Prototype of improved insulation boards

Deliverable 2.1

Revised after review

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Date: 14 December 2023

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 10103685

Technical References

Project Acronym	**CIRCULAR FOAM**
Project Title	Systemic expansion of regional CIRCULAR Ecosystems of End-of-Life FOAM
Grant Agreement Number	101036854
Project Coordinator	Dorota Pawlucka, Covestro Deutschland AG dorota.pawlucka@covestro.com
Project Duration	October 2021 – March 2025 (48 months)

Deliverable No.	2.1
Dissemination Level[1]	PU
Lead Beneficiary	FIL
Issue Date	31.03.2023

[1]PU-public, CO-confidential, only for members of the consortium (including the Commission Services), EU-SEC-classified information: SECRET UE (Commission Decision 200/444/EC)

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Executive Summary

This report summarizes the progress and findings of Unilin Insulation (FIL) in Task 2.2. The objective of this project is to develop a practical and sustainable method for disassembling insulation systems composed of insulation boards at the building level, with the goal of enabling their reuse or recycling. In addition, the report offers valuable insights into the potential challenges associated with recycling technologies explored in WP4, along with a product redesign and prototype aimed at facilitating easier disassembly in WP3.

Approach:

- **Circularity assessment - insulation board**
  Here we will outline the key components of an insulation board and discuss the current challenges related to achieving circularity in this product category. We will identify and, where feasible, demonstrate specific modifications that can be made to improve circularity, with a particular focus on enhancing the facer material.

- **Circularity assessment - insulation systems on a building level**
  In this part, we will discuss the assessment of circularity in the built environment, with a focus on the EU initiative Level(s), which provides a standardized framework for this purpose. The analysis will identify the typical components of most building applications, using insulation boards, and will use circularity assessment tools on these build-ups (such as TOTEM and the disassembly potential measurement method 2.0) to calculate a circularity index for each system.

- **Construction/demolition process**
  We also will showcase a dismantling video that demonstrates the recommended build-up prototype for an insulation board system. This video highlights the ease of disassembly for one of the application systems (cavity wall). To gain deeper insights and more accurate results, we have conducted interviews with sorting, recycling, and demolition contractors. These interviews will help us to better understand the challenges and opportunities related to the disassembly and recycling of insulation board systems, and improve our recommendations.
  Video insulation board

Video insulation board (link to project website)

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1 Improved insulation board design (prototype)

PIR insulation boards are commonly utilized for insulating buildings, and their end-of-life can often result in their recovery as demolition waste. During the construction of new buildings, some materials are inevitably lost and may end up in a construction waste container in the form of "cut-offs." Depending on the country and applicable regulations, this waste is typically sorted from mixed waste containers and directed to a waste-to-energy facility for incineration. To facilitate recycling efforts, it is essential to consider how to collect PIR foam.

A typical PIR insulation board consists of foam and a facer material. The latter serves to fix the board's dimensions by containing the internal stress of the foam. The facer material is made of a multilayer material composed of very thin layers of PE, kraft paper, and/or aluminium. Historically, these facers have been developed to ensure a good and permanent bond between the facing and foam, even after installation, to prevent complaints under all circumstances. Additionally, the gas tightness of the facer is essential to maintain the board's insulating properties.

Removing the facer material from construction and demolition waste streams is challenging due to its excellent adhesion to the foam. At present, the facer material may or may not pose a problem for the recycling methods being investigated in WP4, namely, smart chemolysis and pyrolysis. Nonetheless, WP3 is investigating methods for removing the facer material from the foam for recycling purposes, should the need arise in the future.

To facilitate product redesign for recycling purposes, a monolayer facer material made of pure aluminum and a PU-adhesive that is compatible with PIR for chemical recycling purposes has been studied. This approach overcomes the issue of solvent absorption by kraft paper in smart chemolysis and allows for maintaining good adhesion, fixed dimensions, and sufficient gas tightness.

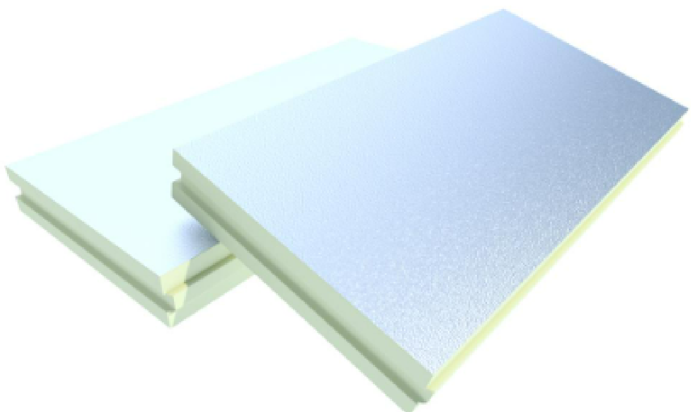

FIGURE 1: PIR INSULATION BOARD WITH MONOLAYER FACER MATERIAL MADE OF PURE ALUMINIUM

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2 State-of-the-art assessment factors circularity

2.1 Level(s), European Commission

The EU initiative integrates ideas about sustainable building by outlining the critical components of sustainability in the built environment and how to assess them both during the design process and after construction. User manuals and reporting templates are provided by *Level(s),* 2022. Each manual outlines a sustainability concept, how to put it into practice, and how to track and evaluate outcomes (using the templates). Although they can each be used independently as stand-alone concepts, they function best when combined, since there is some overlap. It offers a set of prioritized performance indicators for policy level(s) to concentrate on as well as a uniform foundation for establishing requirements. It offers a foundation for establishing carbon reduction targets and more general sustainability goals.

The common framework is organized into three levels, hence the name. The levels provide a choice as to how advanced the reporting on sustainability for the project will be. The three levels represent the following stages in the execution of a building project:

- Level 1: Conceptual design (qualitative assessments)
- Level 2: Detailed design and construction (quantitative assessments)
- Level 3: As-built and in-use (monitoring and surveying)

Level(s) doesn’t set benchmarks and is actually more a set of tools to help think about the many aspects of what sustainability means today. It is based on six overarching macro-objectives;

1. Greenhouse gas emissions along a building’s life cycle
2. Resource efficient and circular material life cycles
3. Efficient use of water resources
4. Healthy and comfortable spaces
5. Adaption and resilience
6. Optimized life cycle costs and value

This report focuses on objective 2: optimize the building design, engineering and form in order to support lean and circular flows, extend long-term material utility and reduce significant environmental impacts. Sub indicator 2.4, design for deconstruction, reuse + recycling, goes into even more detail and will therefore be used to quantify the different applications' circularity.

