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# A Physical Audit of DfD Performance in a Panelised - Modular Construction System

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**Abstract:** Prefabricated, panelized over-cladding façade systems are promoted as a means of accelerating the decarbonization of existing building stock while enabling circular construction practices. Although pilot projects have demonstrated the technical feasibility of this approach, significant challenges remain in defining and measuring circularity - disassembly performance in practice. This study investigates the application of prefabricated and modular systems in deep energy retrofit projects, with particular emphasis on integrating circularity principles - advanced design for disassembly (DfD) within the design and construction process. The paper outlines the rationale, methodology, and findings from a detailed physical audit assessing DfD performance in a pilot mock-up of a modular circular wall panel developed for retrofit within an Irish social housing demonstrator under the Drive 0 project. A novel DfD audit method was employed to evaluate actual disassembly and reassembly performance. Results indicate that DfD principles were largely successful in practice, with substantial potential for reuse and reassembly of elements, components, and materials across multiple levels of the construction hierarchy. Only minor damage and limited material loss, primarily associated with jointing systems, were observed. The mock up and audit also identified opportunities for system refinement to enhance disassembly efficiency, alongside broader architectural and technical improvements. Furthermore, the findings correlate with and provide validation for an innovative design-stage assessment method for disassembly. Overall, the research contributes to the growing body of knowledge on circular construction, addressing key gaps related to empirical physical validation of design for disassembly in case practice, holistic and hierarchical design for disassembly methodology advancement and validation, empirical design and prototyping of modular circular retrofit application, benchmarking to standards and other demonstrators.

**Keywords:** Design for disassembly (DfD); Circularity; Prefabrication; Modular systems; Retrofit; Architectural technical design

## Introduction

### Overview

The built environment has been identified as having significant sustainability impacts, leading to increased policy, legislation, and practice initiatives toward sector transition. Circular economy principles present a pathway to delivering sustainability aims, including greater resource efficiency, waste and pollution reduction, and decarbonization. However, transitioning the construction industry toward greater circularity presents several challenges, including unclear concept definitions, diverse assessment methods, limited case applications, and the specific complexity of the built environment itself. Design for disassembly (DfD), as a key enabler of both technical and biological cycles, is central to circularity and value retention yet remains a significant research and practice gap (Daly & Barril, 2025; Gasparri et al., 2023a; Hossain & Ng, 2018).

This research examines the integration and performance of circularity principles, specifically advanced DfD, in the design and realization of a panelized-modular wall system applied in social housing energy retrofit in Ireland. The paper

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presents a comprehensive physical audit assessing the DfD performance of a prototype prefabricated circular wall panel system developed for the EU Drive 0 project, which aims to accelerate housing decarbonization through modular construction retrofit solutions across European demonstration sites (Drive 0, 2023).

The principal innovation centered on designing, developing, testing, and deploying a modular wall construction guided by circular design principles. This included prototype mock-ups that facilitated detailed auditing of actual DfD performance, examining whether design intent was achieved in practice, at what performance level, and with what implications for research and practice.

## Research questions

This research addresses critical questions in modular construction and circularity assessment:

**RQ1.** How can advanced design for disassembly be determined, implemented, and assessed in real-world modular retrofit practice?

**RQ2.** Can DfD design principles be effectively implemented across all construction hierarchy levels (element, component, material)?

**RQ3.** Can design-stage DfD assessment methods predict actual disassembly performance?

**RQ4.** What material impacts and reuse potentials are achieved through hierarchical DfD strategies?

**RQ5.** How does modular DfD performance compare to conventional retrofit systems and international benchmarks?

## Research overview

The paper summarizes research methods, contextualizes the work within existing literature, introduces the Irish Drive 0 case study and modular over-cladding solution, describes the prototype design, and reports on the planning and execution of a detailed DfD performance audit. The STaMPD (Systems, Technical, Materials, Process, Data) DfD framework (Daly & Gallego Barril, 2025) serves as both the design guidance structure and audit reporting framework, leading to critical discussion, conclusions, and validation support for the STaMPD method.

**Figure 1** presents a schematic overview of the project scope and research presented in this paper, including the Drive 0 case dwelling context, the modular wall system, design development of the mock-up, and the DfD auditing method and its implementation across mock-up stages, with reporting on results, findings, and analysis.

