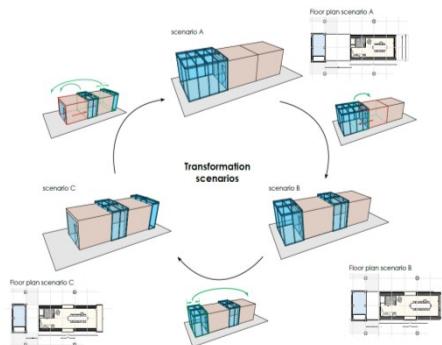


Figure 4 GTB Lab transformation scenarios



Figure 5: GTB Lab transformation scenarios. The maximum scenario imagines the addition of two extra floors to the initial module . Half of the ground floor module can be disassembled and reused on the upper floors.



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2.1.2 Prototype

The GTB Lab focuses on a new steel profile prototype and its corresponding connections.

The aim is to create “**a reference element**” for reversible buildings - a universal steel profile which can be used both as an element of the GTB Lab structural grid and/or as part of the exterior wall system. The multiple functions of the profile would allow its integration at different levels of building configuration. For example, the profile could be used as a base for a movable sun shading panel, a reversible connection of different parts of the building (e.g. partitioning wall, façade, cantilever, ceiling) fully independent of other connections and elements. The profile is called the **GTB Lab Profile**.

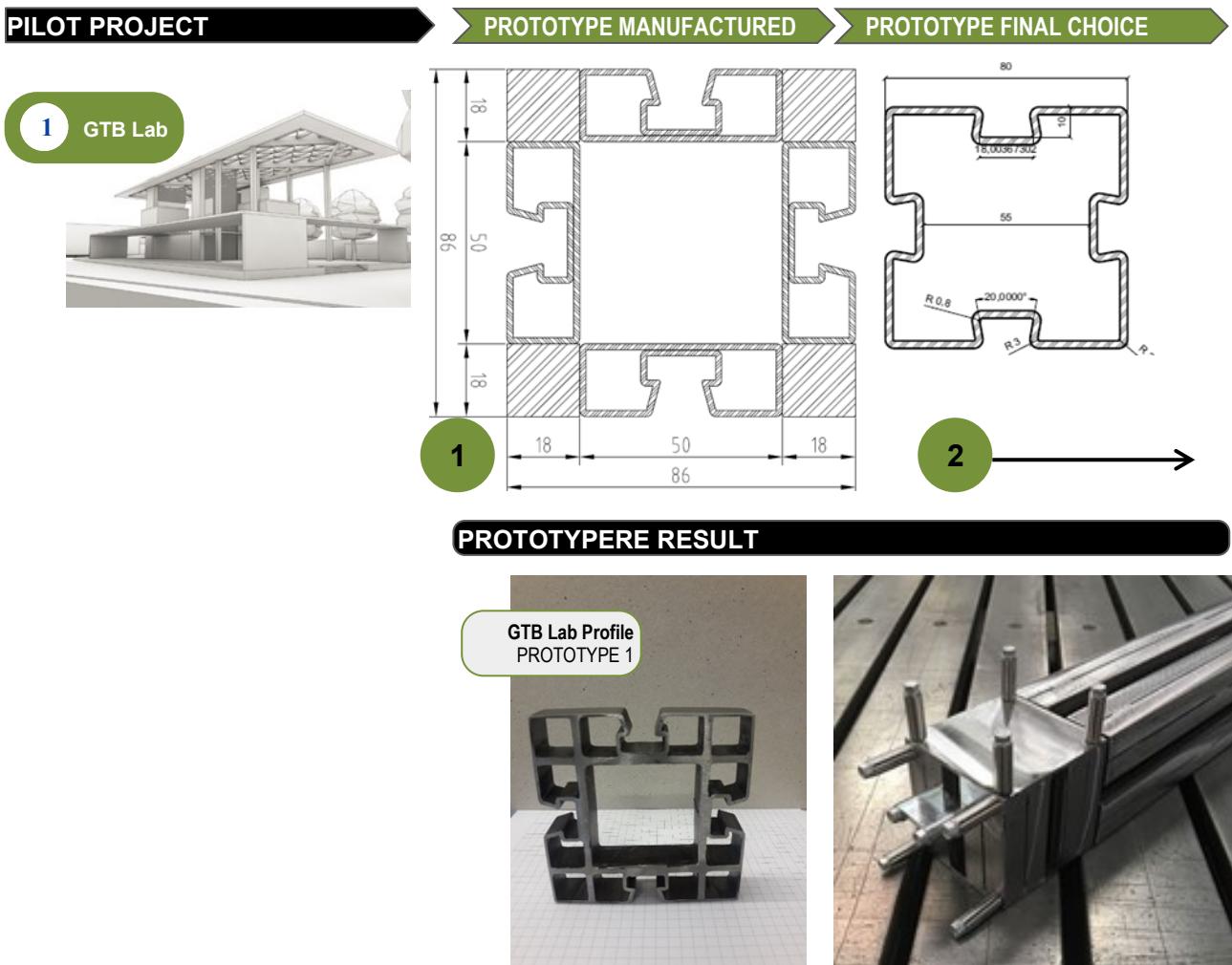


Figure 6: Evolution of the prototype profile + connections



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2.2 REVERSIBLE EXPERIENCE MODULES (REMs)

2.2.1 Pilot concept

The Reversible Experience Modules (REMs) exhibition displays 70 products and systems designed for reuse, recovery and recycling, available on the market today. Together, they form an integrated exhibition showcasing how to realize adaptable, modular and circular buildings. Each material and product in the REM exhibition is labeled with a Materials Passport. This provides information on the circular potential of products, systems and buildings. Inside the exhibition, each product on display, in combination with its passport can be considered a single reversible experience module.

2.2 THE REVERSIBLE EXPERIENCE MODULES (REM)

Focus:

- Materials Passports: The Pilot Project will enable experiencing the use of Materials Passports by providing access to the Materials Passports Platform and the Materials Passports of the different construction products used in the project. It will also invite visitors to physically reconstruct and rearrange the exhibition area, guided by the Materials Passports.
- Reversible Building Design: The Pilot Project can be disassembled and reassembled in different locations and according to different floorplan configurations.

Type:

New Construction

Size:

minimum size: 2m²; maximum size: up to 100m²

Function:

Exhibition

Country:

European countries

Location:

Travels to different locations

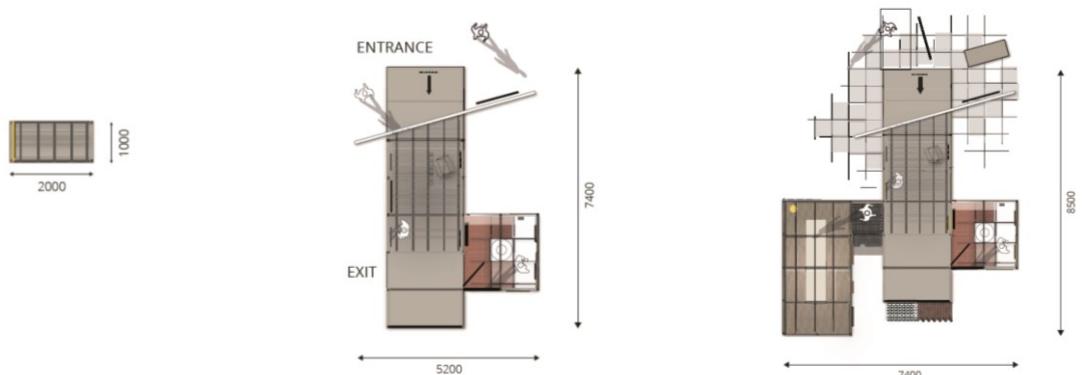
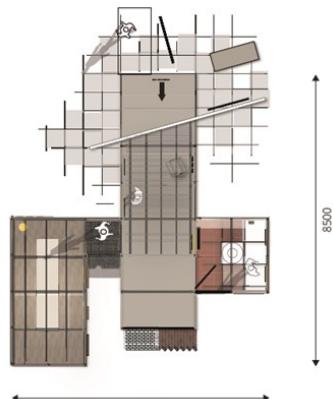


Figure 7: REM base module (2m²) - medium floorplan (38,5m²) - large floorplan (63m²)



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2.2.2 Prototype



Various aspects of the REMs expo have been tested with a prototype to ensure the technical feasibility of the interactions with the materials passports and the multiple build-ups of the main construction. For the consistency of the concept, the interface between the REM modules, the panels, and the aluminum construction frame have also been tested to ensure the durability of the structural integrity of the expo for over a year.

A part of the hallway unit is prototyped, as it combines floor, wall and ceiling elements and three basic modules. The elements composing the prototype are (1) Octanorm Aluminium profiles for wall construction, (2) Octanorm Aluminium ceiling construction, (3) birch panels for printing visual REM modules (1piece), (4) Hunter Douglas Heartfelt ceiling, (5) Desso carpet tiles, (6) BSW lift-off hinges, (7) AMI doorhandle (see Figure 9)

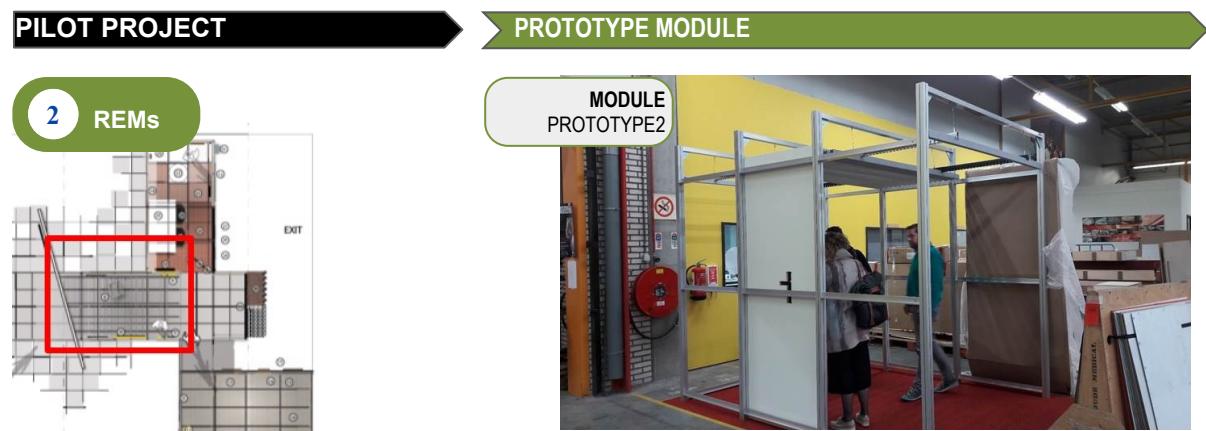


Figure 8: Prototype of REM - part of the hallway unit

PROTOTYPE ELEMENTS AND RESULTS



Figure 9: Elements tested by prototyping



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2.3 GREEN DESIGN CENTER (GDC)

2.3.1 Pilot concept

The Green Design Center (GDC) is a refurbishment of an old military storage unit and will become an innovation hub bringing creative and production industries together around Reversible Building Design concepts. The development of integrated architectural and technical solutions will support both the reversibility of the building function and its structural configuration, without waste generation. It will consist of a multi-purpose and demountable/replaceable structure. GDC will be used for educational purposes and as a construction innovation platform.

2.3 Sarajevo Green Design Centre

Focus:	<ul style="list-style-type: none"> • Reversible Building Design supporting the transformation in size and internal floor plan • Investigation of business model needs and requirements of the local stakeholders participating in the project
Type:	Refurbishment



Figure 10: Existing situation GDC

Size	minimum size: 180 m ² ; maximum size: to 250m ²
Function:	Exhibition and office space



Figure 11: Future situation GDC

Country:	Bosnia and Herzegovina
Location:	Mostar



Figure 12: Facades and sections – two of the possible transformation scenarios



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2.3.2 Prototype

The prototype consists of an interchangeable module which can be replaced and adjusted to different requirements of the façade in the future.

The prototype of GDC is addressing the issue of **reversible façade design** based on the high reuse potential of building elements and components. The project integrates energy efficiency as a selection criterion. The prototype concept is driven by a sustainable approach such as the use of local materials, such as wood and sheep wool.

The project tackles the challenge of an energy efficient retrofitting. The refurbishment of the existent building stock involves both upgrading the façade system and adapting to new functional requirements related to light, comfort, ventilation aesthetics, etc.

The prototype seeks to integrate flexible technical solutions upfront into the design process of highly energy efficient facades. It is anticipated that the use of the prototype will result in reducing waste created by way of demolition or the purchase of new materials.

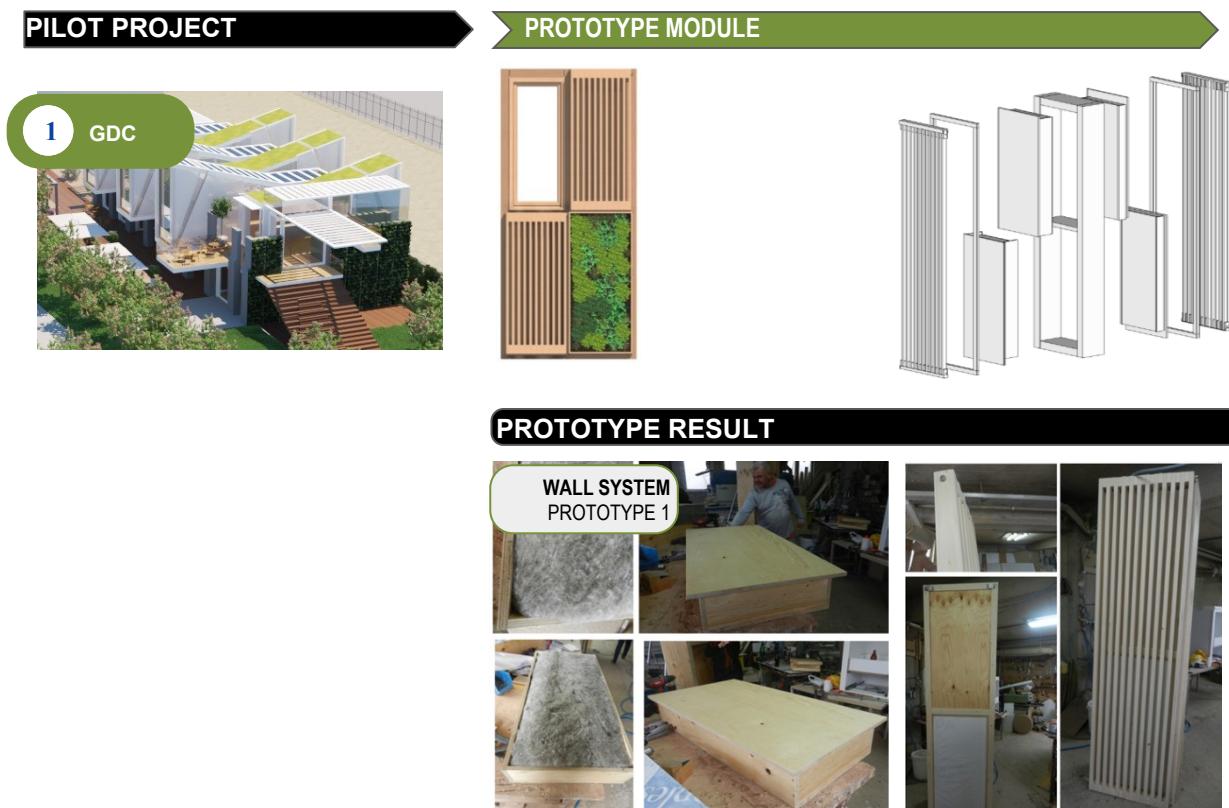


Figure 13: GDC Reversible Building Façade prototype



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2.4 CIRCULAR RETROFIT LAB (CRL)

2.4.1 Pilot concept

The pilot proposal builds on a preliminary explorative study evaluating different scenarios for the reuse and refurbishment of the VUB Campus' prefabricated student housing, without generating a large amount of waste. The study includes a life cycle impact comparison. Three transformation strategies are explored: internal transformation, external transformation and the module's reconfiguration (Figure 13). Only the internal transformation is part of BAMB.