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FIGURE 2: INDICATOR 2 AND ITS SUB INDICATORS FROM LEVEL(S)

The indicator specifically measures the material efficiency of a building. This is determined by calculating the ratio of the mass of materials used in the construction of a building to the mass of materials that were extracted, produced, and imported. The result is expressed as a percentage, with a higher percentage indicating a higher level of material efficiency. To utilize this indicator, the user is required to input data regarding the materials used in the building, including the mass of materials used, the mass of materials extracted, produced, imported, and the percentage of recycled materials. The tool then calculates the ratio, providing a percentage of material efficiency. It is important to note that while Level(s) is primarily used to assess the sustainability of buildings, it is also relevant to building products as they play a significant role in the overall assessment of the building. In the calculation tool, it uses the circularity index found by a flow chart, as an intermediate step. This intermediate step will be the final result in this report, as it would otherwise take us too far. It can also be noted that the circularity scores may be biased towards certain components, as this score is expressed by mass. Following flow chart is used:

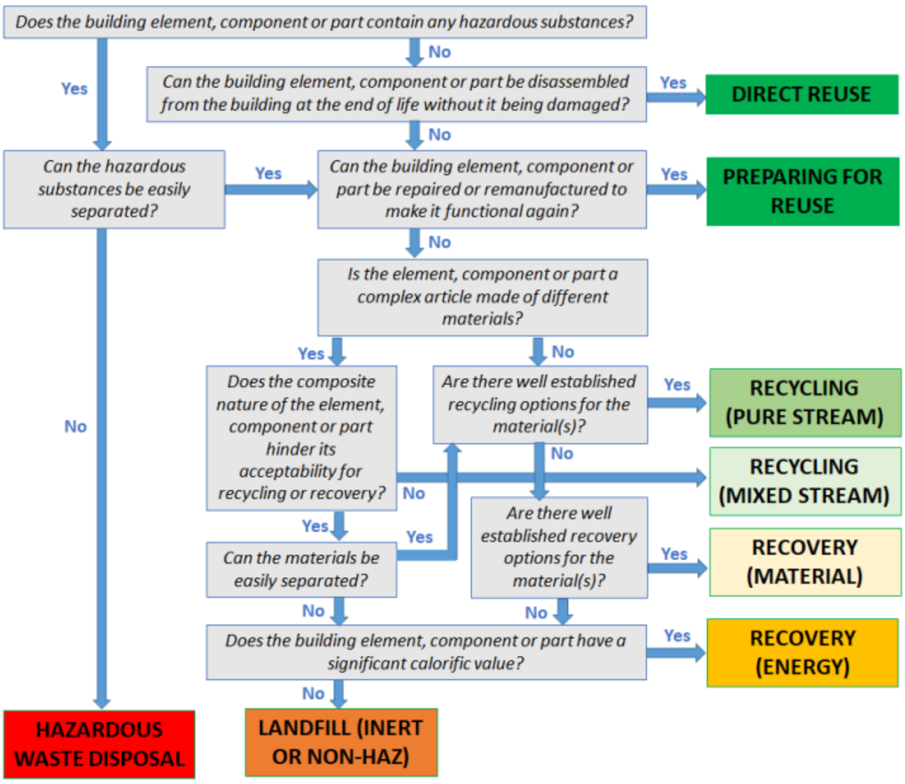

FIGURE 3: GENERAL LOGIC APPLICABLE FOR DECIDING ON BEST OUTCOMES FOR BUILDING ELEMENTS, COMPONENTS, PARTS OR MATERIALS

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The following coefficients can then be given to the result:

- Direct reuse, circularity coefficient = 1,00
- Preparing for reuse, circularity coefficient = 0,90
- Pure stream recycling, circularity coefficient = 0,75
- Mixed stream recycling, circularity coefficient = 0,50
- Material recovery, circularity coefficient = 0,25
- Energy recovery, circularity coefficient = 0,15
- Inert or non-hazardous landfill, circularity coefficient = 0,01
- Hazardous waste disposal, circularity coefficient = 0,00

Previous flow chart assumes an ideal scenario, if the product is detachable without damage, for example, it concludes that the component or element or part can be reused immediately, whereas this depends on many other factors, such as the waste stream, processing companies, demolition companies,... Just because something can be reused or recycled does not mean it will. Interviews with sorting, recycling and demolition contractors are needed to properly follow this flow chart and draw conclusions from it. To assess the detachability and any damages involved, we proceed to other methods, to later return to the flowchart with this information and obtain the circularity coefficient.

2.2 Detachability Potential

"The detachability of a building is the degree in which objects are demountable at all scales, without compromising the function of the object or surrounding objects in order to protect the existing value."

The methodology outlined in *Circular Buildings - een meetmethodiek voor losmaakbaarheid v2.0 - Dutch Green Building Council*, 2021, emphasizes that the detachability index of a product should not be considered an end goal, but rather as a tool to facilitate potential for reuse or recycling, as shown in Figure 4 of the methodology. It is important to note that the measurement method described, is specifically designed to quantify the level of detachability of an object, and should not be considered as an overall indicator of the product's circularity.

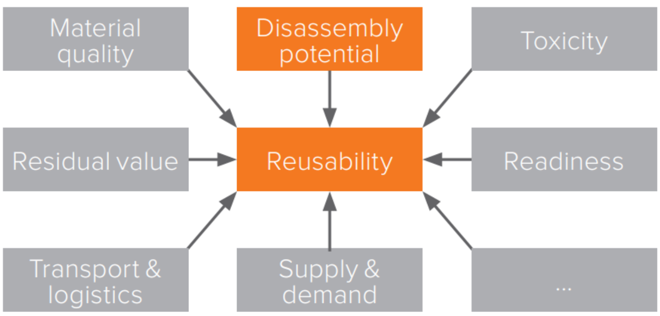

FIGURE 4: DETACHABILITY AS A FACTOR FOR REUSABILITY

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The concept of detachability is very relevant in product development. The method of measurement only considers products and components. Practical experience has shown that the detachability between different components of a product is crucial for the reuse of products.

The Disassembly Potential (DP) of the Connection (DP_c), is a metric that measures the ability to disassemble a product or component at the end of its useful life. It reflects the ease with which the product or component can be disassembled in reverse order of its assembly. This metric will be considered in further analysis and will be used as a basis for determining the feasibility of disassembly of the considered PU application.

The Disassembly Potential of the Composition (DP_{cp}) is a metric that measures the ease with which a product can be disassembled in intermediate stages, such as during renovation, conversion, repair, or replacement. This metric takes into account factors such as the independence and geometry of the product's edges in situations where surrounding products or elements are retained. The DP_{cp} is an important consideration for the feasibility of dismantling a product in intermediate stages and is not typically taken into account in traditional disassembly analyses.

The DP of a product or element is determined by these two indexes (DP_P). The methodology outlined in the report, including the roadmap illustrated in Figure 5, involves evaluating the connection type, accessibility, independency and geometry of the product edge, and using these values to calculate the DP for each specific application where PU is used.

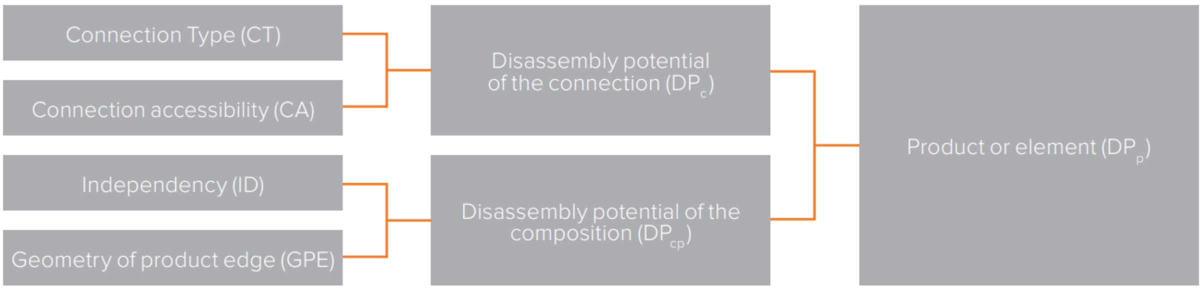

Figure 5: Roadmap for assessing the disassembly potential of a product or element

It is noteworthy that, in the previous methodology *Circular Buildings - een meetmethodiek voor losmaakbaarheid v1.1 - Dutch Green Building Council*, 2019, even if one of the factors scored low, the overall DP of the application may still be high due to favourable scores on other factors. This highlighted the need for a more nuanced and comprehensive assessment of the DP. They addressed this by employing the harmonic mean of the factors instead of the arithmetic mean in the calculation , as seen in the hereinafter mentioned formulas.