## Research contributions

This research contributes to emerging knowledge in circular construction by addressing several identified gaps:

1. Empirical validation of DfD design intent through comprehensive physical auditing across construction hierarchy levels;
2. Methodological advancement through validation of a design-stage assessment tool (STaMPD) against real-world disassembly outcomes;
3. Practical evidence of modular system application in retrofit contexts with integrated circularity principles;
4. Comparative benchmarking against international DfD standards and other leading validated research projects demonstrating reversibility of modular systems for secondary validation.

The research relates to knowledge gaps in modular systems application in retrofit, achieving and assessing DfD at all construction levels, and real-life case validation (Hossain et al., 2020; Ahn et al., 2022; Khadim et al., 2022; Tokazhanov et al., 2022; Munaro & Tavares, 2021).

# Methods

## Research approach

This innovative research arises from several knowledge gaps, notably contributing to circularity/DfD assessment and practice within the context of designing, developing, prototyping, testing, and realizing a prefabricated over-clad wall system applied in a housing retrofit project.

The research combines qualitative and quantitative methods in a mixed-method approach framed as an inductive, grounded, bottom-up detailed case study (Yin, 2018; Stake, 1995). It utilizes various research methods and data sources (both hard and soft data) and explicates practitioner-researcher empirical perspectives on the novel design and testing of a prototype mock-up modular wall system focused on DfD performance (Daly, 2023a; Daly & Gallego Barril, 2025; Johansson, 2003; Groat & Wang, 2004).

## Methods overview

The DfD performance audit comprised a range of integrated research methods:

- Design Research and Case Study Framework: Performance-based design theory incorporating mixed methods within a case study research framework, including iterative design research with both quantitative and qualitative approaches.
- Literature Review: Detailed review on modular systems in retrofit and circularity to contextualize the work and identify knowledge gaps. A secondary review on DfD assessment methods informed the development of the STaMPD framework.
- DfD Assessment Method: Drawing from literature critique and the Drive 0 method (Daly, 2023a), the STaMPD DfD assessment method was designed and piloted (Daly & Gallego Barril, 2025) and is used as the framework for reporting and recording DfD performance in the physical audit.