Depending on their expected rate of change in the floor plan, three different types of interior walls are defined: high rate of change (type 1), high degree of flexibility for the integration of technical infrastructure (type 2), and low rate of change (types 3&4), see Figure 14 .

2.4 Circular Retrofit Lab

Focus:	Reversible Building Design supporting the transformation of the internal floorplan and facade Investigation of business model needs and requirements of the local stakeholders participating in the project
Type	Refurbishment
Size:	200 m ²
Function:	First floor: Housing (1nd Scenario) Office space (2nd Scenario) Ground floor: Dissemination Space BAMB results
Country:	Belgium



Figure 12: existing situation

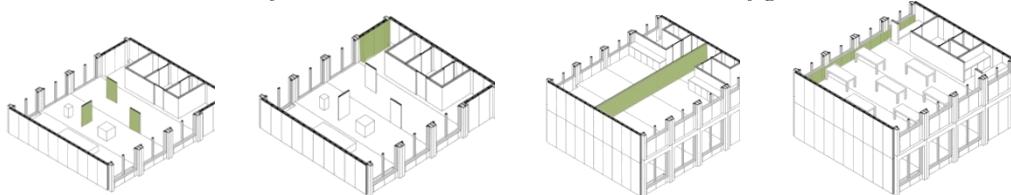


Figure 13: future situation

Location: Brussels (VUB University Campus)



Figure 13 CRL the internal transformation; the external one and the module reconfiguration



TYPE 1
HIGHER RATE OF CHANGE

TYPE 2
HIGH TECHNICAL FLEXIBILITY

TYPE 3
INTERMEDIATE RATE OF CHANGE

TYPE 4
LOW RATE OF CHANGE

Figure 14: Different types of walls related to the change rate



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2.4.2 Prototype

The four prototypes developed by the CRL leverage existing products.

CRL uses existing products that have a high potential to reach circularity objectives as envisaged within BAMB. Together with the concerned industry stakeholders, two wall systems, existing on the market, were transformed into reversible systems and compared with two other reversible partition systems. The final objective of this exercise is to create a catalogue of different partition walls adaptable to different contexts, user needs, economic conditions, and functional requirements.

The wall systems tested within the CRL are the following :

The Geberit GIS system was developed by Geberit for prefabrication of sanitary facilities. By adapting and adding elements to Geberit GIS (P1), CRL focus on the development of a kit of parts for flexible and multifunctional solutions.

The Saint-Gobain: Two products are selected, compared and evaluated: (P2) a preassembled, wood frame system provided with demountable gypsum plasterboard cladding (Gyproc); and (P3) a former product, a flexible and reusable wall system composed of metal-stud profiles covered with two layers of plasterboard.

Wall-linQ suited for a lower rate of change, Wall-linQ (P4) is a wall assembly, combining the benefits of drywall with a low environmental impact of cardboard frames. It offers a lower environmental impact and interesting financial solution.

Systimber (P5) is a prefabricated interior and/or exterior wall and floor realized by laminated wooden beams/columns that are connected by a metal bolt system. The system will be compared with the other enumerated products.

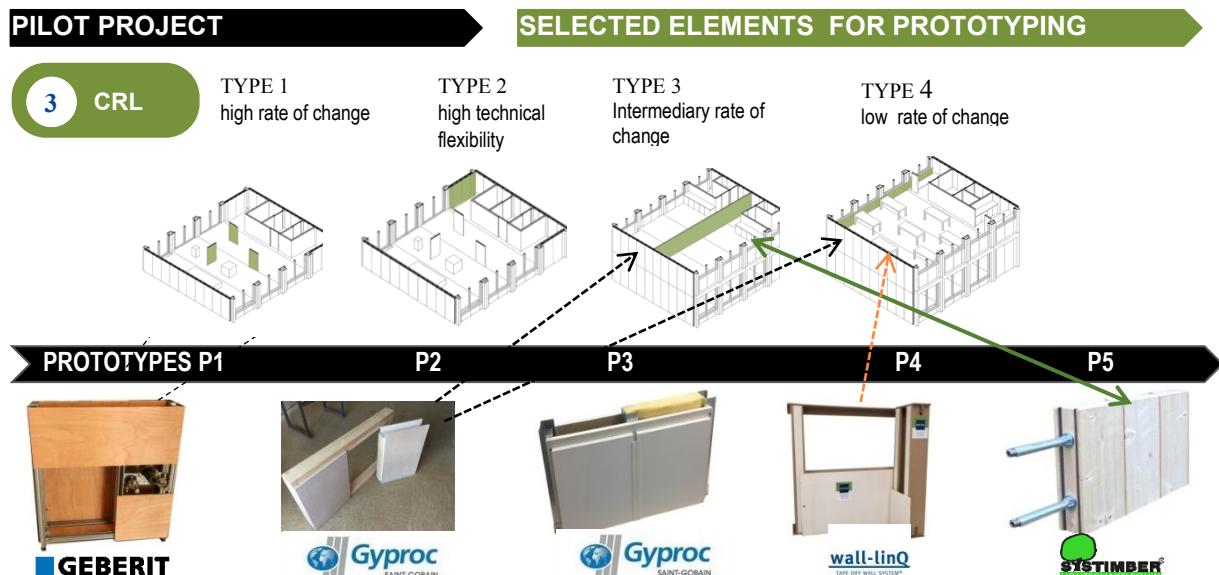


Figure 15: The prototypes and their utilization related to the three types of walls



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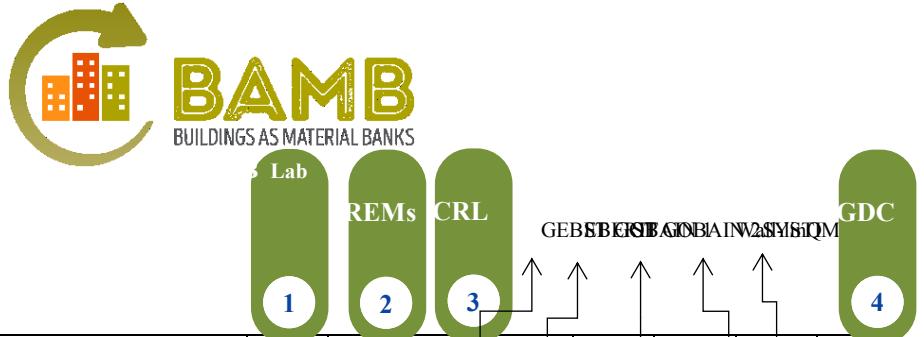
2.5 SELECTION CRITERIA

The drivers behind the selection and improvements of the prototypes are strongly linked with the global objectives of the pilot projects and BAM^B objectives regarding the material passports and the reversible building design. The analyses of the four studies revealed a list of a thirteen criteria (see Table 2), all of them related to the concepts developed by on-going work within BAM^B (WP2 and WP3). The relevance of the criteria to the prototypes is indicated in table 2 which summarise the studied aspects. The table highlights which criteria are addressed, are respected, which are subject to improvements of the prototypes and which are not met. The focus area of each project is explained in detail below:

1. The **GTB** Lab prototype considers **four** of the Reversible Building Design Criteria: the separation of functions, the design of intermediary elements, the geometry, and the connections (design and the outer parts of the product enabling the connections). The project will test the simplicity of the (dis)assembly, reuse and damage sensitivity, the connection's aesthetics and their dimensional tolerances.
2. The **REMs** prototype uses eight criteria of selection. It seeks to test the capacity of the REMs units to be built-up and dismantled by effective means (being manipulated by two people). Testing the strength of the connections between basic modules (each product on display, in combination with its passport) ensures the integrity of the whole concept of reversibility. The capacity to rearrange the basic modules in different floor-plans requires the usage of reversible connection of the panels and the reversibility of the connections of the ceiling systems. Criteria concerning the material passports are related to the interaction between the mobile devices and the passports platform. Nonetheless, the REM pilot project is an exhibition- **an important tool for communication** on circular building concepts. The way products are exhibited and the readability of visuals (explanations about REMs) are important criteria, see chapter 2.2.
3. The **CRL** has a different approach. The selection process emerged from an observation estimating the rate of change of building elements during a building lifecycle. Considering that different zones/spaces of a building plan have a different turnover rate, the prototyping project has identified 4 wall types in relation to their estimated rate of change during a building lifecycle. Additionally, 10 out of the 13 already mentioned criteria were used to identify the necessary requirements for transformation.
4. The **GDC** focusses on assembly, disassembly and reassembly of the facade systems without damaging construction elements. Easy manipulation, connections strength, and the simple geometry of elements are the key issues addressed during the prototyping process.



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			P1	P2	P3	P4	P5		
1	Reversible connections	✓	✓	✓	✓			✓	✓
2	The speed of assembly/disassembly (e.g. preassembly, fast connection techniques, etc.) the simplicity	✓	✓	✓	✓			✓	✓
3	Use and reuse of reclaimed building materials (e.g. recuperated finishing panels, profiles, etc.)			✓					✓
4	Sensitivity to damage (strengthen elements)	✓	✓	✓	✓				✓
5	Aesthetic of the structural element (connections)	✓		✓	✓	✓		✓	✓
6	Acoustic comfort	✓		✓		✓	✓	✓	
7	Flexible integration of technical systems			✓	✓	✓	✓		✓
8	Independence of the system (e.g. can one part be replaced?)	✓	✓	✓	✓				✓
9	Low initial cost	✓		✓	✓	✓	✓		✓
10	Low initial environmental impact	✓			✓	✓	✓		✓
11	The kit of parts: possibility to demount and reuse (e.g. standardization) dimensional tolerances			✓	✓	✓		✓	✓
12	High energy efficiency	✓							✓
13	Physical interaction with the digital Materials Passports Platform		✓						

Table 2: Selection criteria related to technical requirements



Improvement possibility



Criteria fulfilled



Criteria not fulfilled (initially)



Criteria not addressed (as mentioned before, each pilot concentrated on a focus area or research)



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 642384.



3 INNOVATIONS AND OPTIMIZATION

In order to design and build/refurbish more reversible buildings, the four pilot projects are addressing different strategies. Identifying these strategies helps to understand the technical requirements necessary to develop the prototypes and the process behind the transformations needed to achieve circularity.

Technological choices and innovation driven by circular economy values are affecting the whole product ecosystem. Therefore, technological aspects should be continuously assessed and coupled with the preoccupation for new market opportunities and needs, new types of stakeholders' interactions, the redefinition of partnership and ownership, the identification of new operational and financial principles, the integration of new steps and actions within the production process, the preoccupation about policies and regulation, and so on.

This chapter presents the technical transformations applied to each prototype. It calls for a holistic approach and advocates for a process-based mind-set when tackling technical aspects. Within this product ecosystem, one should bear in mind that even a small and simple improvement such as the use of a simple connection, or the involvement of a key stakeholder in a specific stage, might generate considerable innovation within a circular value network.

3.1 INNOVATION STRATEGIES TOWARDS A REVERSIBLE DESIGN CONCEPT

The innovation strategies developed by the four pilot projects are the following:

Completely switching

GTB Lab and GDC prototypes have adapted a disruptive approach related to the development of their projects. This means the prototypes investigate the development **of entirely new products**. Through a trial and error method, both projects look forward to improving the circularity value proposal of their product. This approach involves several steps and technical improvements loops. In order to understand these cases better, the example of the **GTB Lab profile** will be detailed.

Using cross-sectoral experience

The REMs showcases the use of a cross-sectoral experience. Being an exhibition module, it uses reversible construction systems conceived for optimized multiple use. This experience has the potential to be transferred from exhibition building to other construction sectors, e.g. partition walls for residential, commercial, medical, etc. through prototyping, the REMs team aims to improve the interaction between materials passports and reversible building design (see chapter 3.6).

Step by step improvement

The CRL project relies on existing models and products. Products already existing on the market offer the advantage of technically and commercially viable projects. In this framework, the design team focused only on the reversibility aspects and the improvements of the elements that did not fit the BAMB criteria. For a better understanding of the potential of this strategy, the example of the GIS (P1) prototype will be detailed.



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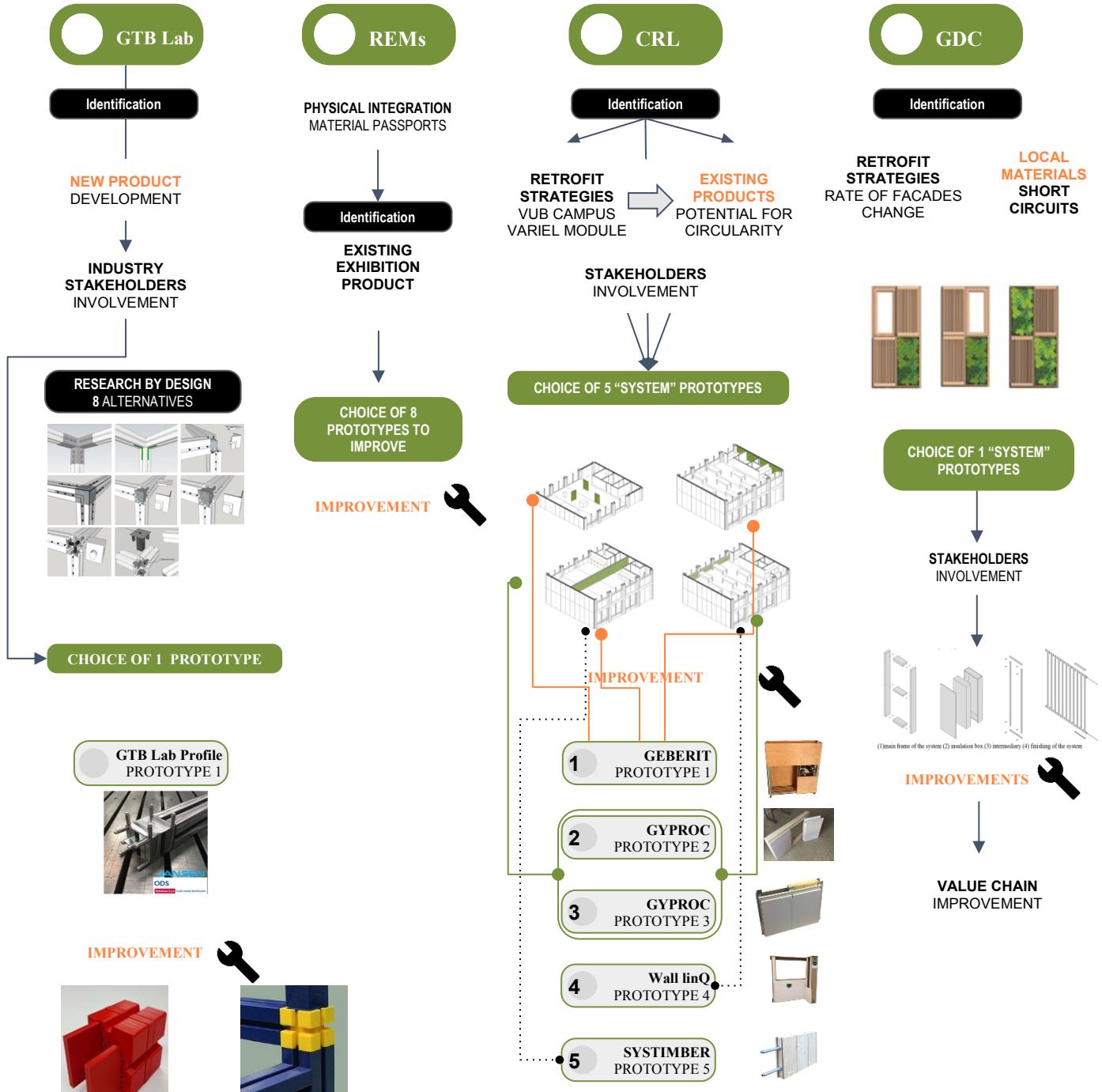


Figure 16: Innovation strategy and the impact on the process and on the prototype development



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3.2 TECHNICAL REQUIREMENTS FOR TRANSFORMATION, IMPROVEMENTS AND ADAPTATIONS

In order to achieve the technical criteria (table 2) for a circular project, the **GTB Lab** focusses on the development of a steel profile and on the development of primary and secondary connections between profiles. The project uses research by design in order to identify the best technical solution to be materialized. The development, improvements and adaptations of the prototype are described in Chapter 3.4.