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The behaviour exhibited by this formula is such that low scores on one or more factors, referred to as "weak links", exert a disproportionate influence on the overall determination of the DP, providing a more realistic result.

To arrive at DP_P we use:

$DP_C = \frac{2}{\frac{1}{CT}+\frac{1}{CA}}$ and $DP_{CP} = \frac{2}{\frac{1}{ID}+\frac{1}{GPE}}$ in order to obtain $DP_P = \frac{2}{\frac{1}{DP_C}+\frac{1}{DP_{CP}}}$

The values for CT, CA, ID, and GPE can be found in the appendices and depend on each application. The closer DP_P is to 0,1 the smaller the detachability potential is. The closer DP_P is to 1, the larger the detachability potential is. If DP_P > 0,7; this is considered a high potential for detachability.

2.3 TOTEM

In addition to the previously described method, the DP is also evaluated utilizing *TOTEM,* 2023 (Tool to Optimize the Total Environmental Impact of Materials). TOTEM is a digital interface designed for use by the Belgian construction industry, with the goal of objectively reducing the environmental impact of buildings. This tool divides the DP into five potential categories and will be employed to assess and determine the DP in relation to reusability or recyclability for various applications of polyurethane (PU) in construction. This tool not only indicates if a connection is reversible or not, but also what kind of damage occurs with this operation.

If a connection is reversible (with or without damage), it is a first important step towards circularity. However, the actual reuse or recycling potential of the component involved will still be influenced by other determining factors, like simplicity of disassembly, speed of disassembly, handling, and robustness.

The following listing and its use in the following text refers only to PU and its connections and are extracted from TOTEM:

1. Non-reversible connections
2. Reversible connections with non-repairable damage
3. Reversible connections with light repairable damage
4. Reversible connections
5. Reversible connections not applicable or dependent on the construction method used

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3 Application types

3.1 Floor applications

3.1.1 PU insulation boards

Floor insulation boards made of PUR or PIR are pressure-resistant. These are placed on the floor base in order to apply the screed on this afterwards. There is a screed layer applied on top of these plates to hide the utilities. Only in function of the insulating characteristics of PU will there be a minimal height gain compared to other insulation materials.

Since in Belgium a PE film is placed above and below the insulation boards, these are well protected. They are also placed loose, which helps with any removal. In France e.g. they do not place these, which may produce a different result.

TOTEM: Reversible connection. Mounting type: loosely laid.

Circular Buildings: $DP_C = \frac{2}{\frac{1}{1}+\frac{1}{0{,}80}} = 0{,}89$ and $DP_{CP} = \frac{2}{\frac{1}{1}+\frac{1}{0{,}10}} = 0{,}18$ -> $DP_P = \frac{2}{\frac{1}{0.89}+\frac{1}{0{,}18}} = 0{,}30.$

0,30: low overall detachability potential. $DP_C = 0{,}89$ is a very high detachability potential of the connection, but because the insulation is under screed and a floor finish, DP_{CP} is the one that brings down the total DP_P. In the end-of-life phase, DP_C is the more important one.

Potential problems:

- Tackers (material: PVC) present in the panels if working with underfloor heating. These cause damage to both the facer at the top of the slab and the insulation material itself. Removal of tackers requires additional processing before proceeding to chemical recycling.

  Toward circularity, the problem of damage depends on the application for reuse, depending on how big the problem is in particular applications; reuse in a flooring application should not be a problem.

FIGURE 6: TACKER ON THE LEFT AND INSTALLATION OF THE UNDERFLOOR HEATING ON THE RIGHT

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TOTEM: Reversible connection with non-repairable damage.

Circular Buildings: $DP_C = \frac{2}{\frac{1}{1}+\frac{1}{0,80}} = 0,89$ and $DP_{CP} = \frac{2}{\frac{1}{0,40}+\frac{1}{0,10}} = 0,16$ -> $DP_P = \frac{2}{\frac{1}{0,89}+\frac{1}{0,16}} =$ $0,27$.

Same comments as above, but here occasional crossing because of the tackers (ID = 0,40).

- One component foam (OCF) is used to seal seams along the floor and the wall. According to Circular Buildings - Disassembly potential measurement method 2.0, an OCF is a soft chemical bond that ranks second to worst in terms of detachability (after a hard chemical bond such as an adhesive or welded bond). The question is whether residual OCF on insulation boards are critical to the recycling process.

FIGURE 7: EXAMPLE USE OCF (HERE, ROOF AND WALL CONNECTION)

TOTEM: The board on itself is reversible connected (loosely laid). The OCF – insulation board connection is a non-reversible connection.

Circular Buildings: OCF – PU board: $DP_C = \frac{2}{\frac{1}{0,20}+\frac{1}{0,80}} = 0,32$ and $DP_{CP} = \frac{2}{\frac{1}{0,40}+\frac{1}{0,10}} = 0,16$ -> $DP_P = \frac{2}{\frac{1}{0,32}+\frac{1}{0,16}} = 0,21$ -> very low overall detachability potential.

This problem applies to all subsequent applications and side applications where OCF is used to seal the seams or possibly fasten the boards.

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3.2 Wall applications

3.2.1 PU insulation boards along the outside

There are a number of reasons why insulating walls along the outside is the most interesting method. The first reason is space gain. If you insulate the walls along the outside, then the interior space remains intact. A second reason is the fact that an insulation layer along the outside forms an unbroken insulation shield around the house. There is a distinction in type of construction of the wall, how the insulation panels are attached or united in the whole of the exterior wall. We can consider four wall constructions frequently used which contains PU; a cavity wall structure, a ventilated façade, ETICS and structural insulated panel (SIP).

- A cavity wall structure is a wall consisting of an inner leaf, which is load-bearing, and outer leaf separated by a layer of air (the cavity). The cavity contains full or partial insulation material. The inner and outer leaves are connected via cavity anchors; the insulation boards are first fixed with PVC or PP plugs to the loadbearing wall (via hole drilling) and then a galvanized or stainless steel anchor is placed in the horizontal mortar beds of the outer brick leaf. They often have a spacer so that the PU board is pressed against the inner leaf and cannot form a moisture bridge/cold bridge. A cavity anchor can also consist of individual parts that provide acoustic insulation via an intermediate element.

FIGURE 8: PLACING THE PLUGS THROUGH THE INSULATION AFTER DRILLING, THE TAPE IS VISIBLE ON THE MIDDLE PICTURE, THE ANCHOR ON THE RIGHT

It is advised to maintain at least 5 cavity anchors per square meter as opposed to the 2 in the Eurocode for the minimum requirement. The strains in the masonry increase as the distances between the cavity anchors increase.

TOTEM: Reversible connection with non-repairable damage. Mounting type: mechanically fixed.

Circular Buildings: $DP_C = \frac{2}{\frac{1}{0{,}80}+\frac{1}{1}} = 0{,}89$ and $DP_{CP} = \frac{2}{\frac{1}{0{,}40}+\frac{1}{0{,}10}} = 0{,}16$ -> $DP_P = \frac{2}{\frac{1}{0{,}89}+\frac{1}{0{,}16}} = 0{,}27$.

High DP_C, very low DP_{CP} -> low DP_P

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Potential problem: The tape used to provide a windtight finish to the seams of the insulation boards.

TOTEM: Reversible connection.

Circular Buildings: $DP_C = \frac{2}{\frac{1}{0,10}+\frac{1}{1}} = 0,18$ and $DP_{CP} = \frac{2}{\frac{1}{1}+\frac{1}{0,10}} = 0,18$ -> $DP_P = \frac{2}{\frac{1}{0,18}+\frac{1}{0,18}} = 0,18$.