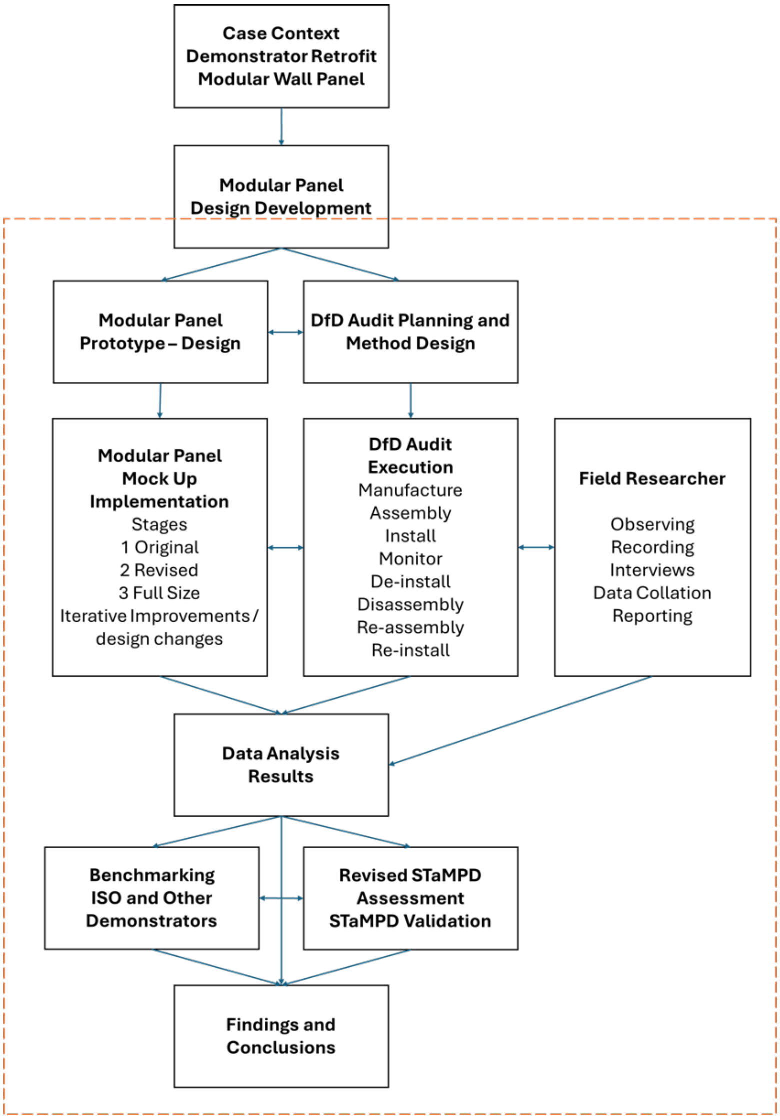

**Figure 1 | Schematic showing research scope and actions in context of case demonstration and design and execution of prototype modular wall solution with integral DfD Audit, STaMPD assessment and benchmarking**

- DfD Audit Design and Implementation: A detailed DfD auditing plan was developed incorporating three main stages assessing assembly, installation, de-installation, disassembly, re-assembly, and re-installation. Data collection utilized observation, semi-structured interviews, material and product impact assessment, and documentation analysis. The physical audit was conducted across all mock-up stages with observations and data recorded according to the audit plan.
- DfD Audit Analysis and Reporting: Data and results were collated and reported using the STaMPD DfD framework, providing structured performance auditing and facilitating comparison to design-stage assessments.

## DfD audit plan

A high-level plan for physical DfD audit was developed comprising three main stages, each with auditing/recording activities for analysis at each construction hierarchy level, comprising observation, recording (using photos, video, and notes), collation of documents for analysis, and interviewing manufacture, engineering, and installation staff.

### *Key stages*

**Stage 1: Manufacture, Transport, Installation, and In-situ Observation.** Covered manufacture, transport, installation, and a period observing in-situ performance while exposed to external weather conditions.

**Stage 2: De-installation, Disassembly, and Re-assembly.** Involved first actual disassembly across multiple construction levels:

- Level 1 (Element): De-installation of upper panels intact from host wall
- Level 2 (Component): Disassembly of wall-to-window components

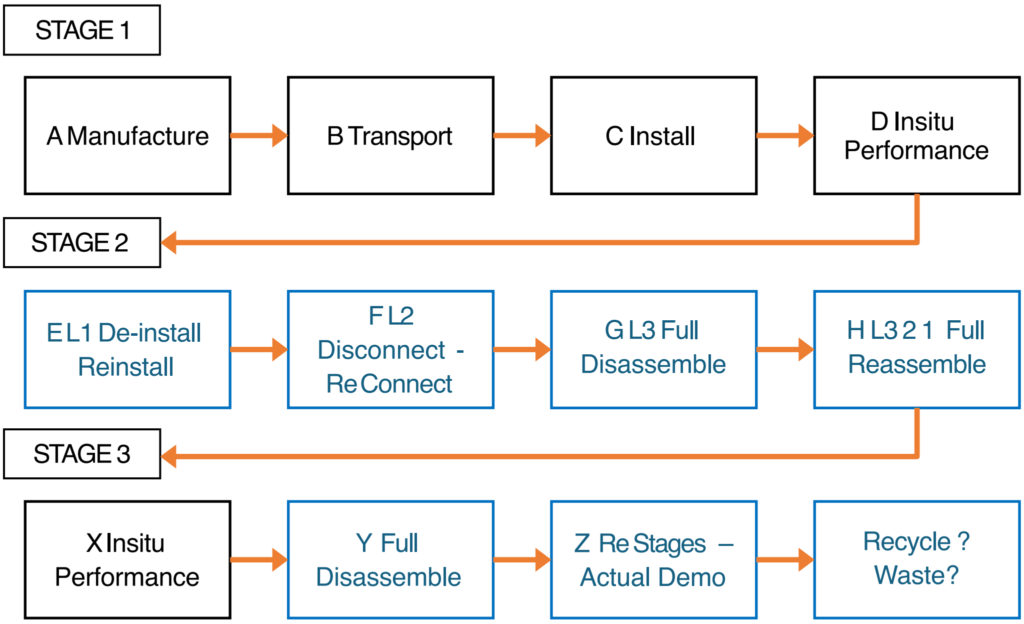

**Figure 2 | Schematic of physical DfD auditing plan showing proposed stages of manufacture, installation insitu assessment and partial and full disassembly and re-assembly and re-installation, with specific DfD audit stages in blue**

- Level 3 (Product/Material): Full disassembly of entire panel back to base materials and products, followed by full re-assembly

**Stage 3: Re-installation and Supplemental Testing.** Involved re-installation of panels and observation of another period of in-situ performance in external conditions prior to final full disassembly, including supplemental under-eaves installation trial (See Figure 2).