Figure 17: Manufacturing of the GTB LAB metal profile (P1)

The **REMs team** concentrates its attention on increasing the reliability and capacity of its module to bear the weight of the exposed products, integrating new reversible connectors for the ceiling, and adapting the initial connectors to Z profile connectors for a faster assembly and disassembly of the exhibition panels. Through prototyping, the readability of the passports by the means of mobile devices is evaluated. Two wireless communication technologies: NFC and QR code are tested (see chapter 3.6).



Figure 18: Construction of the REMs prototype (P2)

As mentioned before, through the prototyping of the **Geberit GIS** (Figure 19), the team of Circular Retrofit Lab looks forward to improving the initial product qualities such as the reversibility, reuse potential, speed of (dis)assembly, multiple reconfiguration related to height, wall thickness, island solutions, etc. Achieving a standardized, adaptable and reusable GIS wall system for multiple applications involves the design and testing of new connection techniques. Demountable boarding replaces the traditional finish with gypsum pasteboards.



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The aim is to complete the **GIS building kit** catalog of functional solutions **for fully reusable solutions**. The kit of parts offers an opportunity to develop multifunctional products such as partitioning walls, interior furniture, or an exhibition module. Criteria such as aesthetics, acoustical performance, air tightness and the integration of technical services are also part of the investigation. Chapter 3.5 describes the development of the prototype.



Figure 19: Construction of a partition wall with integrated desk and bookshelves created with the Geberit GIS system during the Summer School (finished with plywood panels)

The Saint-Gobain, prototype 1 is a preassembled wood frame system with gypsum plasterboard cladding (Gyproc). These different preassembled modules enable building up a wall in a short time span. The sequential assembly does not allow for individual replacement. Components are mechanically connected with nails, which makes the system difficult to disassemble without creating waste. Some qualitative improvements were suggested by the team, in terms of reuse potential and flexibility of the integrated technical systems.

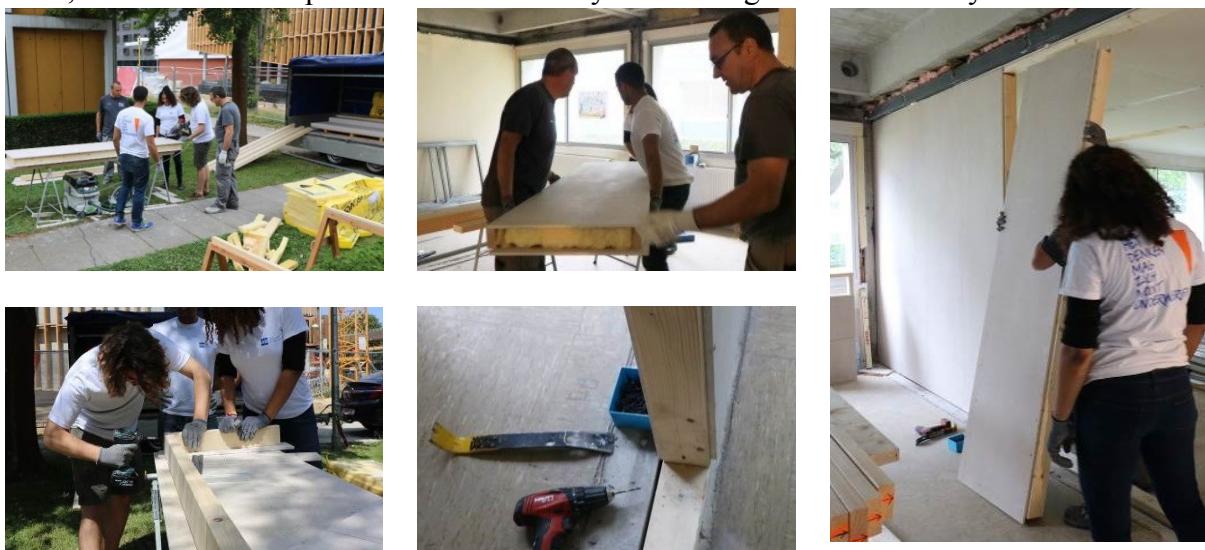


Figure 20: Construction of the Saint-Gobain P2 system, based on pre-assembled wall elements with a wooden structure

The Saint Gobain prototype 2 is a variant of the classic metal studs walls, with visible jointing elements between the plasterboards, and a flexible technical plinth. The innovative part of the prototype is an omega joint profile which is placed on top of the plasterboard allowing the finishing panel to be demounted. The removable plinth allows the integration of



technical services. Qualitative improvements related to the aesthetic of connections and the selection of the finishing boards were identified.



Figure 21: Development of the prototype P3Saint Goban

Less flexible, the **Wall-linQ product** focusses on reducing initial final and environmental impacts by replacing the metal profiles with cardboard profiles, or the use of high-performance double-sided tape as a connector between the wall structure and the finishing panels. The use of raw materials is reviewed.



Figure 22: Construction of the Wall-LinQ system, based on metal profiles, during the summer school

Systimber is a prefabricated interior and/or exterior wall and floor realized by laminated wooden beams/columns that are connected via a reversible metal bolt system. The team identified its role in the building partition according to its reversible capacity (see Figure 15).



Figure 23: Testing the Systimber system



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GDC focusses on the creation of an interchangeable module which can be replaced and adjusted to different requirements a façade might need. This regards modifications resulting from functional building changes. The prototype uses a wood frame as a structural basis. Four independent wooden boxes, filled with insulation can be assembled into the frame and attached to the base structure by the means of intermediary elements.



Figure 24: Manufacturing of the GDC facade module

In order to understand these improvements, Table 3 below synthesizes the initial technical characteristics of each prototype. It provides information on the role of the prototype at the building level, its initial capacity to be reused or to be adapted, and the degree of reversibility. It explains whether the prototype is a system or an independent component, and gives information on the composition of the materials used and the types of connections.



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	P1 Profile	P1 Unit	P1 (Geberit)	P2 St-Gobain Group	P3 St-Gobain Group	P4 Wall-LinQ	P5 Systimber	P1 Façade system	
ROLE	Profile structural or not	Elements exhibition module	Sanitary partition (current role)	Partition wall (interior)	Partition wall (interior)	Partition wall (interior)	Wall, floor, ceiling (interior and exterior)	Façade module	
TYPE	Single components (profile and connections)	Parts assembled in situ	System Kit of parts Preassembled, assembly in situ	System Preassembled , assembly in situ	System Assembly in situ	System Fast assembly in situ, difficult disassembly	System Prefabrication and easy assembly in situ	System Preassembled	
	New assembly of existing components	New assembly of existing components	Existing	Exiting	Existed, no longer on the market	Existing	Existing	New	
COMPOSITION	Galvanized steel with stainless steel reusable connections	Aluminium structure, birch panels, heartfelt ceiling, carpet tiles, products provided with material passports readers	Steel profiles that can be combined with multiple set of connectors and bolts,	Gypsum plasterboard cladding slid into wood frame system, mechanical connected components	Two layers of plasterboard mechanically fixed to metal-stud profiles ,and an omega profile Infill of insulation	Low impact cardboard profiles, a single gypsum plasterboard layer per side -lower amount of screws.	Solid wood connected by a metal bolt system	Wood Wool Waterproof membrane	
REVERSIBILITY CAPACITY	INITIAL	Fully reversible	Fully reversible	Partially non-reversible (<i>Finishing</i>)	Partially reversible	Reversible	Low reversibility	Fully reversible	
	RE-USE	Reusable	Reusable	Needs adaptation	Reusable preassembled wall built out of components	Adaptable and reusable system with omega profile	Low reuse potential associated with waste	Reusable	
	DISASSEMBLY	(Dis)assembly of additional elements without damaging the whole	Can be disassembled		Individual elements not demountable No individual replacement	One part can be disassembled without damaging the whole	Disassembly damage due to additional mechanical fixtures	(Dis)assembly requires care	
SPECIFIC ELEMENTS			Rubber profiles for acoustic		Omega profile on top of the first plasterboard (innovative existing reversible connection)		EPDM strips and metal connectors ensure good tolerance, air tightness and thermal efficiency	Energy efficiency calculation of cold bridges integrated	
IMAGE									

Table 3: A recapitulative table containing information about the function of the prototype, its initial capacity to be reused or adapted, the degree of reversibility, the type (system or independent element, and the material



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In order to ease the reading of the following section, the improvements are gathered together in the following recapitulative table (Table 4):

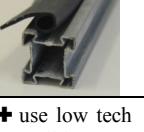
	TB Lai	REMs	CRL	GDC				
P1 Profile	P1 Unit	P1 Geberit GIS	P2 Saint-Gobain Group	P3 Saint-Gobain Group	P4 Wall-Lin Q	P5 Systimber	P1 Façade system	
FUNCTIONAL INDEPENDENCE:	+ different steps and improvements to achieve the reversible connection	+ add the reversible connecting hook between ceiling structure and the ceiling 	+ Add visible and invisible connections for reversible suspension of (wall) boarding 	+ replace the mechanical connection with nails by screws	+ explore integration of technical infrastructure into the plinth 	XX No possible improvement + Conclusion: Optimal for permanent walls	+ static integration of electrical cabling 	+ replace the initial rotating façade module with the four submodules boxes
ASSEMBLY/ DISASSEMBLY SEQUENCES:	+ several connection improvements: through design, manufacturing, and 3D printing (see chapter 3.4)		+ Replace finishing with resistant reusable wood panels 	XX No improvement		XX No possible improvement of disassembly (which produces a lot of waste)		
GEOMETRY AND MORPHOLOGY		+ use a rubber profiles to improve airtightness and acoustical performance 	+ integration of the technical appliances + propose alternative edges to reduce the damage of the finishing plaster boards	+ aesthetic improvements, colours + Add new materials for finishing + Integrate lighting	XX No improvement	XX No improvement but attention to aesthetical aspects and rejection risk		
TYPE OF CONNECTIONS	+ add reversible connection Z profiles for a reversible connection of the panels <img alt="Close-up of a metal Z-profile connector." data-bbox="85 895 165 965) and a small metal bracket." data-bbox="195 895 295 965)</td> <td>+ use low tech reversible connectors <img alt="Close-up of a simple metal connector." data-bbox="315 895 415 965) and a close-up of a metal panel edge." data-bbox="315 905 415 975)</td><td></td><td>+ replace the traditional refill between boards with reversible solutions – double tape</td><td>XX No improvement</td><td></td><td>+ Identify and integrate low tech reversible connectors (found on the local market) <img alt="Close-up of a green and silver metal connector." data-bbox="895 895 995 965)</td></td></td>	+ use low tech reversible connectors <img alt="Close-up of a simple metal connector." data-bbox="315 895 415 965) and a close-up of a metal panel edge." data-bbox="315 905 415 975)</td> <td></td> <td>+ replace the traditional refill between boards with reversible solutions – double tape</td> <td>XX No improvement</td> <td></td> <td>+ Identify and integrate low tech reversible connectors (found on the local market) <img alt="Close-up of a green and silver metal connector." data-bbox="895 895 995 965)</td></td>		+ replace the traditional refill between boards with reversible solutions – double tape	XX No improvement		+ Identify and integrate low tech reversible connectors (found on the local market) <img alt="Close-up of a green and silver metal connector." data-bbox="895 895 995 965)</td>	
	+ improvement							
	XX no improvement							

Table 4: Synthesis of the improvements operated during prototyping concerning functional independence, assembly/disassembly sequences, geometry and morphology, and the type of connections



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3.3 MATERIALS: ADAPTATIONS / INNOVATIONS

For some of the pilot projects, the prototyping phase was an opportunity to explore the role of materials and their innovative potential achieved through a better use of resources.

From the five analyzed products, the CRL team has identified innovative elements with high reuse potential and proposed actions for resources optimization. For example, the P3 Saint Gobain system contains OMEGA profile (see Table 5). Although an existing element, this profile is innovative. It allows a reversible and elegant connection for the finishing.

Both structure and composition of the Wall LinQ wall system can be improved by the use of an innovative reversible double-sided tape. The positive impact on the acoustic performance, in terms of vibration and sound transfer reduction, allows for a quantitative reduction of the plaster boards' utilization. It allows the reduction of plasterboards from 4 boards x12,5mm thick to 2 boards x15mm for the same acoustic performance. Consequently, cardboard studs can be used to replace the metal profiles and yet bear the reduced load of the wall. Moreover, this measure reduces the ecological footprint of the system and eases the recycling process.

For the REMS, the cardboard panels are replaced by birch panels to increase the expected durability of the exhibition. This change ensures the strength of the connections between the physical REMs and the panels and decreases the risks associated with the handling.

The same principles, with a focus on the smaller circular loops within the value network and the use of renewable materials, were applied for the GDC project detailed further on. The initial design of the metal profile was replaced, with local wood.

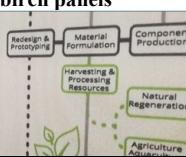
	P1-P8 Module	P1 Geberit GIS	P3 Saint-Gobain Group	P4 Wall-LinQ	P1 Façade system
CONNECTION			Existing reversible Omega profile 	Use as connection a double-sided tape 	Simplify the connections (magnets) 
STRUCTURE				+ replace metal with structural cardboard profile 	+ Use of renewable resources.
FINISHING	+ direct printing on birch panels 	+ more resistant wood panels 		+ use thinner plasterboards 	

Table 5: Synthesis of material adaptation and innovation



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3.3.1 Green Design Centre - A case study of material adaptation

The Green Design Center prototype focuses on the development of connections enabling the reversibility and independence of the construction systems. It takes into consideration all associated elements, their different end-of-life horizons, and consequently, the different rates of change.

The GDC prototype was built up by a structural frame allowing four boxes to be inserted. The boxes were made of wooden frames containing insulation. The different boxes were connected to each other with a wooden beam.