0,18: very low detachability potential. (tape – insulation board)

FIGURE 9: DAMAGE TO THE FACER, SEEN AT THE BOTTOM OF THE FIGURE

Each situation has to be considered separately, as each joint can be different, in the appendices we find a value for CT of 0,1 because this is an adhesive joint (tape). In practice, it has been shown that the tape can be removed from the boards smoothly and with limited damage (facer is damaged though).

FIGURE 10: INSULATING UNEVEN WALL

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Another potential problem: If the substrate of the bearing wall is not completely level, you can fill it out with a leveling mortar (after-insulation situation). Since this is a rather expensive and labor-intensive task, you can opt to place PU sheets with a layer of mineral wool affixed to it. The mineral wool cushions the unevenness so the insulation boards can still be placed fairly flat and so there is no convection behind the boards. This product category can also be used in a ventilated facade or ETICS application. So this issue also hits subsequent bullets.

TOTEM: Here the composite insulation board – rest of structure is a reversible connection with non-repairable damage. Mounting type: mechanically fixed.
The connection PU sheet – mineral wool is a non-reversible connection.

Circular Buildings: (mineral wool – PU insulation board): $DP_C = \frac{2}{\frac{1}{0,10}+\frac{1}{1}} = 0,18$ and $DP_{CP} = \frac{2}{\frac{1}{1}+\frac{1}{0,10}} = 0,18$ -> $DP_P = \frac{2}{\frac{1}{0,18}+\frac{1}{0,18}} = 0,18$.

0,18: very low detachability potential.

Composite board – wall: supra cavity wall insulation (overall $DP_P = 0,27$, $DP_C = 0,89$).

- A ventilated façade is composed of a load-bearing wall, an insulation layer and a cladding fixed to the building's load-bearing structure. Thanks to this structure, between the load-bearing wall and the cladding, an air cavity allows ventilation. First, the insulation is fixed against the supporting wall with the plugs described above. Then, a frame made of moisture-resistant material (aluminium or wood) is mechanically anchored with stainless steel fasteners in to the plugs. Hereafter cladding in sidings or sheeting are attached to the frame.

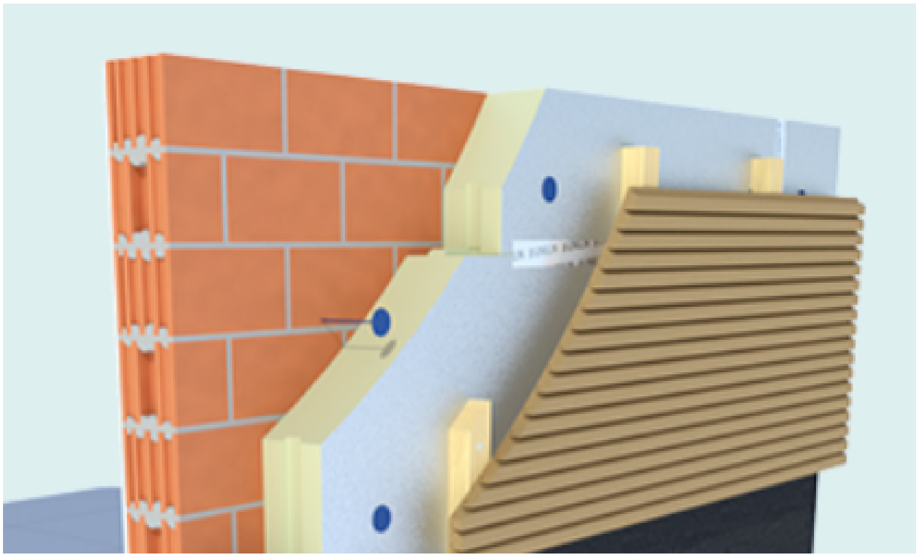

FIGURE 11: VENTILATED FAÇADE

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TOTEM: Reversible connection with non-repairable damage. Mounting type: mechanically fixed.

Circular Buildings: $DP_C = \frac{2}{\frac{1}{0,80}+\frac{1}{0,80}} = 0,80$ and $DP_{CP} = \frac{2}{\frac{1}{1}+\frac{1}{0,10}} = 0,18$ -> $DP_P = \frac{2}{\frac{1}{0,80}+\frac{1}{0,18}} = 0,29.$

0,29: low overall detachability potential. But high DP_C (0,80).

FIGURE 12: DAMAGE TO THE INSULATION BOARD AFTER REMOVAL MECHANICAL FASTENING MATERIALS

- ETICS is the abbreviation for "External Thermal Insulation Composite System". The ETICS is distinct from other exterior insulation methods in that the exterior surface is integrated with the insulation material, creating a unified and sealed finish, as seen on Figure 14. The compatibility and durability of the "finish-insulation" combination is crucial. The system is built in layers, starting with the interior and moving outward. These layers include the fasteners (such as adhesives [1] or mechanical fasteners [3]), the thermal insulation material [2] (commonly EPS or mineral wool, but polyurethane can also be used), and the plaster finish (consisting of a reinforced base layer [4 & 5] and a final plaster layer [6]). So the insulation boards are glued and mechanically fixed to the load-bearing wall, plus these are hereafter plastered.

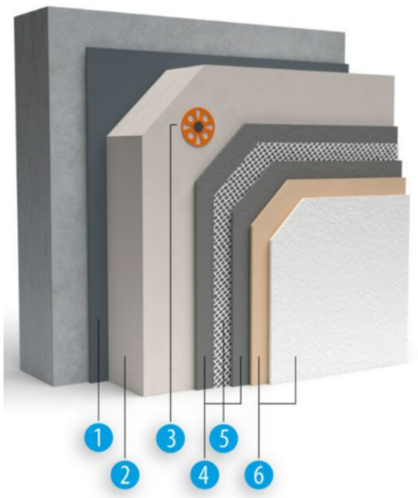

FIGURE 13: ETICS CROSS-SECTION

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TOTEM: Non-reversible connection.

Circular Buildings: $DP_C = \frac{2}{\frac{1}{0{,}10}+\frac{1}{0{,}10}} = 0{,}10$ and $DP_{CP} = \frac{2}{\frac{1}{0{,}40}+\frac{1}{0{,}10}} = 0,16$ -> $DP_P = \frac{2}{\frac{1}{0{,}10}+\frac{1}{0{,}16}} =$ $0{,}12$.

0,12: very low overall detachability potential.

- SIP stands for Structural Insulated Panels; structural insulating sandwich panels. This means that SIP panels combine insulation (PU) and the load-bearing structure in one. Depending on the type

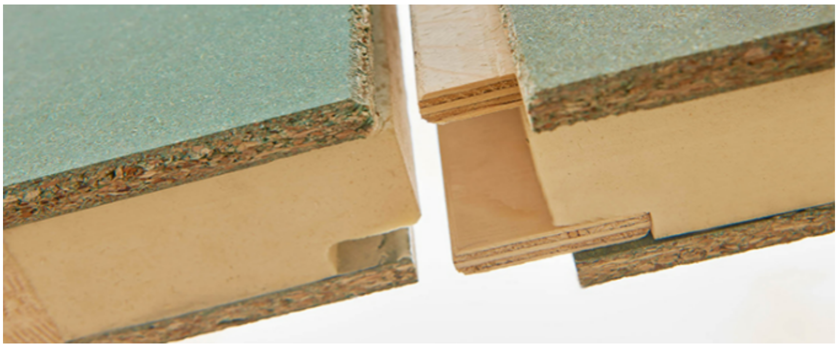

FIGURE 14: SIP WITH PU AND CHIPBOARD TRIM

of SIP panel, these panels are interconnected with an insulated connecting spline or integrated coupling bars, creating an airtight connection. Direct fixation or full-surface bonding of the inner and outer leaf with the rigid insulation core creates a structural sandwich element with high rigidity and strength. OSB, chipboard, plywood, steel , or fiber cement are the most common sheet materials used for this application.