### *Impact assessment and re-application framework*

A key focus of the physical DfD audit was assessing the impact of disassembly on elements, parts, products, and materials and their re-assembly and re-application potential. A simple reporting and scoring framework based on Likert type scale was developed comprising five levels of impact ranging from none to severe (score 1 to 5) with lower scores meaning poorer performance and visa versa. Framework included definition, description, and example of each, with corresponding re-application potential identified, which also had five levels ranging from highest re-use to lowest recycled levels.

See Appendix 1 for complete Impact and Re-application Assessment and Scoring Guide.

### *Fieldwork and data collation*

Given the extent of information required to undertake the DfD Audit, it was proposed that a researcher should be on site during all stages to undertake the required observational study with key data recording and collation as follows.

1. Observation: Observe all aspects of the works and record by various means, requiring safe access.
2. Recording: Record all relevant aspects of the work via notation, sketches and photo / video.
3. Interviews: Undertake a combination of informal (during works) and semi structured interviews (on completion).
4. Documents Review: Collate all relevant documents, drawings, schedules, specifications etc., for review and analysis.
5. Data Collation: Several templates and guides were developed to assist research, reporting and collation of data including use of material impact and re-application scoring, general reporting via STaMPD framework and interview questionnaires.

Researcher Context: The research team comprised design professionals involved in the modular panel design, Drive 0 circularity assessments, and research/development of the STaMPD assessment method itself, providing essential knowledge and insight into design circularity principles, DfD assessment, and auditing intent and method.

Limitations: Some modification and adaptation to planned researcher observation and recording during works was required, notably for transport and revised supplemental Stage 3b full scale panel install test, where non-researcher presence required reliance on manufacturer reporting and interviews-as noted in Section 6. However all key DfD activity was undertaken in presence of technical researcher.

### *Reporting framework*

Collated data from fieldwork study was documented and reported using the STaMPD category framework, facilitating comparison to design-stage STaMPD assessment and validation support of the method. The reporting framework comprised five categories:

- Systems: Interrelationship between parts and elements and resulting system complexity. Key indicators: product standardization, geometry, functional independence, part relationships, number of components, nature of connections and fixings.

- Technical: Physical assembly and disassembly of connections. Key indicators: edge and interface detailing, connection type, accessibility, tolerance management.
- Materials: How material properties influence DfD performance. Key indicators: toxicity, durability, resilience, material diversity, chemical composition.
- Process: Methods by which components are assembled, disassembled, and reassembled. Key indicators: fabrication location, production and transport processes, on-site assembly, tools, storage, safety, knowledge and skill levels, operational complexity, time.
- Data/Information: Availability and quality of supporting information enabling effective DfD implementation. Key indicators: construction and material documentation, disassembly instructions, safety guidance.

## Literature Review

### Context

The building and civil sector consumes approximately 3 billion tons of raw materials annually (World Economic Forum & The Boston Consulting Group, 2016) and accounts for 32% of global energy consumption (Lucon O. et al., 2014). In response to this resource intensity (Benachio et al., 2020), (Joensuu et al., 2020) the EU has introduced significant policy and legislative initiatives focused on sustainability (European Commission, 2012) energy efficiency (European Commision, 2011) and circular economy principles (European Commission, 2014). Ireland is advancing similar objectives through the Climate Action Plan (Department of the Environment, 2023) and Circular Economy Act (Govt Ireland, 2022) supported by frameworks from the Irish Green Building Council (IGBC, 2022), (IGBC, 2025).

### Circularity and design for disassembly

Circularity represents a paradigm shift from linear "extract, produce, dispose" models to regenerative systems maintaining continuous resource flow (Ellen MacArthur Foundation, 2014). Building on earlier frameworks (Shooshtarian et al., 2021) including cradle-to-cradle (McDonough & Braungart, 2002), regenerative design (Lyle, 1996), and closed-loop strategies (Stahel, 1982), circularity is increasingly recognised as significant within the built environment (Mhatre et al., 2021; Charef & Lu, 2021). However, standardised definitions remain elusive, with numerous frameworks, criteria, and metrics proposed (Kirchherr et al., 2017; Saidani et al., 2019), (Parchomenko et al., 2019).