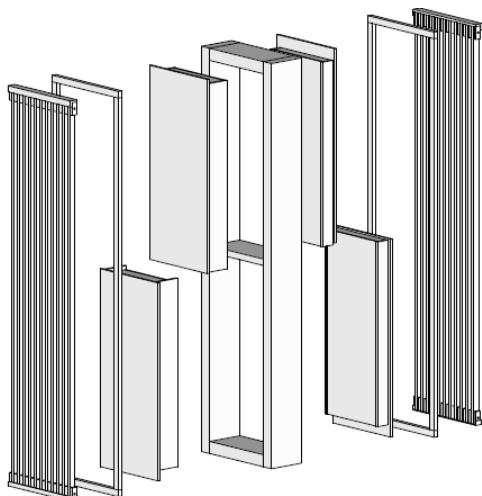


Figure 25: Four boxes system

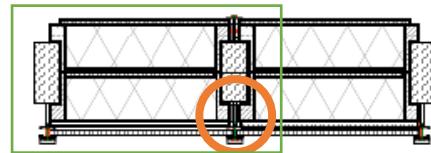


Figure 26: Initial steel profile

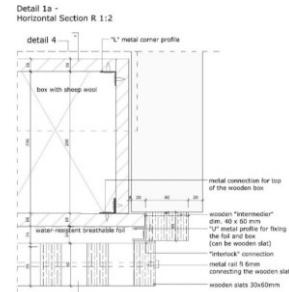


Figure 27: Wooden detail

Initially, the prototype planned a steel rail profile as an intermediary element between the wooden frame and the removable components (insulated boxes, windows, etc.). The profile inserted into the frame allowed the replacements and changing of other parts of the system without drilling additional holes into the frame or adding new connections. (Figure 28)

During the prototyping phase, the availability of the steel profile on the market raised concerns. Therefore, the team explored the use of a wooden intermediary that could be fixed to the main frame. Exchangeable elements (insulated boxes, windows, etc.) would be assembled to the wooden intermediary through a connector fixed to this element. Insulation boxes remained intact without connecting devices and drilled holes. (Figure 27, 28, 29).

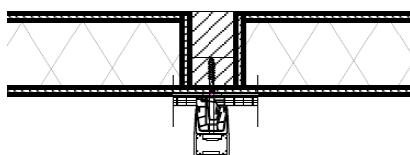


Figure 29: Ideal connection with steel rail and anchor

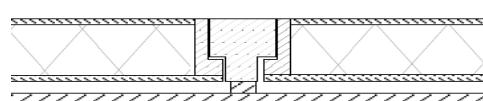


Figure 28: Final choice -Wooden intermediary



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3.4 CASE STUDY 1- DEVELOPMENT OF THE GTB LAB PROFILE

The development of a new prototype demands a methodology based on several tests and feedback loops. In order to achieve an efficient circular product, different steps and procedures were necessary all throughout the process such as a research by-design phase, the manufacturing, and evaluation by the means of the selection criteria. These steps were followed by necessary improvements.

3.4.1 Profile design

GTB Lab focusses on the development of a universal steel profile and its primary and secondary connections.

The purpose of the profile is to be able to play several roles, such as a structural role, but also an intermediary role, part of a non-structural construction system (façade, etc.). Figure 31 highlights the evolution that the section profile has experienced since the feasibility study. The materialization of the prototype is tributary to the manufacturing conditions, the availability of raw material, the early stage of R&D, etc. Consequently, the prototype was manufactured by assembling existing profiles. It aims to achieve circularity principles.



Figure 30: Manufacturing

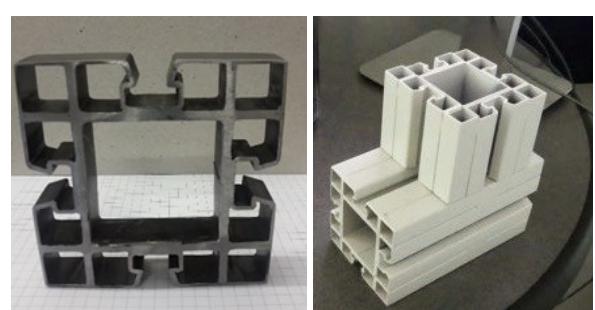
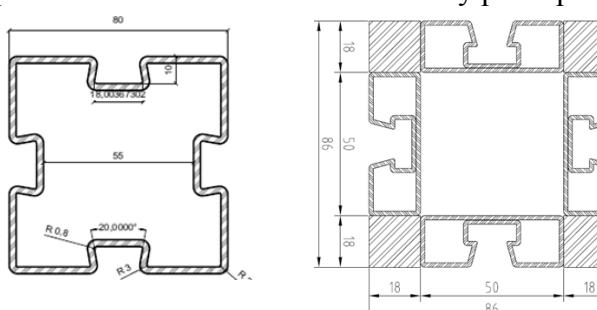


Figure 31: Evolution of the profile

Several scenarios were developed in order to identify the multiple possible linear connections that the profile offers. Figure 32 shows the reversible connections studied: connection with a fixed glass façade, connection with a window, connections with interior panels attached to the profile, connection of the cantilever, connection of the sliding panel, connection of the roof structure. The prototype is showcasing most of the applications of the new profile that have been analyzed within the reversible building design study.

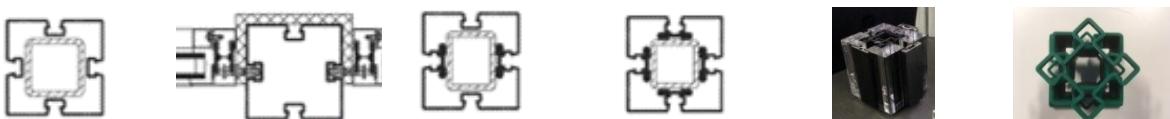


Figure 32: Overview of different connections with a number of different building parts



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3.4.2 Connection design- a research by design process

In order to develop the connections between the same profiles, the research-by-design method was used. It allowed an early stage conceptual test that helped to narrow the choices and to identify reliable solutions. (Table 6).

The **design of the connections required** a complex conceptual process. Eight technical key design indicators emerged from the Reversible Building Design Criteria. In order to identify the best technical design, these indicators were associated with performance ratios, defined within an interval from -2 to 2 from less performant, higher failure, etc., to high performance, high reversibility, etc. (see the final selection used an evaluation matrix (Table 6) based on:

1. **The constructive strength ratio** that provides a qualitative assessment of the strength of the connection and the profiles made by the producer (Janssen and ODS),
2. **Dimension adjustability ratio concerns:** the dimensional tolerance of the connection, the capacity to add several beams to the connection,
3. **Reuse of materials highlighting** the material capacity to be reused in other situations,
4. **Damaging of the structural beam ratio** associated with this criteria indicates the degree to which the structural beam is modified by the connection (e.g. additional holes for screws),
5. **Capacity and availability to reinforce the structural beam** This criterion evaluates the available space left by the connection for an internal reinforcement of the structure,
6. **Slot availability for façade elements** evaluates the space available for secondary connections,
7. **Aesthetics** criteria uses qualitative principles that score lower if the visibility of the connections is engaged,
8. **Assembly criteria** evaluate the speed and easiness of the assembly and disassembly.

Evaluation matrix color code:

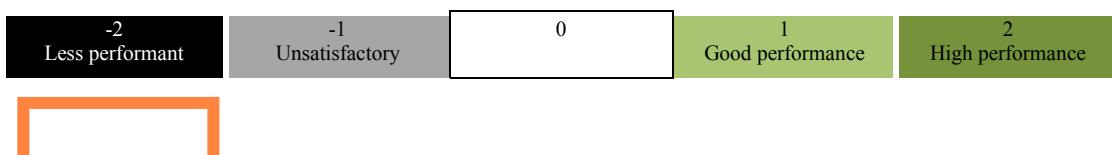


Figure 33: Evaluation criteria



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1 GTB Lab

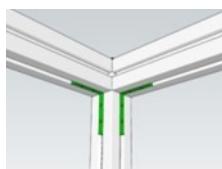
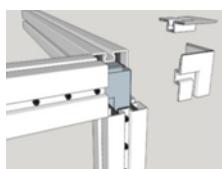
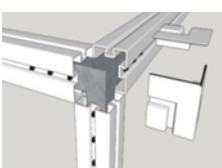
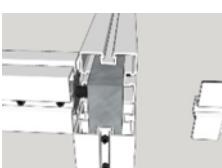
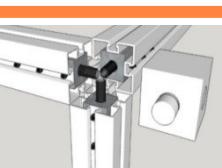
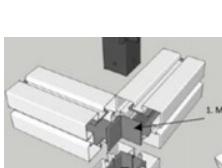
		3 L shape steel plates attached to the profiles without damaging the profiles. Constraints on the facade assembly and risk of potential thermal bridges.	SLOT USE							
			1	2	AESTHETICS ASSEMBLY	2	2	-1	1	
1	L shaped profile connected to the slot		1	2	2	2	2	-1	1	
2	L shape in slot			-1	2	2	2	-1	1	2
3	Interior steel plates		1	2	-1	-1	0	0	2	
4	Cube with slots		2	2		-1	-1	0	2	1
5	Solid three way connection		1	2	0	-1	-1	0	2	1
6	Solid two way connection with screw on arms		0	2	2	-1	-1	0	1	0
7	Solid 80x80x80 cube with screw on arms		1	2	2	-1	1	0	2	0
8	Interlock connection		1	2	2	-1	1	1	2	1

Table 6: evaluation matrix of the 8 profile alternatives, research by design



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1 GTB Lab

3.4.3 GTB Lab profile

The evaluation matrix (Table 6) highlighted two reversible connections, the number 7 “Solid 80x80x80” and “the interlock connection” number 8. The two designs are the basis of a prototype able to provide direct mechanical fixing of components and elements. The final design (Figure 34) integrates both the combination of load bearing capacities of the number 8 connection and the rigidity of the number 7 interlocked connection.

The connection number 8 has a heavy load carrying capacity. It offers a high degree of resilience allowing for multiple handling and re-use without being damaged.

The connection 7 provides a strong and rigid geometry with the lowest risk of deformation that might occur from the distribution of the mechanical forces behind different assembly configurations. The lack of additional fixing devices strengthens the reliability of the system.

The new profile was called the **GTB Lab** Profile and has been developed together with ODS Kloeckner company. The company provided engineering expertise and followed the step-by-step evolution of the prototype. In order to illustrate the reversible connection, an initial 3D print was created.

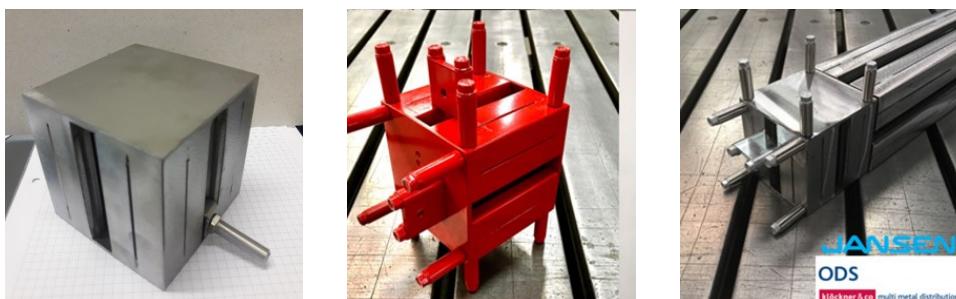


Figure 34: Evolution of the GTB Lab profile

3.4.4 Connection improvement

After the manufacturing, a final optimization step was made. The standardization of some parts made possible multiple horizontal and vertical connections with less waste. Aesthetic principles were also integrated and careful attention was given to the relation between the connection and the profile slots (Figure 35).

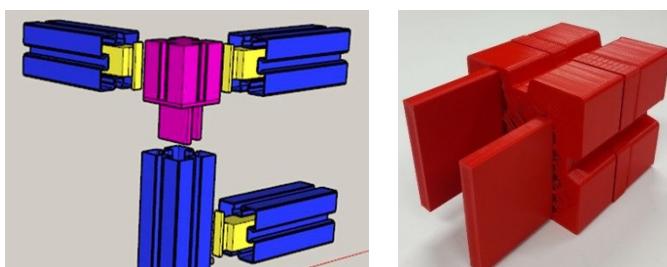


Figure 35: Figure the improvement of the quarto profile 3d modelling and 3d printing



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1 GTB Lab

By integrating a reflection on the needs at the level of the pilot project, several positions and directions required by the project were identified. Four major connection types were defined: (1) the corner connection, (2) the vertical extension of the horizontal connection (3), the vertical extension of the structure, (4) the horizontal and vertical extension of the structure.

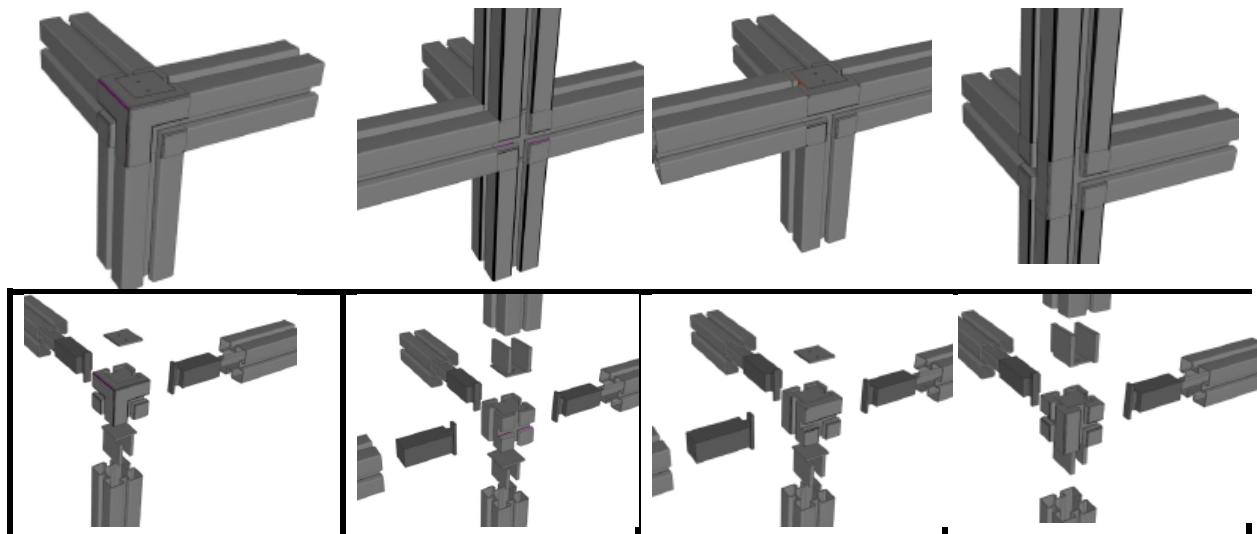


Figure 36 :Four main reversible connections

These four standardized choices allow further reflection on the design of one universal connection capable to meet a multitude of buildings' structural and architectural needs.

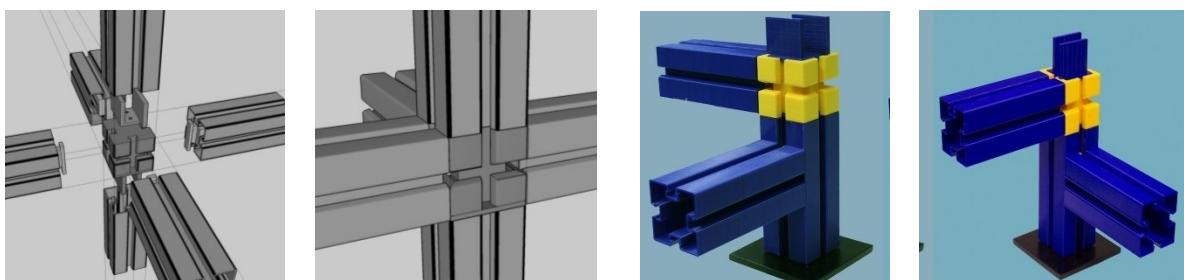


Figure 37: Towards the universal reversible metal profile



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3.5 CASE STUDY 2 - DEVELOPMENT OF GEBERIT GIS PROTOTYPE

The GIS- system developed by Geberit is an efficient installation kit of parts for sanitary facilities. **The system offers reversibility opportunities, reuse potential and multi-functionality.**

It is a reversible building system, that allows adapting the height, integrating island solutions and single/double layered wall solutions. Customization and the integration of functionalities and technical services are also possible.