TOTEM: Non-reversible connection (PU – structural panels). Reversible connection with light repairable damage (SIP on its own).

Circular Buildings: (PU – structural panels): $DP_C = \frac{2}{\frac{1}{0{,}10}+\frac{1}{0{,}10}} = 0{,}10$ and $DP_{CP} = \frac{2}{\frac{1}{0{,}10}+\frac{1}{0{,}10}} = 0{,}10$ -> $DP_P = \frac{2}{\frac{1}{0{,}10}+\frac{1}{0{,}10}} = 0{,}10$ -> lowest possible overall detachability potential possible.

(SIP on its own): $DP_C = \frac{2}{\frac{1}{0{,}80}+\frac{1}{0{,}80}} = 0{,}80$ and $DP_{CP} = \frac{2}{\frac{1}{1}+\frac{1}{0{,}10}} = 0,18$ -> $DP_P = \frac{2}{\frac{1}{0{,}80}+\frac{1}{0{,}18}} =$

0,29 -> low overall detachability potential possible. But high DP_C $(0{,}80)$.

3.2.2 PU insulation boards along the inside

In the case of interior changes or renovations, but also in the case of new construction, insulating the outside wall from the inside can be a good alternative to insulating from the outside. Monumental buildings and protected townscapes or row houses can also pose problems when insulating from the outside. We can divide this application into 3 categories. The first is the glued or the chemically

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attached, the 2nd includes the mechanically fixed and finally there are the composite systems, such as the combined PU – plasterboard or OSB elements.

- Usually the insulation boards are glued (adhesive plaster / foam glue) without mechanical fastening. After this (on the installed latticework) the finishing layer (plasterboard, ...) is mounted.

  TOTEM: Non-reversible connection.

  Circular Buildings: $DP_C = \frac{2}{\frac{1}{0,10}+\frac{1}{0,40}} = 0{,}16$ and $DP_{CP} = \frac{2}{\frac{1}{0,40}+\frac{1}{0,10}} = 0{,}16$ -> $DP_P = \frac{2}{\frac{1}{0,16}+\frac{1}{0,16}} = 0{,}16$

  0,16: very low overall detachability potential.

- The insulation boards can also be applied on the inside of the bearing wall using mechanical fastening only. Here the glue or foam is omitted and the boards are mechanically fastened against the load-bearing wall. After this (on the installed latticework) the finishing layer (drywall, ...) is mounted.

  TOTEM: Reversible connection with non-repairable damage. Mounting type: mechanically fixed.

  Circular Buildings: $DP_C = \frac{2}{\frac{1}{0,80}+\frac{1}{0,80}} = 0{,}80$ and $DP_{CP} = \frac{2}{\frac{1}{0,40}+\frac{1}{0,10}} = 0{,}16$ -> $DP_P = \frac{2}{\frac{1}{0,80}+\frac{1}{0,16}} = 0{,}27$

  0,27: low overall detachability potential. But high DP_C $(0{,}80)$.

- Combined elements consist of a PU insulation board with vapor-tight covering provided on one side with a plasterboard finishing board or another finish material. The method of attachment ultimately ensures what reversibility is obtained.
  - The attachment can be full-face glued, but generally, in dots with continuous lines around the edges, to the wall behind or a combination of mechanically and chemically fastened. (more common in large projects)

    TOTEM: Non-reversible connection. (elements on their own)

    Non-reversible connection. (PU – finishing layer/plate)

    Circular Buildings: $DP_C = \frac{2}{\frac{1}{0,10}+\frac{1}{0,40}} = 0{,}16$ and $DP_{CP} = \frac{2}{\frac{1}{0,40}+\frac{1}{0,10}} = 0{,}16$ -> $DP_P = \frac{2}{\frac{1}{0,16}+\frac{1}{0,16}} = 0{,}16$

    0,16: very low detachability potential

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FIGURE 15: COMBINED ELEMENT (GLUED), PU WITH A PLASTERBOARD AS INTERIOR FINISH

- Most common in smaller projects, is mechanical fastening. Mechanical fastening on wooden or aluminium latticework is prescribed. The elements are screwed to the rafters with phosphated drywall screws, if drywall is the chosen finish layer, otherwise non-phosphated screws are sufficient.

  TOTEM: Reversible connection with non-repairable damage. Mounting type: mechanically fixed. (elements on their own)

  Non-reversible connection. (PU – finishing layer/plate)

  Circular Buildings: $DP_C = \frac{2}{\frac{1}{0,80}+\frac{1}{0,40}} = 0,53$ and $DP_{CP} = \frac{2}{\frac{1}{0,40}+\frac{1}{0,10}} = 0,16$ -> $DP_P = \frac{2}{\frac{1}{0,53}+\frac{1}{0,16}} = 0,25$

  0,25: low overall detachability potential.

3.3 Roof applications

3.3.1 Flat roof

- Warm roof

Warm roofs are the most commonly used solution. It consists of installing the insulation on the roof floor without providing an air cavity between layers. The waterproofing is applied on the insulation with or without a separating layer and may also be provided with a ballast layer. The roof floor should usually be lined with a vapor barrier. The fastening of the insulation boards can be done in several ways: mechanical fastening, full or partial adhesion (glue) or loose laying with ballast.

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The various methods are outlined below. When using slope insulation, using 2 layers of insulation or when 2 layers of insulation is required anyway, any fastening method/construction discussed below can be used.

When you talk about mechanical fastening, it means 1 of 2 things:

- Securing the insulation to the substructure using a screw and pressure distribution plate or screw and grommet, hereafter bonding or welding the roofing to the insulation

  or

- Securing the roofing through the insulation layer to the substructure using a screw and pressure distribution plate or screw and plastic grommet and if necessary by additional fixings in the boards itself

FIGURE 16: MECHANICAL FASTENING OF BOTH INSULATION AND ROOFING MATERIAL

Unlike glued systems, mechanical fastening always allows for correction should a fastener be improperly placed/assembled. For each zone on the roof, the exact number of fasteners and type of fastener can be determined by wind load calculation. It is prescribed that at least 4 fasteners are required for boards up to 1.5 m² and at least 6 for boards up to 3 m². Immediately after the roof fasteners are installed, they can take the full wind load. Insulation is increasingly used in multiple layers due to higher insulation requirements. Mechanical fasteners allow these layers to be secured with a single roof fastener. (This method is very suitable for lightweight roofs, such as steel roofs.)

If the roofing is also connected along with the mechanical fastening as mentioned above in the 2nd bullet, only then is the insulation board, according to;

TOTEM: reversibly connected with non-repairable damage.

Circular Buildings: $DP_C = \frac{2}{\frac{1}{0,80}+\frac{1}{0,80}} = 0,80$ and $DP_{CP} = \frac{2}{\frac{1}{1}+\frac{1}{0,10}} = 0,18$ -> $DP_P = \frac{2}{\frac{1}{0,80}+\frac{1}{0,18}} = 0,29$

0,29: low overall detachability potential. But very high DP_C $(0,80)$.