Design for disassembly is widely regarded as central to circular construction, facilitating recovery and reintegration of building materials and elements back into supply chains (ISO, 2021), (Bakx et al., 2016; Mazzoli et al., 2022; Gasparri et al., 2023).

Despite its relevance, both circularity and DfD remain under-researched, particularly regarding comprehensive life-cycle assessment methodologies (Ness & Xing, 2017; Ghisellini et al., 2018; Hossain & Ng, 2018b; Singh et al., 2021; Andersen et al., 2022; Benachio et al., 2020).

The literature identifies several methodological gaps, including the need for holistic circularity assessment methods and tools in construction (Tokazhanov et al., 2022), for the early design stages (Munaro & Tavares, 2021), and case-based verification (Hossain et al., 2020; Bucci Ancapi et al., 2022), (Wuni, 2022). Additionally, there is a call for the development of comprehensive indicators (Hossain & Ng, 2018; Hossain et al., 2020; Ahn et al., 2022b; Khadim et al., 2022b; Tokazhanov et al., 2022) and the quantification of performance, benefits and value (Bucci Ancapi et al., 2022; Wuni, 2022; Gasparri et al., 2023). There are ongoing technological knowledge gaps, particularly in advancing DfD to enable deconstruction for reuse, facilitate disassembly and promote greater standardization (Hartwell et al., 2021). Furthermore, it is essential to investigate the relationship between modularity and circularity, as well as the role of off-site manufacturing and construction, through practical case studies (Machado & Morioka, 2021; Osobajo et al., 2022). The development of circular solutions and typologies faces several barriers (Eberhardt et al., 2022), and there is a recognized need for further exploration of circularity in the retrofitting of existing buildings, an area that has been largely under explored (Andersen et al., 2022; Gasparri et al., 2023).

### Modular construction / Retrofit

Modular construction involves off-site fabrication of building elements in controlled factory environments, with prefabricated modules transported for final assembly at construction sites (Modular Building Institute, 2024). Claimed advantages include standardization, simplicity, mass production potential, cost reduction, shortened timelines, improved maintenance, adaptability, ease of disassembly, and design flexibility through interchangeable components (Kamrani & Salhieh, 2002; Miller, 1998; Miller T.D., 1997; Du et al., 2019).

Across Europe, modular construction is increasingly applied to energy retrofits, supported by research, innovation, and demonstration projects. The International Energy Agency's Annex 50 evaluated demonstration projects using prefabricated façades in apartment retrofits, reporting benefits including enhanced energy efficiency, improved occupant comfort, higher construction quality, cost-effectiveness, better space utilization, and substantially reduced retrofit durations with minimal occupant disruption (Zimmermann, 2011).

D'Oca et al. (2018) reviewed approximately 30 EU-funded deep energy retrofit projects, many incorporating prefabrication in energy systems or façades (D'Oca et al., 2018). Notable examples include the iNSPIRE project (2012–2016), which developed timber-based modular façade systems integrating micro heat pumps and ductwork, and the MORE-CONNECT project, which achieved NZEB standards with multifunctional prefabricated façades and roofs, reducing installation time from two months to five days. A wide range of modular retrofit strategies has been developed, including opaque wood-based vertical panels (Callegari et al., 2015), flexible wood-based façade systems adaptable to different structural types (Sandberg et al., 2016), preassembled insulated panels for façade and roof retrofitting (Pittau et al., 2017; Torres et al., 2021), and systems incorporating renewable energy technologies applied across diverse climatic conditions and building typologies (Du et al., 2019; D'Oca et al., 2018). While these projects demonstrated the technical feasibility of modular retrofits, few included rigorous physical DfD demonstration and auditing, a gap this research seeks to contribute to.