This Geberit system can be assembled together with a wide set of connectors and bolts. Dimensional tolerances are compensated thanks to the design features in the kit of parts, like the adjustable foot, an assembly connection element, etc.

The preassembly of sanitary technical walls is brought as a module on site and further finished on site with boarding and wall finishing.



Figure 38: Reversible connection and preassembly principles of the Geberit GIS installation system © Geberit

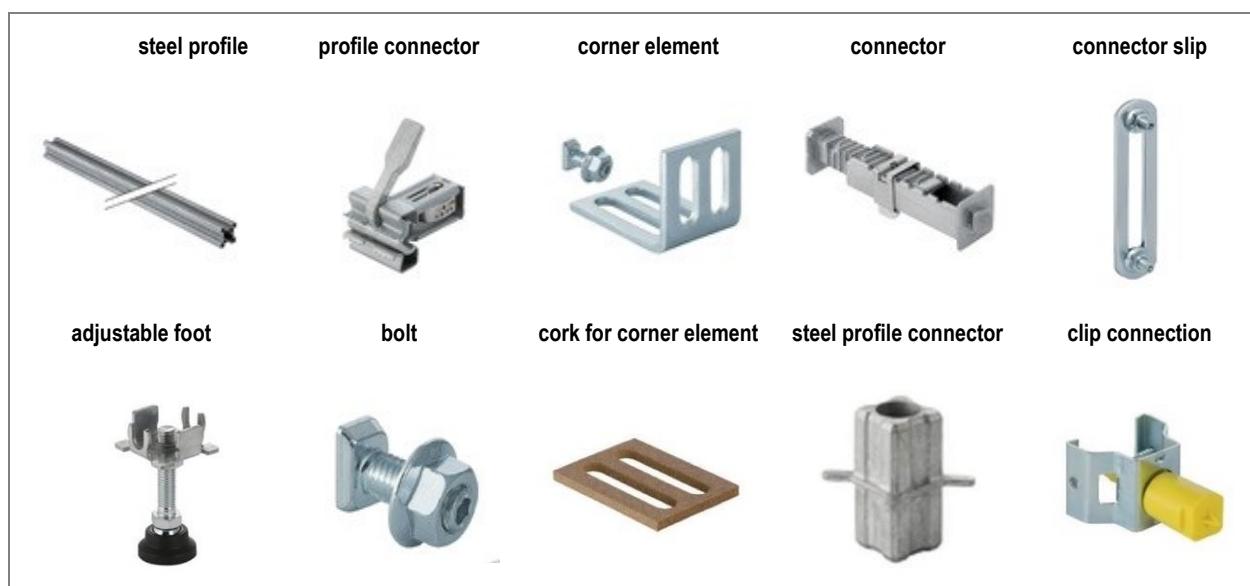


Figure 39: Catalogue of the GIS kit of parts of Geberit © Geberit



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 642384.

3.5.1 Technical requirements for transformation

Towards a standardized, adaptable and reusable GIS wall system for multiple applications.

The aim of the CRL lab is to develop solutions that can be transformed, adapted, upgraded or reused for a wide set of (functional) applications, ideally with the same building kit. The goal is to create a catalogue of functional solutions based on the GIS building kit. In this framework, three scenarios were tested for the prototyping, in relation to the three wall variants for which they could be applied: (1) A preassembled wall with a high degree of change, (2) a partitioning wall assembled on site, (3) a multifunctional / technical wall, partially preassembled and finished on site. (Figure 40)

Depending on the envisaged function of the wall, technical requirements should address different aspects such as *acoustic performance, vertical impact resistance, fire safety, preassembly and flexible integration of technical systems*.

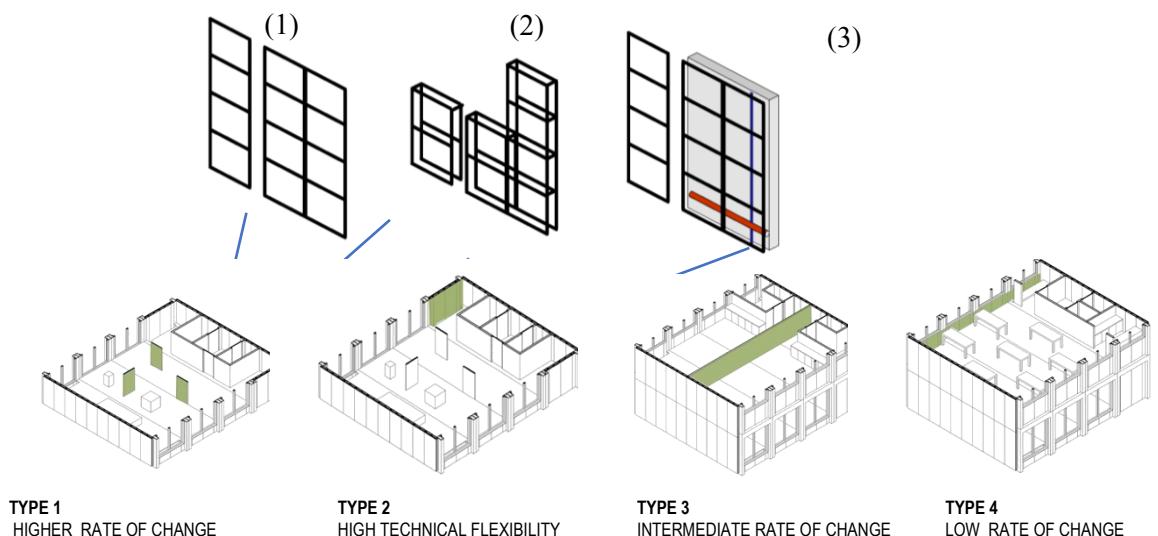


Figure 40: Overview of the applications of the wall variants based on the GIS system, as a result of the multi-criteria exercise with the group of involved industrial stakeholders of the working group ‘wall solutions’

3.5.2 Improvements/adaptations made after the feasibility report

Improvements are necessary to implement the system in the context of BAMB’s circularity ambitions. These adaptations mostly consist of an extension of the current GIS kit of parts catalog for a larger field of application and a larger group of future users at a lower price. Specific areas of concern were investigated such as *multi-functionality, new connection and (invisible) suspension types, dimensional tolerance, cost of the production, airtightness, acoustic, reversible finishing, and the flexibility of the building services (e.g. electricity)*.



This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 642384.

Low tech reversible connectors

The profile connectors that Geberit developed (Figure 39) were optimized for a rapid and stable connection between the steel GIS profiles and the suspension of sanitary products. GIS steel profiles can be reused in a large range of configurations due to the symmetric design of the cross-section and the higher steel thickness (compared to metal stud walls). GIS connectors allow multiple (dis)assembly sequences without quality loss of the profiles.

During the prototyping process, the CRL team identified alternatives to replace high-tech connectors associated with high investment costs and excessive steel consumption, with simple low-tech connectors that could be combined with the profiles.



Figure 41: Addition of low-tech connection elements that are compatible with the kit of parts of the Geberit GIS system



Different simple and low-cost connection elements (Figure 41) from DIY-stores, are compatible with the steel GIS profiles and can be added to GIS' current catalogue.

Figure 42: Addition of low-tech connection elements to the Geberit GIS system ©Transform

Reversible suspension of (wall) boarding

The addition of the new connectors (Figure 41) combined with suspension elements (Figure 42) and the elements from the current GIS building kit (Figure 39) offers a simple innovative suspension solution that can replace the plastered gypsum board panels.

Visible connection

The suspension of reusable boarding panels (e.g. wood panels) to the GIS steel structure could be made reversible by connecting pre-perforated panels by the means of GIS bolts.

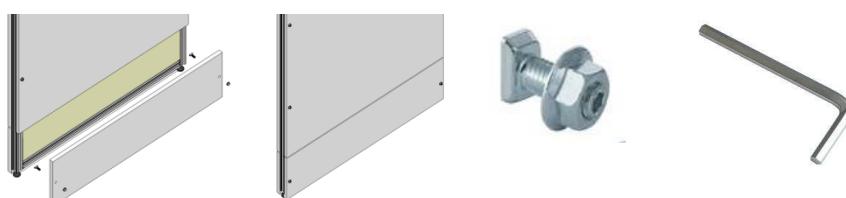


Figure 43: Visible reversible connection of e.g. wood-based boarding with GIS connector bolt and hex key



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Invisible connection

The 2nd suspension solution provides an invisible aesthetic connection on the finishing side.

A **first** concept was developed based on a multifunctional U-connection element, mounted on against the profile. The U-connector can also accommodate electrical cables. A **second** suspension principle uses vynex corner element (Figure 44) which allows an invisible connection on one side. More difficult to apply for a ceiling, it is suitable for connections in interior fitting-out. A **third** simple and economical suspension principle was based on two additional metallic elements: screw corner elements and a metallic hook corner, used in the furniture industry. The **fourth** invisible connection uses a corner element adapted to the use of GIS bolts. The lateral access makes the model most suitable for preassembled wall units.

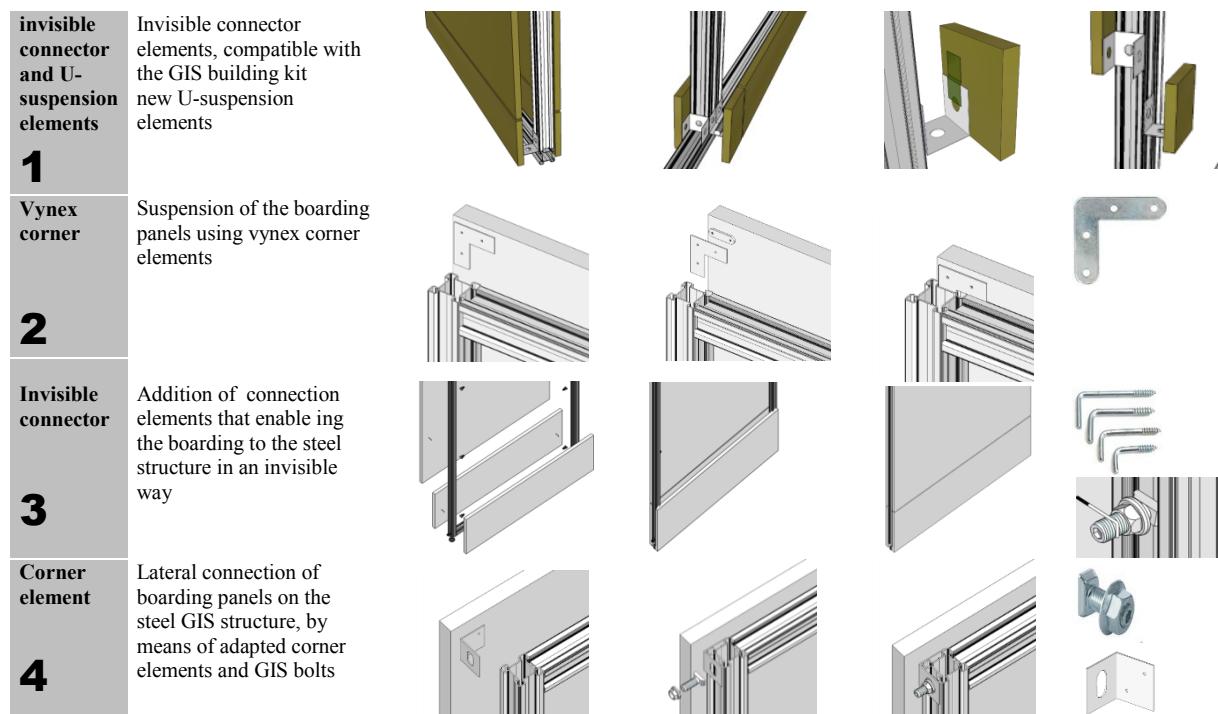


Figure 44: Invisible aesthetic connections

Airtightness in relation to acoustical performance

In order to improve the acoustical performance of the walls, the CRL team addressed the airtightness challenge of closing the joints between demountable panels and the structure. By making use of the grooves in the Geberit steel profiles, different extruded EPDM rubber profiles (omega-profiles, T-profiles or sigma-profiles) can be pressed and enclosed.



Figure 45: Addition of rubber profiles that can be inserted in the GIS profile groove: omega and U-profile (left), t-profile (middle) and GL mousse (right)



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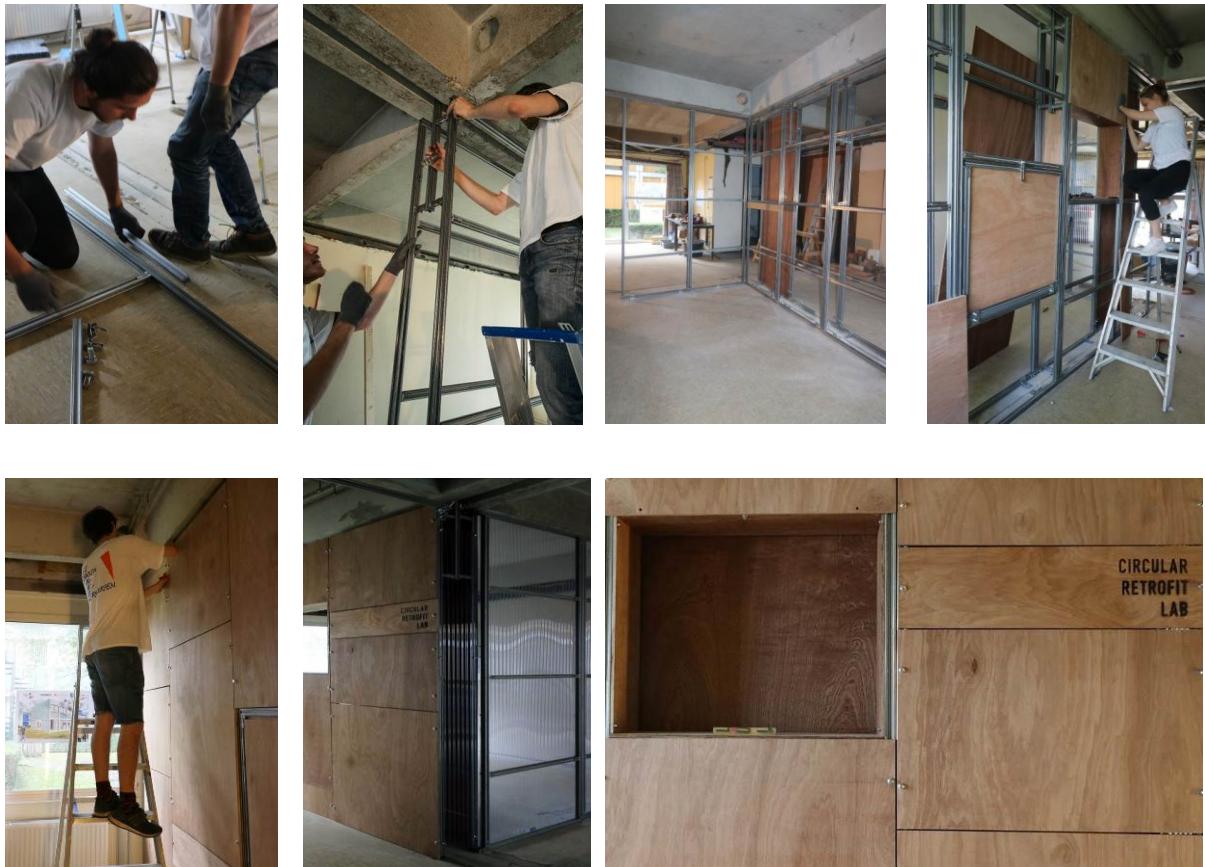


Figure 46: Manufacturing of the prototype GIS

Multifunctional building kit

To ensure that the building elements of the GIS building kit can be reused multiple times, for instance in furniture, some additional designs and construction set-ups were done. Further designs such as an integrated closet, a chair, and a table on wheels, etc. show the infinite capacity of the system.