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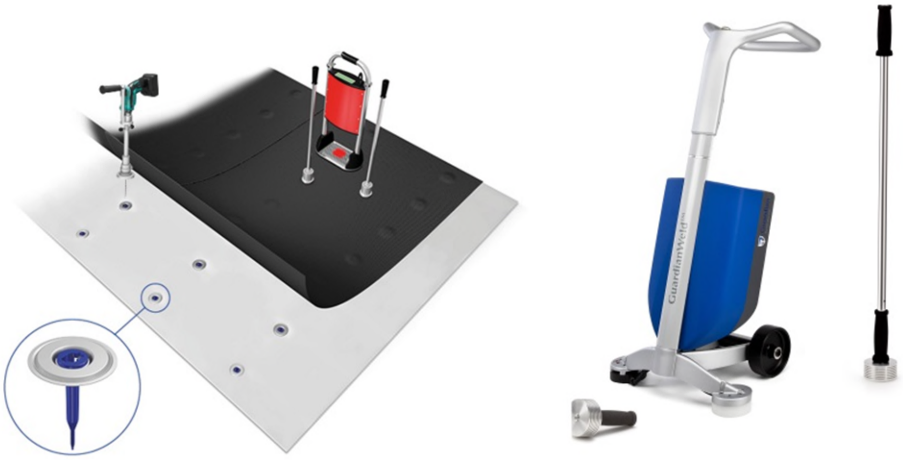

FIGURE 17: PRINCIPLE OF INDUCTION WELDING

An exception is the induction welding system, in which the roof membrane in PVC, TPO and EPDM is fixed without penetration of the roof membrane. Using induction technology, the roof membrane is bonded to the specially developed pressure distribution plates, as seen on previous Figure.

If the roofing is connected to the insulation in another way, reference is made to the fastening method that is explained hereafter.

There are 2 types of adhesives used to attach the PU boards to the roof floor in most cases.

- First one is cold adhesives; thermal insulation boards on flat roofs are increasingly bonded with synthetic polyurethane (PU) based cold adhesives. PU foams are usually applied in a striped or pendulum fashion. The spacing of the foam beads depends on the expected wind load and will therefore be smaller in the edge and corner zones than in the middle zone of the flat roof. A bituminous cold adhesive can also be used. Bituminous cold adhesives are applied to a roof floor that has been previously dusted and degreased, either over the entire surface or in points or evenly spaced strips.

FIGURE 18: GLUING INSULATION BOARD WITH PU COLD ADHESIVE

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- Second one is adhesion with hot bitumen. The placement consists of pouring a continuous layer of bitumen on the surface of the supporting floor (roof floor or bituminous vapor barrier) and to press the insulation boards into the still warm bitumen. One should ensure that an adequate amount of bitumen is applied and that the insulation boards are installed immediately afterwards, before the bitumen hardens and loses its adhesive ability.

TOTEM: Non-reversible connection.

Circular Buildings: $DP_C = \frac{2}{\frac{1}{0,10}+\frac{1}{0,60}} = 0,17$ and $DP_{CP} = \frac{2}{\frac{1}{1}+\frac{1}{0,10}} = 0,18$ -> $DP_P = \frac{2}{\frac{1}{0.17}+\frac{1}{0,18}} = 0,18$

0,18: very low overall detachability potential.

Loose laying with ballast means as much as loose insulation boards, so they are not mechanically or via an adhesive layer attached to the supporting structure. Above this, the roof cover is laid loose and held in place with a ballast. A ballast layer is usually a layer of gravel or tiles as weight to hold the roofing package in place on a flat roof and to protect the roofing from UV radiation (UV radiation causes bitumen roofing to age faster). Tiles are also sometimes used as walkways to protect the and at the edges of the roof to prevent the gravel from rolling off the roof in a heavy storm.

The structure is as follows, on the bearing floor [1] (+possibly a slope concrete layer [2]) a vapor barrier [3], for example bitumen that is fiberglass reinforced (loose laid), then the PU insulation boards [4] (loose laid), on top of that a bituminous or a synthetic roofing [5] (loose laid), above this possibly a separation layer in polyester to separate the ballast from the roof finish and the ballast [6] placed last on this assembly. In order to prevent the seal from being lifted by the wind, the contractor must provide a temporary ballast (immediately after the placement of the seal).

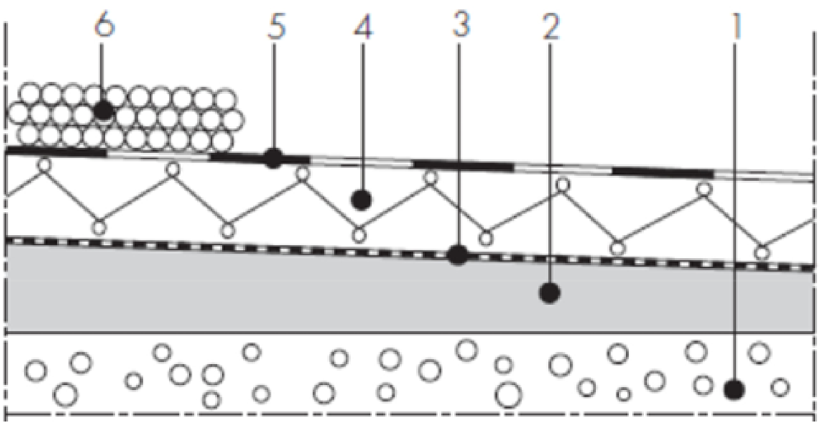

FIGURE 19: CROSS-SECTIONAL BALLASTED ROOF STRUCTURE

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TOTEM: Reversible connection.

Circular Buildings: $DP_C = \frac{2}{\frac{1}{1}+\frac{1}{1}} = 1{,}00$ and $DP_{CP} = \frac{2}{\frac{1}{0{,}80}+\frac{1}{1}} = 0{,}89$ -> $DP_P = \frac{2}{\frac{1}{1}+\frac{1}{0{,}89}} = 0{,}94$

0,94: very high overall detachability potential. Highest DP_C (1,00).

3.3.2 Pitched roof

- Rafter roof

In architecture, the function of a rafter is to support the roof structure, including the loads applied to it by roofing, snow, wind and so on. It transfers the total of these forces, including its own weight, vertically to the building structure below. Usually these are load-bearing walls or a parapet of an attic on which the wall plate is anchored.

There are three ways to apply PU boards to this type of roof. The first is to cut boards to size and place them between the rafters. A second possibility, more commonly used with after insulation, is to place PU sheets below (inside) the rafters. A third and also the most performing solution is to place PU plates on top (outside) of the rafters. The great advantage over insulating from the inside is the uninterrupted insulation shield and the elimination of thermal bridges.

- PU boards between the rafters (insulating from the inside) is rather a theoretical solution, because this technique requires many labour hours to customize each board. Usually soft insulation materials are used in this application. The sheets are usually not mechanically fastened, but placed between the rafters via a fit and/or a OCF. After this, the vapor barrier is also placed through the inside against the rafters and the insulation placed between them. Seems are filled with OCF.

FIGURE 20: PU BOARDS BETWEEN THE RAFTERS

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TOTEM: Reversible connection with non-repairable damage.

Circular Buildings: $DP_C = \frac{2}{\frac{1}{0,20} + \frac{1}{0,60}} = 0{,}30$ and $DP_{CP} = \frac{2}{\frac{1}{1} + \frac{1}{0,10}} = 0{,}18$ -> $DP_P = \frac{2}{\frac{1}{0.30} + \frac{1}{0,18}} =$

$0{,}23$

0,23: low overall detachability potential.

- If opted for PU boards below the rafters (insulating from the inside) then the insulation boards are mechanically fastened in 1 plane against the rafters using mechanical fastening. Afterward a finish can be placed against it to hide the insulation.

FIGURE 21: INSULATION BOARDS AGAINST THE RAFTERS

TOTEM: Reversible connection with non-repairable damage. Mounting type: mechanically fixed.

Circular Buildings: $DP_C = \frac{2}{\frac{1}{0,80} + \frac{1}{0,60}} = 0{,}69$ and $DP_{CP} = \frac{2}{\frac{1}{1} + \frac{1}{0,10}} = 0{,}18$ -> $DP_P = \frac{2}{\frac{1}{0.69} + \frac{1}{0,18}} =$

$0{,}29$

0,29: low overall detachability potential. But high DP_C (0,69).

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Also combined products/elements are used for this. That is, a finishing layer (mostly drywall) is already attached to the insulation board and it is attached to the rafters via screws through the assembly to the roof construction. Seams are present around the roof surface and are also filled with OCF.

FIGURE 23: COMBINED PU - OSB ELEMENTS

FIGURE 22: COMBINED PU - DRYWALL BOARD

Attic floors are finished similarly in some cases. Here the composite boards are fastened to the wood floor construction with screws. The finish of the insulation boards is then usually an OSB board or a chipboard.

TOTEM: Reversible connection with light repairable damage. Mounting type: mechanically fixed. (elements on their own)

Non-reversible connection (PU – finishing layer/plate).

Circular Buildings: $DP_C = \frac{2}{\frac{1}{0,80}+\frac{1}{1}} = 0{,}89$ and $DP_{CP} = \frac{2}{\frac{1}{1}+\frac{1}{1}} = 1$ -> $DP_P = \frac{2}{\frac{1}{0.89}+\frac{1}{1}} = 0{,}94$

0,94: very high overall detachability potential. Since no finish is normally placed afterwards.

- The best thermally performing way to insulate a truss roof is via PU boards on top of the rafters (insulating from the outside) this method of construction is called a sarking roof. In sarking construction, the PU insulation boards are placed on top of the supporting structure, eliminating thermal bridges and creating a windtight insulation shield. This system is mainly used in renovation projects and applied after removal of the roofing, the tile battens and other lathing through the outside of the roof. This is also a user-friendly method for new construction projects. First, a vapor barrier is placed. Usually rigid, pressure-resistant insulation boards made of PU or another type of rigid foam are then placed on top.

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These boards, which are tongue and grooved, are screwed (including battens) to the rafters with long screws. Any seams at the ridge of the roof are filled with OCF. This is followed by a under-roof liner and the roof finish.

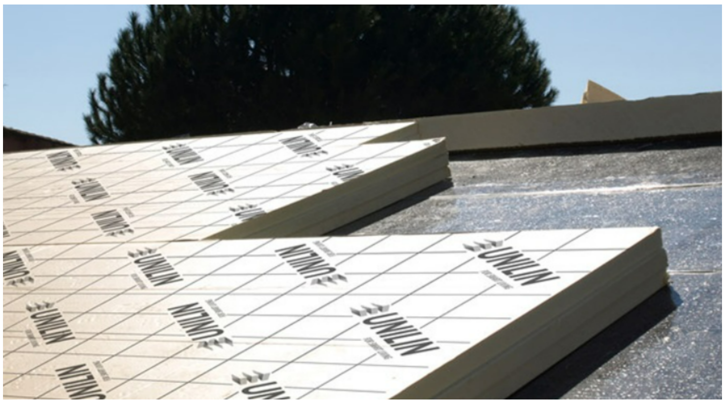

FIGURE 24: INSULATION BOARDS ON TOP OF THE RAFTERS

TOTEM: Reversible connection with non-repairable damage. Mounting type: mechanically fixed.

Circular Buildings: $DP_C = \frac{2}{\frac{1}{0,80}+\frac{1}{0,80}} = 0,80$ and $DP_{CP} = \frac{2}{\frac{1}{1}+\frac{1}{0,10}} = 0,18$ -> $DP_P = \frac{2}{\frac{1}{0.80}+\frac{1}{0,18}} = 0,29$

0,29: low overall detachability potential. But high DP_C (0,80).

- Purlin roof

A purlin roof, consists of heavy wooden beams, also called purlins. The purlins are placed horizontally and run from wall to wall. The purlins are also bricked into the wall at the ends. Purlins may be spaced a certain distance apart. Over the purlins are placed vertically less-thick, the rafters. The purlins and rafters form the basis for the under-roof. Because the purlins are connected to both side walls, a large distance is bridged. If the distance between the two side walls is too large, you can choose to build another wooden structure in the middle around which the purlins rest. As with the rafter roof, there are several options for installing the insulation.

- Usually renovations will use insulation from the outside. Again, reference is made back to the rafter roof because, with respect to fastening and reversibility, these correspond. A quicker and easier solution are combined insulation panels. These are strong, ready-to-use panels made of rigid foam (PU) that are already equipped with a vapor barrier, insulation, underlayment and battens in wood or metal.

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With these panels, a sarking roof can be realized quickly and the roof is immediately airtight, windproof and waterproof after the panels are installed. This is a great advantage over traditional insulation, where the vapor barrier, the under-roof, the insulation and the battens have to be installed separately. A solution for better sound insulation is that there is wood fibre board attached to the PU board. This is also glued and serves as an underlayment.

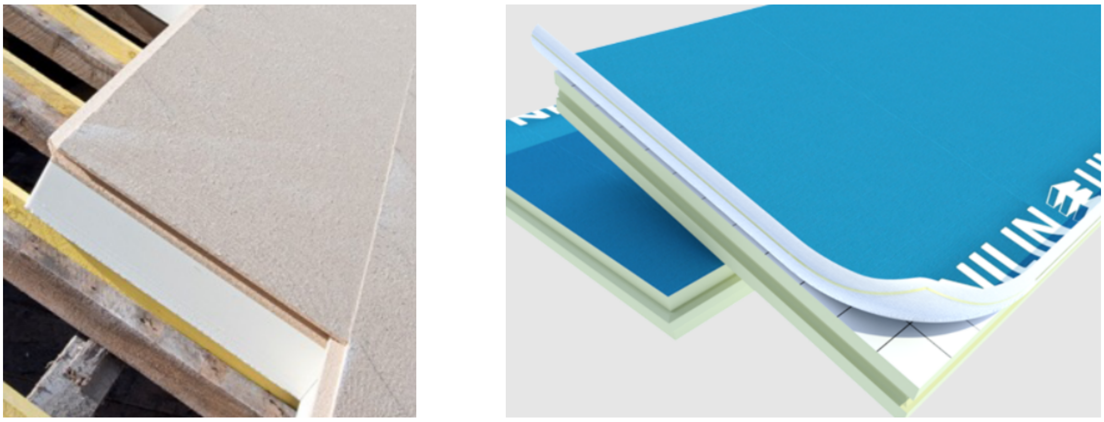

FIGURE 25: COMBINED ELEMENT WITH WOOD FIBER BOARD AS AN UNDERLAYMENT LEFT, RIGHT WITH A UNDERLAYMENT SCREEN

<u>TOTEM:</u> Reversible connection with non-repairable damage. Mounting type: mechanically fixed. (elements on their own)

Non-reversible connection (PU – rest of element -> underlayment and vapor barrier).

<u>Circular Buildings:</u> (PU – underlayment and vapor barrier): $DP_C = \frac{2}{\frac{1}{0{,}10}+\frac{1}{0{,}10}} = 0{,}10$ and $DP_{CP} = \frac{2}{\frac{1}{0{,}10}+\frac{1}{0{,}10}} = 0{,}10$ -> $DP_P = \frac{2}{\frac{1}{0{,}10}+\frac{1}{0{,}10}} = 0{,}10$ -> lowest possible overall detachability potential possible.