Figure 47: Design of alternative solutions with the GIS building elements combined with low-tech connector elements



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3.6 Case study 3 Development of REMs - Integration of Material Passports

The Reversible Experience Modules Exhibition (REMs exhibition) is a traveling exhibition that lets you experience the new possibilities created for the built environment by combining Materials Passports with reversible building design.

Reversible buildings can adapt over time to the changing needs of users and society. By remaining relevant, demolition can be prevented, and the threshold to optimize and improve buildings is lowered. Reversible buildings may be changed more often than traditional ones. Materials Passports are a digital tool that helps to identify which materials and products are used in buildings, how they can be detached, reclaimed, and reused. Together with reversible building design, Materials Passports enable the change of buildings from static depositories of materials and products that will depreciate towards zero value, into a dynamic temporary collection of reusable products and materials that retain their value over time.

The Reversible Experience Modules are an example of what can happen when both tools are combined: the traveling exhibition is built from 40 physical and 30 visually represented products and materials, all optimized for reversibility. Each material has a Materials Passport in the BAMB prototype platform. The exhibition is built and rebuilt six times, as it travels to six locations. The floorplan can be adapted to fit different locations with different needs. The exhibition itself demonstrates to professionals from the built environment a collection of available circular building materials, and the value of Materials Passports to trigger circular building practices.

The prototype of the REMs is a pragmatic test of several main features of the total exhibition. Even though most products and materials used in the exhibition are not new, the way they are combined in the REMs is. To ascertain that the construction, the designed interactions, and the (re-)build process are technically feasible, a subset of the REMs were built as a prototype.



Figure 48: REM prototype



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The prototyping gives interesting insights into the interaction between mobile device and passports platform.

a. NFC interaction

Two types of NFC chips were tested: MIFARE and NTAG. The MIFARE chips proved not to be compatible with a series of smartphones such as Samsung models. The NTAG chips, however, are compatible with most current smartphones, as they follow a standardized design.

The placement of the NFC chip was tested. The proposed placement behind the wooden panels turned out to result in very low to no readability of the chip. An alternative placement behind the stack of business cards yielded similar poor readability. Placement on the front side of the panels gives good readability. Even though this front position results in an aesthetically less desirable result, it was chosen to place all NFC chips here to ensure minimal needed functionality. The white sticker in the right photo next to the printed text is the NFC chip. Placement of NFC chips is changed to the front of the panels rather than the backside of the panels. NFC chips behind the wooden panels could not be read by regular smartphones because the water content in wood panels block the low energy microwave signal sent by mobile phones.

b. QR code interaction

Depending on the software installed on the mobile phone, the QR codes are readable and can link successfully to the online Materials Passports.

c. Readability of platform on mobile devices

The BAMB materials passports platform is not optimized for smartphone browsers, however, it is readable on the tested smartphones. (see screenshot on the right) The platform is automatically translated into a responsive version in all the tested smartphone browsers.



Figure 49: Relation between the product and the material passport platform (MPP)



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4 STAKEHOLDERS

4.1 A NEW ECOSYSTEM OF STAKEHOLDERS

The prototyping process highlighted that the development of circular products requires working within an ecosystem of stakeholders. It showed the importance of integrating downstream value chain contributors in the upfront conceptual phase. Yet, it confirms the interest of some stakeholders to extend their role over primary activities, traditionally outside of their scope.

If materials and systems should be reused and continuously improved, if ownership paradigms change, if co-creative ways of developing products are actively integrated in value networks and if sharing economy paradigms scale up, different partnerships and relationships are required to ensure a sustainable transition from a product to a service model.

Several aspects were identified through the prototyping process:

1. The stakeholders' ecosystem of the pilot projects can be assimilated with a decentralized network. Stakeholders operate within a value network vs. a classical linear value chain.

For example, **GDC's** aim is to involve local stakeholders (:Figure 50), the wood cluster in Mostar, which brings together ca 80 companies specialized in supplying and processing wood raw material. Three different companies participated in different development phases under the coordination of the university.

2. A new role of coordination is necessary to articulate different actions, interventions and integrate upfront circularity concepts.

As in the case of **the GDC, CRL** uses different partition walls developed by different producers. Managing producers, designers, experts, and contractors require a new role of coordinator who is able to conduct the activities of the ecosystem and extract the maximum value, creating win-win situations for different actors and users.

3. The construction industry is interested in testing new models. Looking forward to keep the pace with new technologies and societal changes of customer segments and their needs, more and more companies are participating in new products' development.

ODS Kloeckner, a member of the Janssen group, agreed to develop a reversible and multifunctional new steel profile with fitting connections that can be used, to be applied within the **GTB Lab**. ODS Kloeckner has supported the process by providing know-how about the engineering and production of steel profiles as well as the production of the prototype.

4. The designer is actively involved in the realization process. More than following the building site, it is asked to be involved during the use phase of the construction, co-create future transformations together with all of the stakeholders.

During several meetings, the design team (&Lotte), the client (EPEA) and the constructor (Gielissen) of the **REMs** have been discussing the design optimization and



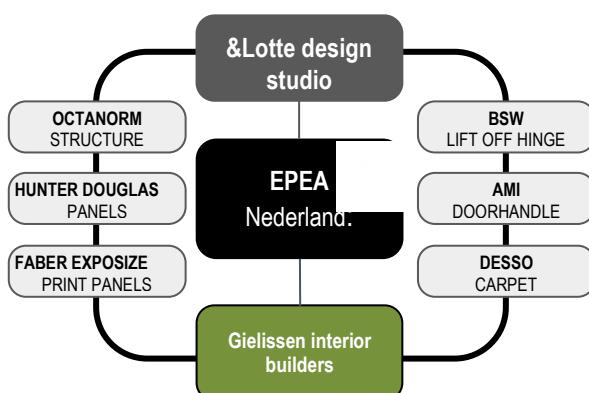
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the cost efficiency. During these sessions, several adjustments were made to the design to ensure the reversibility and improvement of the prototype.

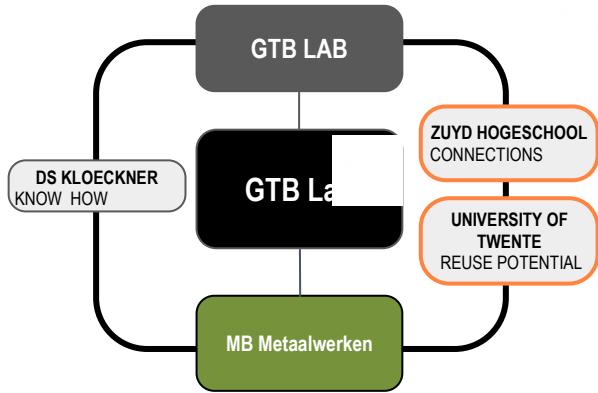
5. A process opened to contributors

For the **GTB Lab** project, together with the pilot team, 6 students from Zuyd Hogeschool have developed and analyzed alternatives for the connections. Zuyd has also made analyses and the comparison between the new and conventional steel profiles. The University of Twente analyzed the reuse potential of steel profiles.

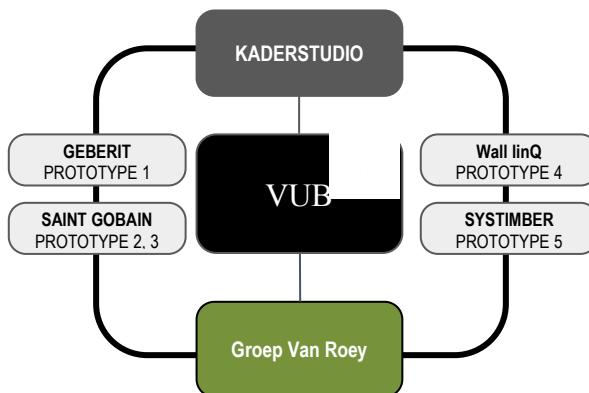
Stakeholders REMs



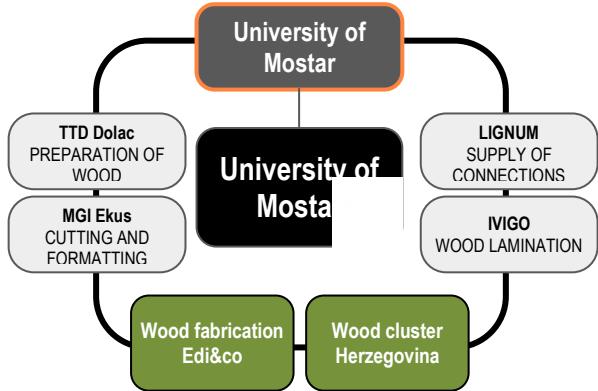
Stakeholders GTB Lab



Stakeholders CRL



Stakeholders GDC



- Process coordinator
- Designer
- Products/ technology
- Constructor, potential seller

:Figure 50: The stakeholder ecosystem



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4.2 BUILDING A VALUABLE PROCESS

Building a strong eco-system of partners should be articulated around a valuable process of creation and development of the product. The active interaction, the disruption of the linear sequencing of actions, and the precise role of the actors are key factors influencing success.

For example, The CRL worked together on a regular basis with their industry stakeholders. The steering committee group Kaderstudio, VUB Van Roey, MK Engineering, Brussels Environment and VITO meet and discuss monthly the important and pressing topics, short and long-term decisions. Workshops are being organized on specific themes to search together for integrated solutions, e.g. on techniques, exterior walls, interior walls, etc.

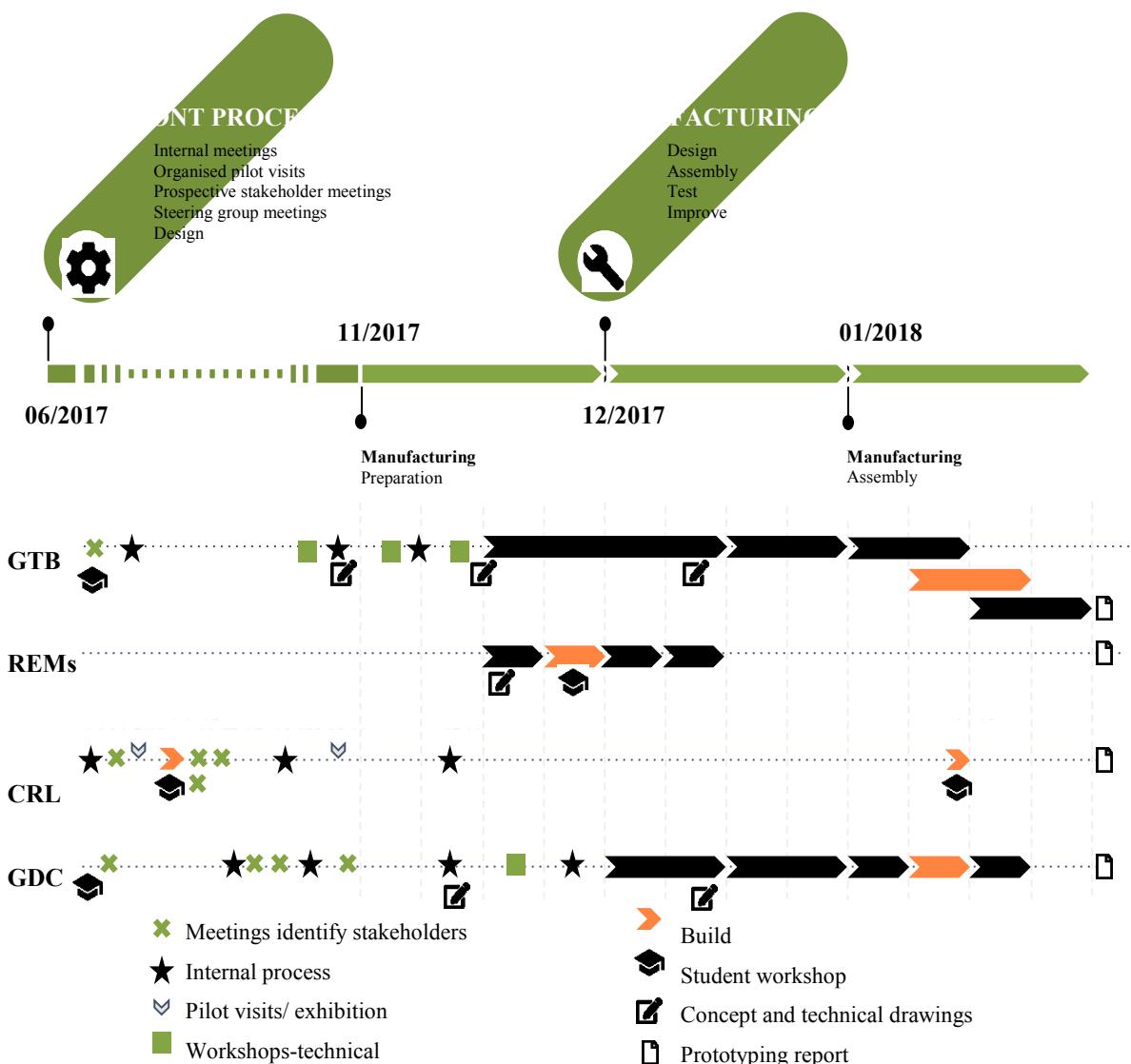


Figure 51: D13 prototyping phase process



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5 ENVIRONMENTAL ASSESSMENT

5.1 WASTE REDUCTION ASSESSMENT: OBJECTIVES AND RESULTS

As part of the prototyping development phase, more insight is needed into the advantages (expressed as environmental impact) of using reversible building components. Three pilot projects did an extensive assessment concerning waste reduction and the use of virgin materials. The objectives described in the Work Plan, the projects' achievements and the methodology used by each project are described in the following lines.

By the means of a multipurpose and demountable/replaceable structure, the objectives of the **Green Design Centre** were set to demonstrate a waste reduction of **60%** of total construction waste compared to a conventional building and **50%** less virgin resource use. At the end of the prototyping, the results are satisfactory. The reversible **GDC** façade system provides a waste reduction of **93%** of total construction waste traditionally produced by a traditional facade. Raw materials use was reduced by **78%**.

The methodology developed by GDC consists of comparing the amount of the materials used and the quantities of the waste produced for a **conventional passive façade system** (Figure 52) and the reversible GDC façade system (see Figure 2). It takes into consideration a transformation taking place every 10 years, over a period of 50 years. In the case of the conventional system, components are permanently stuck together. It is assumed that the whole system will become demolition waste. On the contrary, the reversible façade can be removed and replaced with limited leftovers. The team identified technical vulnerabilities and risks which helped to generate the quantitative calculation of waste.



Figure 52: Conventional passive facade

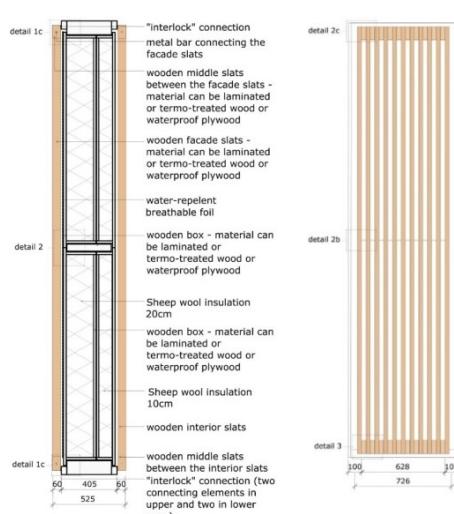


Figure 53 GDC reversible facade system

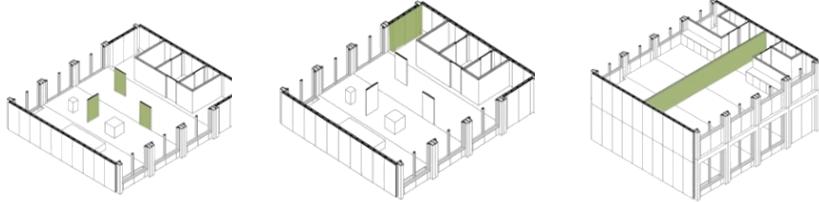


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For the **GTB Lab**, the objective was to demonstrate that waste generated by changing functions of a building, can be reduced by **70% through the use of upgradable modular and exchangeable components. The use of virgin materials will be reduced by 60%**.

In order to assess the waste reduction during the transformation of the buildings, the team compared two 3D modules: (1) the GTB Lab profiles and (2) a conventional steel profile. The GTB profile is a fully reversible steel element, which means that the reuse rate will be higher than the recycling rate. On this basis, the team calculated the amount of material (kilograms of steel) saved during four reuse sequences. The results reveal a waste reduction of **75% of the construction waste**.

In the **CRL**, one of the objectives was to reduce waste production in housing refurbishment by **75%-90%**. By calculating the estimated waste reduction during the design phase and verifying these estimates in practice, it is possible to demonstrate the positive impact of the BAMB approach on waste reduction in refurbishment. CRL uses a calculation method based on the amount (or percentage) of waste reduction calculated over a total period of 60 years. Different scenarios of transformation are assessed: once every year, every ten years and every fifteen years. In addition, the waste reduction estimates at the design stage are checked against a baseline representative for the current practice. The results illustrate that with the proposed reversible wall solutions, considerable waste reduction can be achieved compared to the baseline (current traditional building solutions). The initial estimate of 75-90% of waste being reduced was confirmed within the interior fit-out of the CRL lab.



	TYPE 1 HIGHER RATE OF CHANGE every 2 years	TYPE 2 HIGH TECHNICAL FLEXIBILITY Every 10 years	TYPE 3 INTERMEDIATE RATE OF CHANGE Every 15 years			
	Year 0	Year 60	Year 0	Year 60	Year 0	Year 60
Geberit		23,0 kg (-94.9%)	41,8 kg (-94.9%)	13,7 kg (-71,2%)	23,6 kg (-71,2%)	27,4 kg (-58.5%)
Systimber		37,5 kg (-95,2%)	39,3 kg (-95,2%)	Not applicable	Not applicable	37,5 kg (-68,0%)
Saint-Gobain		Not applicable		Not applicable	Not applicable	33,9 kg (-37,2%)
Baseline		27,4 kg	822,8 kg	13,9 kg	83,2 kg	27,8 kg 114,0 kg

Figure 54: Waste assessment for different types of wall systems. The percentage represents the reduction in waste of the prototyped wall compared with the baseline type, over a period of 60 years and after several transformation





In regard to the use of virgin materials within the pilot project, **CRL** assesses these figures in different stages of the transformation. The first stage corresponds to the current prototyping phase. Only in the second and third stage, the reuse of the structural elements will reduce waste production by about 50-70% and 40-60% respectively, both by reusing existing elements and avoiding virgin resource extraction.

For the **REMs**, the design optimization towards reversible design (e.g. using standardized aluminum construction systems) makes it possible to take back the construction materials after one year of use, and re-use them in an unrelated, next building project. The role of passports in this arrangement is not tested yet. This will be tested in the course of the REMs' year of travelling. Take-back and re-use options for all products and materials will be noted in the materials passports. The passports will be the main source of information on how to re-use the products and materials. It is expected that few, if any, materials will be considered waste after first use, and rather be re-used in a new project or building.



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5.2 ENVIRONMENTAL ASSESSMENT METHODOLOGY

The **GTB Lab** and the **CRL environmental assessment** uses a methodology currently under development, developed by VITO, one of the BAMB project partners. Slight modifications have been brought within the Product Environmental Footprint (PEF) formulas for each life cycle stage of the environmental and economic assessment. N.B. Module D (see PEF) concerning benefits or loads due to (future) recycling/reuse/energy recovery is already taken into account in other modules. The modification integrates parameters related to recyclable or reusable materials. The experience of the pilot project will allow the improvement of the calculation method, necessary for the development of Circular Building Assessment Tool. Further information will be available in the D15 report from BAMB's Work Package 5.

The assessments are calculated based on the following parameters. Please note that the methodology and the results are under revision.

LIFE CYCLE STAGES	CIRCULAR FOOTPRINT FORMULA
A1,processes	(1-R1)*EV,extraction+R1*A*Erecycled
A1,substitution	-R1*(1-A)*E*V,extraction,in*(Qsin/Qp)
A2,processes	(1-R1)*A*EV,transport+R1*Erecycled,transport
A2,substitution	-R1*(1-A)*E*V,transport,in*(Qsin/Qp)
A3,processes	(1-R1)*A*EV,production+R1*Erecycled,production
A3,substitution	-R1*E*V,production,in
A4	directly based on LCI
A5	directly based on LCI
B2	directly based on LCI cleaning: yearly; maintainance based on cycles
B4,processes	#REPL*(C1+C2+C3,processes+C4+A1,processes+A2,processes+A3,processes+A4+A5)
B4,substitution	#REPL*(C3,substitution+A1,substitution+A2,substitution+A3,substitution+A4,substitution)
B5,processes	#TRANS*(C1+C2+C3,processes+C4+A1,processes+A2,processes+A3,processes+A4+A5)

PARAMETRE	DEFINITION
<i>A</i>	Allocation factor of burdens and credits between supplier and user of recycled materials and/or reclaimed products. A low A-factor means a low offer of recyclable/reclaimed materials/products and a high demand. Within the Circular Building Assessment (CBA) a value of 0,5 is taken into account, simulating stable market conditions.
<i>B</i>	Allocation factor of energy recovery processes; applying both to burdens and credits.
<i>E_D</i>	Environmental impacts of disposal of waste material (part that isn't in R ₂ and R ₃)
<i>E_{D*}</i>	Environmental impacts of "avoided" disposal of R ₁
<i>E_{ER}</i>	Environmental impacts of energy recovery process
<i>LHV</i>	Lower heating value
<i>X_{ER}</i>	Efficiency of the energy recovery process
<i>E_{SE}</i>	Environmental impacts of substituted energy sources
<i>E_{recycled}</i>	Environmental impacts of recycling/reuse process of R ₁ (incl. collection, sorting, transport)
<i>E_{recyclingEOL}</i>	Environmental impacts of recycling process at EOL
<i>E_v</i>	Environmental impacts of virgin content (of raw materials in production)
<i>E_{v*}</i>	Environmental impacts of substituted virgin materials after recycling ("avoided virgin materials")
<i>Q_s</i>	Quality of the secondary material
<i>Q_p</i>	Quality of the primary material
<i>Q_{s/Q_p}</i>	Q _s /Q _p is a dimensionless ratio, an approximation for any differences in quality between the secondary and the primary material ("downcycling")
<i>R₁</i>	Recycled content (of raw materials at production) recycled from previous system [%]
<i>R₂</i>	Recycling/reuse fraction (at EOL) for a subsequent system [%]
<i>R₃</i>	Fraction incinerated with energy recovery (at EOL) [%]
<i>#REPL</i>	Number of replacements within the estimated life span of the building (part)
<i>#TRANS</i>	Number of transformations/refurbishments within the estimated life span of the building (part)

Figure 55: Overview of parameters and calculations used in the different EoL allocation approaches, with comments on data availability



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5.2.1 GTB LAB - GTB Lab profile

An analysis was performed of two metal profiles with the same dimensions 0.08x0.08x 0.0025m:

- the **GTB Lab reversible building profiles made by galvanized steel with stainless steel reusable connections to be deconstructed, moved and rebuilt after each transformation and recycled at the end of life, and**
- a **conventional square building profile** made of galvanized steel with welded connections that will be demolished after each transformation, recycled and replaced with a new one.

It uses multiple scenarios based on three transformation cases: extreme, realistic and conservative scenarios, each associated with a rate of change of 7, 10 and 20 years over a lifetime of 100 years. The assessment uses the circular footprint formula in the extreme, realistic and conservative scenarios for climate change impacts. It uses a reuse and recycling allocation factor of 0.5, based on the **assumption** that in a circular economy, supplier and user share equally reuse and recycling burdens.

First partial results highlight the following aspects:

- due to the reuse of materials at the recycle at the end of life, **GTB Lab** has higher substitution benefits **in the use and the disposal stage** (B1-B5, C1-C4),
- The benefits of the reuse are relevant on the long-term see graphs 53-55.
 - the profile is in R&D phase. This explains why in the **product stage** impacts for **GTB Lab** are higher than the baseline case. However, there are high margins for the material use optimization with improvement potential for environmental performances (A1-A5).

 GTB Lab profile	
 Conventional profile	

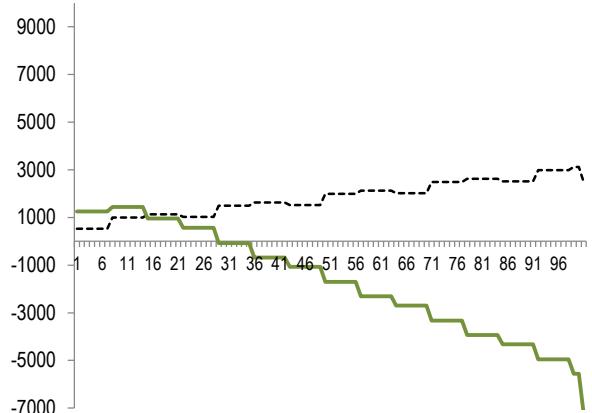


Figure 56: Climate change impact (100 yrs) for extreme scenario, 1 transf. every 7 yrs

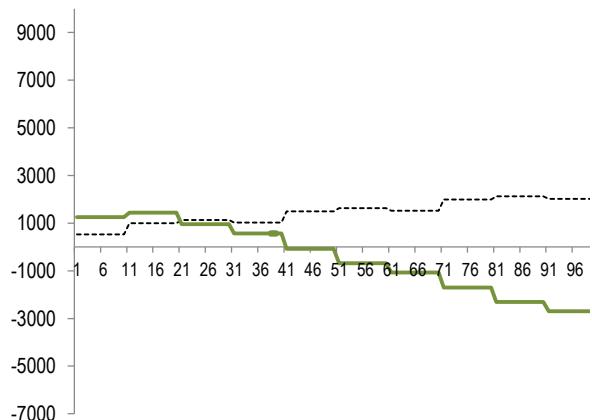


Figure 57: Climate change impact (100 yrs) for realistic scenario 1 transf. every 10 yrs

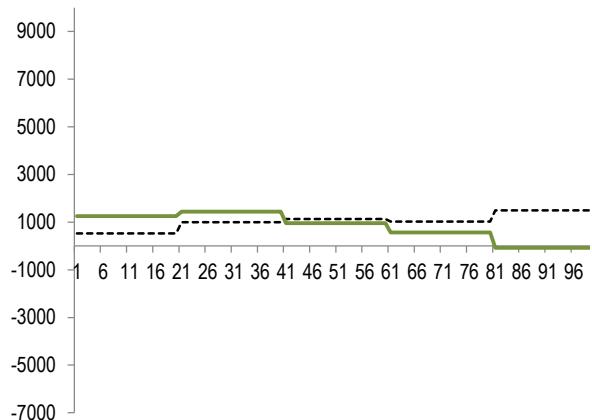


Figure 58: Climate change impact (100 yrs) for conservative scenario 1 transf. every 20 yrs



5.2.2 CRL-Interior Walls

The prototyping results on the financial transformation scenarios and technical solutions have been assessed:

Scenario 1 - interior wall - Yearly

transformations

- Baseline gypsum cardboard with metal stud on both sides ($t=0.012m$)- no reuse
- P1 Geberit GIS
- P5 Systimber

The prototypes have minimal impacts especially in the maintenance and replacement scenarios compared to the baseline design.

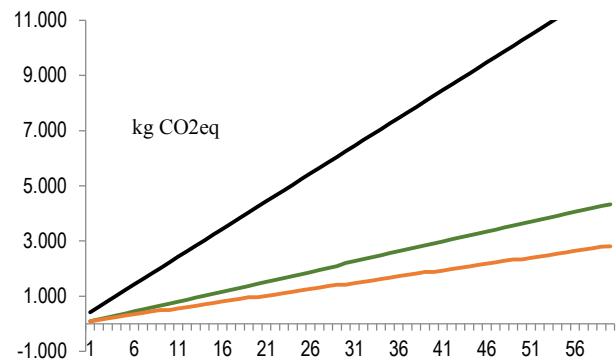


Figure 59: Environmental impacts per m². Yearly transformation

Scenario 2 - Technical interior wall - Transformations every 10 years

- Baseline gypsum cardboard with metal stud- double plasterboard on one side ($t=0.019m$)
- P1 Geberit GIS

P1 Geberit avoids a large portion of the maintenance, replacement and refurbishment due to a reversible design. The avoided impacts in the product stage are due to the reduced extraction of virgin materials.

Scenario 3 - Partition wall - Transformations every 15 years

- Baseline (idem Scenario 2)
- P1 Geberit GIS
- P5 Systimber
- P2 Saint-Gobain Group

The prototypes have minimal impacts especially in the maintenance and replacement scenario compared to the baseline design. However, P2 and P5 are better placed for lower transformation rates.

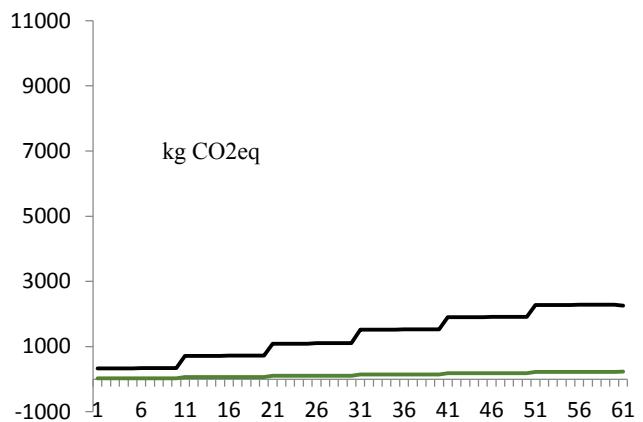


Figure 60: Environmental impact per m . Decennial transf.