(element on its own): $DP_C = \frac{2}{\frac{1}{0{,}80}+\frac{1}{0{,}80}} = 0{,}80$ and $DP_{CP} = \frac{2}{\frac{1}{1}+\frac{1}{0{,}10}} = 0{,}18$ -> $DP_P = \frac{2}{\frac{1}{0{,}80}+\frac{1}{0{,}18}} = 0{,}29$ -> low overall detachability potential possible, but high DP_C (0,80).

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4 Ranking of the attachment methods and applications

The Detachability Potential and TOTEM calculations have allowed us to analyse the circularity index by method of fixation based on Level(s) as depicted in Figure 3. A ranking system can be established that results in three distinct outcomes, using previous results and insights. When polyurethane (PU) is adhered to one or both sides, the connections are considered non-reversible, making it impossible to separate the pure stream of PU for recycling purposes. The combined product can only be utilized for energy recovery, resulting in a circularity index of 0,15. In the case of mechanically attached methods, damage to the products is irreversible, but they can still be detached from the structure in their pure form, allowing for chemical recycling. This results in a circularity index of 0,75. Finally, when PU is placed loose or clamped, it can be reused directly, resulting in a circularity index of 1,00.

Based on the analysis, we should prioritize promoting mechanically attached and loose applications in the market. We plan/are working on to share these findings during stakeholder interviews to gauge their reactions and attitudes towards this strategy.

The results of our assessment of our insulation boards summarized:

Gluing → in function of detachability and thus circularity: avoid!

circularity coefficient of 0,15

Mechanical fastening → recommended toward chemical recycling

circularity coefficient of 0,75

Loose applications → recommended toward direct reuse

circularity coefficient of 1,00

FIGURE 26: GENERALIZED FINDINGS OF THE ASSESSMENT

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5 Stakeholder interviews

Moving forward, engaging with stakeholders is crucial to gather their perspectives on the analysis results. The stakeholders, including architects, contractors, and demolishers, offer valuable insights into various aspects of the polyurethane (PU) product lifecycle. Architects and specifiers play a critical role in determining how PU products will be used, and their decisions on attachment methods are highly relevant to the circularity index. Meanwhile, contractors and demolishers offer practical insights into the feasibility of different attachment methods and the necessary steps to facilitate effective pure stream recycling or reuse.

5.1 Demolition and recycling companies

Incorporating the feedback of these stakeholders is essential to ensure that the circularity index analysis leads to meaningful and positive outcomes for all parties involved. Involving them in the discussion can also encourage greater collaboration and cooperation between different industry players, ultimately leading to more sustainable outcomes. In conclusion, engaging with architects, contractors, demolishers, sorters, and recyclers is vital in ensuring the success and impact of the detachability and circularity index analysis.

The visits to recycling and demolition companies has revealed a concerning finding regarding the handling of polyurethane (PU) sheets from demolition sites and renovations. Despite the detachment potential or method of fixation, the PU sheets were found to be mixed and sorted for incineration. This is a clear indication of the lack of effective recycling and reuse efforts for PU products. The pictures below from De Meuter, a demolition and sorting company, further reinforce this finding.

FIGURE 27: PU AMONG OTHER PLASTICS AND LIGHT MATERIAL AFTER SORTING

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FIGURE 28: PLASTICS AND OTHER CONTAMINANTS BEFORE SORTING

5.2 Contractors

During an interview with a flat roof and façade contractor (SIX by Tectum), the topic of discussion focused on the feasibility of mechanical fastening and loose-fitting applications as the standard method of installation. It was revealed that this is not a viable option due to several key reasons. One of the primary challenges associated with mechanical fastening is the significant amount of labour time required to pre-drill every necessary location in a pre-cast concrete support structure. This presents a significant challenge in terms of both the time and resources required to complete the process. Another issue is the inapplicability of ballast roofs with loose boards in certain build-ups, such as industrial buildings, where there are numerous steel structures. The additional weight imposed by the ballast can become a significant burden on the building, making this approach untenable. Furthermore, ballasting also presents practical challenges in terms of processing times, as it is dependent on both altitude and weather conditions. This requires the provision of a provisional ballast, adding further complications to the installation process.

Further interviews will be conducted.

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6 Conclusion

To conclude, this report provides a detailed analysis of the circular potential of insulation boards, with a particular focus on detachability and the circularity index. The findings highlight the critical role of the fixation method in determining the feasibility of recycling and reuse, and the importance of the circularity index as a decision-making tool for manufacturers and consumers.

The demonstration video not only teaches the correct method for removing insulation boards in cavity wall construction, but also highlights the potential for deconstruction for recycling in other construction processes. The one-minute video is particularly valuable for demolition contractors, as it can help them optimize their processes. The accompanying video first demonstrates how to remove the tape from the boards, followed by the removal of the cavity anchors, and finally the release of the plates by removing the plugs. And can be used in the platform elaborated in T2.4 and 2.5.

It is important to note that the findings are subject to change with the advancement of technology. However, this report serves as a valuable starting point for considering the sustainability of PU products and emphasizes the need to address challenges faced by the recycling and demolition sector. The visit to recycling and demolition companies in Belgium also highlights the importance of further research and stakeholder engagement to drive positive change in the industry.

The project work leading to this deliverable has investigated in close interaction with the recycling technology development, the influence of additives/ raw materials on the smart pyrolysis / chemolysis depolymerization. Based on these results and the insight from the recycling processes, new recipes and polyols were developed. The foams that were produced on the basis of the new developed formulations, will be tested in the frame of the recycling-related work. These results will show if these formulations can increase the recyclability. The results of these tests will be reported D4.3 “Procedure of the chemolysis and the separation of amines and polyols at 250 ml scale and pressure) for the chemolysis process including separation of amines from polyol at typical lab-scale eg. 250 mL” in M36. Then also results of the recycling of the new foams will be available.

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8 Appendices

[Video insulation board]

[Video insulation boards (link to project website)]

TABLE 1: CONNECTION TYPE VALUATION

Connection type (CT		
Dry connection	Loose (no fastening material)	1,00
	Click connection	
	Velcro connection	
	Magnetic connection	1.00
Connection with added elements*	Bolt and nut connection	0,80
	Spring connection	
	Corner connections	
	Screw connection	
	Connections with added connection elements**	
Direct integral connection	Pin connections***	0,60***
	Nail connection	
Soft chemical connection	Caulking connection	0,20
	Foam connection (PUR)	
Hard chemical connection	Adhesive connection	0,10
	Dump connection	
	Weld connection	
	Cementitious connection	
	Chemical anchors	
	Hard chemical connection	

* Added connecting elements must be made in materials that are insensitive to degradation due to weather and/or use conditions (e.g. stainless steel).

** For example, a façade hanging system

*** For example, a non-connection

TABLE 2: CONNECTION ACCESSIBILITY VALUATION

Co…	…e
Freely accessible without additional actions	1.00
Accessible with additional actions that do not cause damage	0.80
Accessible with additional actions with fully repairable damage	0.60
Accessible with additional actions with partially repairable damage	0.40
Not accessible - irreparable damage to the product or surrounding products	0.10

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TABLE 4: VALUATION OF INDEPENDENCY

Independency (ID)	Score
No independency - modular zoning of products or elements from different layers.	1.00
Occasional independency of products or elements from different layers.	0.40
Full integration of products or elements from different layers.	0.10

TABLE 3: GEOMETRY OF PRODUCT EDGE VALUATION

Geometry of product edge (GPE)	Score
Open, no obstacle to the (interim) removal of products or elements.	1.00
Overlapping, partial obstruction to the (interim) removal of products or elements.	0.40
Closed, complete obstruction to the (interim) removal of products or elements.	0.10

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