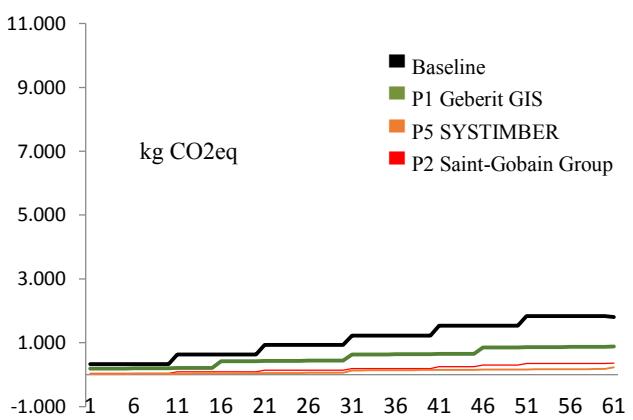


Figure 61: Environmental impact per m². Transf. every 15 years



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6 BUSINESS MODELS OPPORTUNITIES

6.1 GENERAL FEEDBACK

Each innovation strategy adopted by BAMB pilots is potentially subject to the development of new business models. Based on the prototyping, the work package five action 2 (WP5A2) “New business models based on reverse logistics and circular value chains in buildings” is exploring the interaction between the development of the pilots projects and the emergences of new building models supporting circularity. Therefore, aspects such as ownership transfer, leasing versus purchasing, and changes in the primary activity value chain have been considered by the pilot project team during the prototyping.

The GDC and GTB Lab team stress the importance of making circular products competitive through cost reduction and by maintaining a higher value of materials for longer. Identified strategies are pointing out different key aspects such as the optimisation of production process, the rethinking of the logistic strategy, and ownership transformation based on the take back concept.

In the case of CRL, the stakeholders involved in the prototyping process have analysed the financial sustainability of developing circular products and buildings during the workshops described in the chapter 4.2). Making use of his experience, the contractor in charge of the pilot project, Group Van Roey, has identified possible win-win scenarios for the different value chain actors: **for the users or owners**, circular building are likely to improve the quality, maintenance and comfort of the building; **for the investors/ owners**, the functional and spatial reversibility is likely to facilitate future transformation and therefore reduce the risk of uncertain future utilisation. Moreover, if the investors remains the owner of the building over a certain duration, reversibility reduces the operational costs. The team identified a growing interest from engineering offices, product manufacturers, general contractors, etc. to learn how circular buildings may create new business opportunities.

Based on the workshops ‘results, VITO (as part of WP5A2) has tested a financial model which takes into consideration the benefits issued from several financial life cycles, inherent to circular models. The tested model uses multiple scenarios based on three transformation cases related to the three types of walls identified by the CRL (see Figure 14), each associated with a rate of change of 1, 10 and 15 years over a lifetime of 60 years.

Scenario 1 compares both the P1 Geberit GIS and the P5 Systimber with the a non-re-usable Baseline gypsum cardboard with metal stud on both sides ($t=0.012m$). Scenario 2 compares a baseline gypsum cardboard with metal stud- double plasterboard on one side ($t=0.019m$) with P1 Geberit GIS. The third scenario compares the previous baseline version against P1 Geberit GIS, P5 Systimber and P2 Saint-Gobain Group.

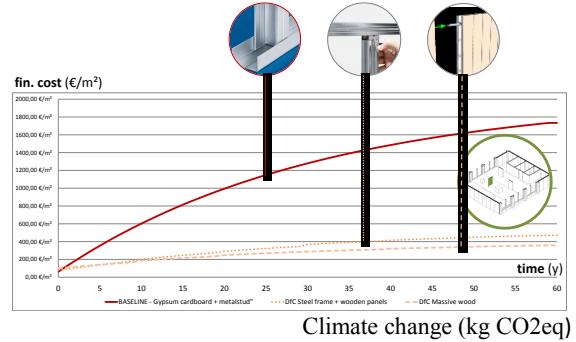


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6.2 FINANCIAL ASSESSMENT CRL

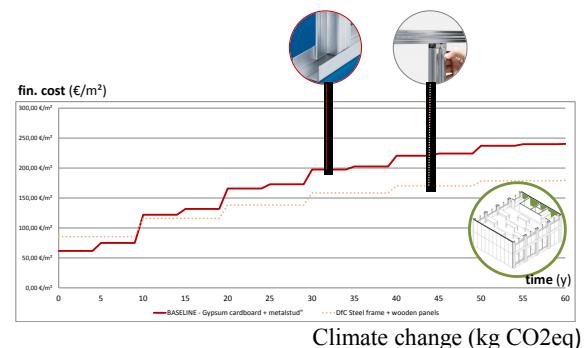
Scenario 1 - interior wall - Yearly transformations

- higher initial financial costs for all reversible interior wall solutions compared to the baseline interior wall
- the financial investment is already returned after the first transformation (i.e. after one year) for both reversible wall solutions.
- lower refurbishment costs and deconstruction/reassembly costs, with Systimber scoring the best



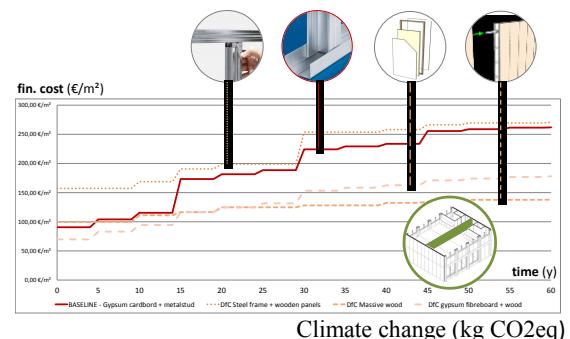
Scenario 2 - Technical interior wall - Transformations every 10 years

- higher initial financial costs for all reversible interior wall solutions compared to the baseline interior wall
- after the second transformation, it is the reversible wall solution that has a better (life cycle) financial performance
- design characteristics of the reversible solution and direct reuse of the wooden panels



Scenario 3 - Partition wall - Transformations every 15 years

- P2 Saint-Gobain solution has a lower initial financial cost than the Baseline wall, due to low material and installation costs,
- the P1 Geberit GIS remains the most expensive element. There is no incentive to consider this reversible wall solution for the dwelling, but rather for spaces with higher transformation rates
- Systimber is already competitive after year 5
- The P2 Saint-Gobain Group has a lower initial cost and lower life-cycle costs.



7 LESSON LEARNED

Leveraging on systemic social changes and opportunities brought by on-going technological progress opens up new opportunities for effective valorization and re-utilization of existing resources. In order to reduce the ecological footprint, intensive research is needed to identify ways to extract more value from existing assets, minimize waste and create innovative models to transform it into a new resource.

Through the pilot projects' development, BAMB is aiming to identify links between new and existing products; new stakeholders; bottom-up and top-down approaches; towards new optimized, circular models and products; and new forms of organization and governance. Different aspects have been tested and assessed through the prototyping. Table 7 is bringing together the lesson learned. These insights have to be interpreted within the research and innovation strategy each pilot team has chosen.

RESULTS – ACHIEVEMENTS - FOCUS				
	1 GTB Lab	2 REMs	3 GDC	4 CRL
TECHNICAL 	NEED FOR STANDARDISATION <i>Standardization has impact on geometry, Integration of energy as a next step</i>	ALIGN TECHNICAL WITH FINANCIAL CONSIDERATIONS <i>Design reversible modules by reducing costs</i>	ADAPTABILITY OF THE DESIGN TO THE LOCAL RESOURCES <i>Use local resources that involves circular short loops</i>	INCREASE VALUE AND IMPROVEMENT POTENTIAL OF AN EXISTENT SYSTEM <i>Collaborate with producers (the R&D department)</i>
PRACTICAL 	START FROM SCRATCH <i>Limited time for a consistent development</i>	REQUIRES IMPROVEMENTS IN TECHNOLOGIES <i>Compatibility between NFC, mobile devices, material passports platforms not yet effective</i>	THE SIMPLICITY OF THE GEOMETRY	COMBINE PRODUCTS WITH EXISTING REVERSIBLE ELEMENTS <i>Use existing low cost connectors on the market</i>
FINANCIAL 	R&D – INVESTMENT APPROACH <i>Requires high investment upfront Standardization needed to lower the costs</i>	HIGH RELOCATION COSTS <i>Address IP restrictions</i>	LONG-TERM PROFITABILITY DUE TO REUSE <i>Need for several transformation and standardization</i>	LONG-TERM PROFITABILITY DUE TO REUSE <i>Make use of standardization - mass production - maintenance - existent know-how</i>
RECOMMENDATION 	PROTOTYPE A WHOLE SYSTEM, OR A MODULE) EXTEND FUNCTIONALITY <i>(e.g. Partition wall)</i>	PRIORITIES TO BE INTEGRATED IN THE UPFRONT DESIGN	TEST THE PROTOTYPE BY USING DIFFERENT MATERIALS and BUSINESS MODEL	STRENGTHEN COLLABORATION <i>Stakeholders and technical bodies Have a Market approach</i>

Table 7: Lesson learned



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7.1 TECHNICAL STANDARD VS. CUSTOMIZED

One of the main preoccupations of the pilot projects teams was related to the standardization and the impact on the technical aspects of the prototype.

Within the **GTB Lab**, the prototype is a newly developed steel profile produced by Jansen Group and a sub manufacturer of this group (ODS Kloeckner). Developing a totally new steel profile, which does not fit standard production lines, turned out to be challenging since this process affects the majority of the suppliers. It also has an impact on the final manufacturing of the profile at the Jansen factory in Switzerland. Due to the complex technology and process involved, it was decided to make the prototype of the profile manually and use the mock-up as a tool to inform the parties of the whole process chain of which type of innovation is required. The mock-up has been presented to the Jansen group in Switzerland, which has decided to continue further development.

This is often the case for R&D products. The **GTB Lab** profile necessitates complementary process innovation accompanied by important upfront investments in manufacturing and a significant amount of time necessary for trials.

CRL tries to make use of the initial qualities and values of the studied systems, such as the existent mass production advantages, the ease of maintenance and the existent know-how. Further improvements of the technical aspects should be explored later on, together with the producers.

For the **REMs**, all panels have the same dimensions to make them interchangeable. The standardized building system 'Octanorm' was chosen for the structural frame instead of the tailor-made construction proposed initially. The project is an example of cross-sectoral technology transfer. Originally an exhibition component, the profile is fully reversible. It broadens the horizon for extending its use to other construction sectors and applications and leverages its lower cost.

Another important technical aspect was raised by **GDC**. The availability of resources and the impact of the technical decision on economic aspects. The positive impact lies in the valorization of the local resources within a shorter value chain.

7.2 PRACTICAL ASPECTS

In all of the cases, standardization and simple geometry are crucial for the reuse of components. Through prototyping, **GTB Lab** and **GDC** look forward to optimizing their prototypes. GTB Lab identifies timing issues and stresses the importance of planning optimization.

According to the **REMs** team, property rights should be flexible enough to allow for the adaptability of the design.



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In the case of **CRL**, it is shown that the development of reversible building solutions can be realized by using existing products. The success of such an approach lies in the opportunity to use the production and logistics lines already available. Tackling innovation through a straddling approach allows the **CRL** team to build their prototypes by making use of: the existing products' qualities; standardization; existing know-how; mass production advantages; existing maintenance systems; an ecosystem of producers, sellers, contractors; and an existing market of customers and users. Producers are also interested in participating in such a development, not only for the sake of testing new models, but also for the opportunities to diversify their products' portfolio.

With reduced R&D requirements upfront, this approach has the advantage of making a faster transition from design to manufacturing and scaling up production through a smoother process. Based on existing successful models, the **CRL** adapts products to respond to new needs, circularity and re-use potential.

7.3 FINANCIAL

Practical and technical aspects have a huge impact on the financial aspects. The **GTB** lab profile confirms the potential need for expensive upfront investment to create new products.

Relocation costs and IP restrictions have financial consequences on the cost of the **REMs**. Cost is one of the major preoccupations of the project teams, especially since circular solutions are often more expensive in the first stage and only become more financially interesting over time. The cost also has influences on other stakeholders. The construction teams' preference to work with existing solutions that are not reversible is significant, especially when the builders are responsible for the durability of the end-result and are not familiar with circular construction principles.

In the case of the **CRL**, the mix between existing systems and the use of low cost connectors has a positive impact on cost reduction for the P1 GIS prototype. Similarly, the reduction in the raw material usage of **P4Wall-linQ** generates an important cost reduction.

7.4 RECOMMENDATIONS

The **GTB Lab** stresses the importance of working with a full-size 3D module, which shows the full potential of the newly developed prototypes and can be used to communicate and convince other stakeholders to become partners.

The **REMs** team recommend a continuous financial assessment to ensure the feasibility to switch to production. The **GDC** team recommends the prototyping of a whole system, or a module, which allows assessing the feasibility of an element within a complex construction system. Strengthening the collaboration between different actors is a must for the **CRL** team. Further research is also necessary to achieve improved reversible solutions. For the **REM**, it became clear that it is important to clearly determine the design priorities before the start of prototyping as an effective measure to align design processes and stakeholders' objectives.



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8 CONCLUSIONS

The development of the prototyping has revealed that a multitude of opportunities are available for achieving circular building solutions. With a circular economy mindset, the prototyping exercise proves that single elements or systems, new or improved products in the market, all have the potential to make buildings more flexible, reversible, increase the value of their components and reduce waste.

Developing different construction systems to achieve BAMB objectives shows the necessity to translate circularity goals into **relevant selection criteria**, based on which, the continuous improvement of the prototypes/products can be monitored and evaluated. The reversible building and material passports selection criteria were based on the knowledge developed in the work package two and three of the BAMB project. (Reversible Building Design and Material Passports).

For a successful result, it is essential to understand the whole context; the user's needs; the functional requirements for reversibility; technical, operational and market opportunities; and constraints with which reversible components have to comply. This comprehensive approach helps to adopt specific development strategies.

The prototyping process has shown that different approaches to achieving circular buildings are possible. The BAMB teams have tested various ways to achieve innovative results, such as technical end engineering innovation, cross-sectoral knowledge transfer, improvement of existing products, and the use of local resources.

Strategic technical intervention on key essential components requires circular design capabilities. A holistic approach is necessary. **The circular design** of particular components should cope with essential building aspects such as, but not limited to: the comfort, the aesthetics, and the energy efficiency.

Within circular models, developing prototypes together with architects and engineers involves a longer collaboration, which exceeds the usual project duration and should be prolonged over the life cycle of the product. This change requires the **profound modification of the profession**. Reciprocally, other stakeholders such as material producers, sellers, and building contractors are likely to be more proactively involved in the design process. In this new context, not only the continuous **interaction of stakeholders** is important, but also the understanding of the new required roles.

New tools for assessment are necessary to keep the circular technical goals on track, such as lower environmental impact and carbon emissions, waste reduction and sparing the use of virgins materials and resources. The circular economy involves a systemic shift. This means



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assessment tools, calculation parameters such as allocation ratios, etc. have to be updated with circularity conditions, where responsibility and burdens are distributed differently amongst partners. The Circular Building Assessment tool will be developed within work package 5 action 1 (WP5A1) “Integrated decision making support and assessment model for management in buildings” and will build on feedback from the prototyping within the pilot projects.

All of these elements are making possible the emergence **of new business models** based on a value network eco-system. The prototype experiences test and feed the reflection on the business models developed in the WP5A2. It highlights the need for cross-sectoral partnerships; rethinking the revenue model and profitability patterns; and the need to pay careful attention to users’ needs, societal changes, and the convenience and experience that the circular economy solution should offer.

Finally, an important conclusion is based on the fact that failure should be part and parcel of the development. Lessons learned from errors are important resources for continuous improvements and success and can lead to unexpected innovative solutions.

The circular economy is a new global initiative. As our prototypes show, circularity is possible today and thus, now is the right time to put together opportunities, enthusiasm, strong beliefs and perseverance, and to build a more circular environment and society.



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