The literature identifies several challenges, with Hu Du et al. outlining key issues in their review of Modular Façade Retrofit with Renewable Energy Technologies (MFRRn). These challenges are categorized into technical aspects, including modular design, fixation method, integration of renewable energy systems, and addressing site-specific variations and tolerances. Financial issues such as performance, market penetration, business models, and supply chains, along with concerns related to warranties and servicing, are also highlighted, (Du et al., 2019). Torres et al. identify two major technical challenges: the integration of systems across a diverse range of real-world buildings and the adaptation of these systems to accommodate structural irregularities, (Torres et al., 2021). In a review of European projects, Pope identified several key challenges for scaling up modular energy retrofitting, including the development of multi-stakeholder supply chains, regional regulatory variations, the establishment of common protocols, data transfer systems, and tools for building data capture and sharing. Additionally, addressing the diversity of building typologies and archetypes, and developing innovative financing solutions, particularly for tenant-owner issues, were noted as critical factors. Pope further emphasized that, until the market reaches sufficient scale to drive down costs, increase investment, and stimulate workforce growth, governmental support may be necessary to advance the sector, which may otherwise remain marginal, (Pope, 2024). In their comprehensive review of four Horizon 2020-funded modular retrofit projects, S. D'Oca et al. emphasize that the primary challenges are not technical in nature, but rather relate to awareness, knowledge gaps, and excessive investment costs (D'Oca et al., 2018).

# Modular System Design and Development

## Case demonstrator and design concept

The Irish demonstrator retrofit targeted a significant 65% energy upgrade to two 1970s social houses of masonry wall and timber roof construction, which had undergone some previous retrofitting works. The principal innovation was to design and pilot a novel modularized wall panel for wall over-cladding based on circular and DfD principles.

The system was based on adaptation of an existing light gauge steel (LGS) structural wall system into a prefabricated 'closed' wall unit for over-cladding application. Concept designs were developed for overall energy retrofit, including architectural elevations for modular plug-and-play wall over-cladding and extension to the front elevation.

The proposed modular wall panel comprised 89mm LGS stud framing with bio-based quilt insulation between studs, membrane, and 25mm compressible insulation with neoprene edge seals to reduce thermal looping behind the panel. The external build-up included wood fibre board, breather membrane, battens, cement board, and render finish, designed to achieve a target U-value of 0.18–0.20 W/m$^2$K, in excess of Irish regulatory retrofit wall back stop U-value of 0.35 W/m$^2$K and toward new build standard of 0.18 W/m$^2$K for walls.

## Hierarchical design for disassembly strategy

A key element of design development was integrating circularity principles with particular emphasis on advanced DfD. This approach was shaped by circularity/DfD assessments undertaken in the Drive 0 project and findings from wider literature review. The Drive 0 assessments, informed by Alba Concepts (van Vliet et al., 2021) and indicators proposed by Durmisevic (2006), were simplified and adapted throughout the project. A critical review revealed both their value in supporting design but also limitations, including narrow methodological scope, evolving indicators, inconsistent data sources, lack of weighting for bio-based materials, absence of building hierarchy perspective, and lack of unifying benchmark (Daly, 2023).

These insights led to strong design focus on DfD as a central enabler of circularity, particularly within the technical cycle. The design strategy aimed to enable DfD across all construction levels—panel, component, and material—ensuring value retention at each level. This approach allowed modular panel de-installation from the host wall for potential reuse or further disassembly into components (e.g., wall-to-window/cill interfaces) and base materials for reuse or recycling. See **Figure 3**.

## STAMPD method

The critique of the Drive 0 framework and focus on DfD led to the creation of a proposed holistic DfD assessment method—STaMPD, (Systems, Technical, Material, Process, and Data). Developed from detailed literature review—beginning with Durmisevic (2006a), Guy et al. (2007), Akinade et al. (2017), Vliet (2018), Drive 0 Deliverable 6.1 (2020), and ISO 20887 (ISO, 2020a)—the STaMPD framework harmonies a broad range of DfD indicators into a coherent structure.

The method distinguishes between what is physically assembled (Technical, System, Material) and how it is assembled and disassembled (Process, Data). From an initial pool of 49 indicators identified in literature, 29 were refined and harmonized into the STaMPD framework. The 29 indicators are distributed across Systems (6), Technical (7), Materials (5), Process (6), and Data (5), with each indicator tied to a specific construction hierarchy level (element, component, material), providing transparent coverage across the modular retrofit system. This framework was then developed into a detailed assessment tool with a simple scoring system, for pilot application during design of the modular 2D wall system prototype. STaMPD also served as a guide and framework to report and assess the DfD audit, which in turn was used for valida-

**Figure 3 | Showing case dwellings, pre-retrofit works and proposed modular panel assembly. Source Authors and Coady Architects**

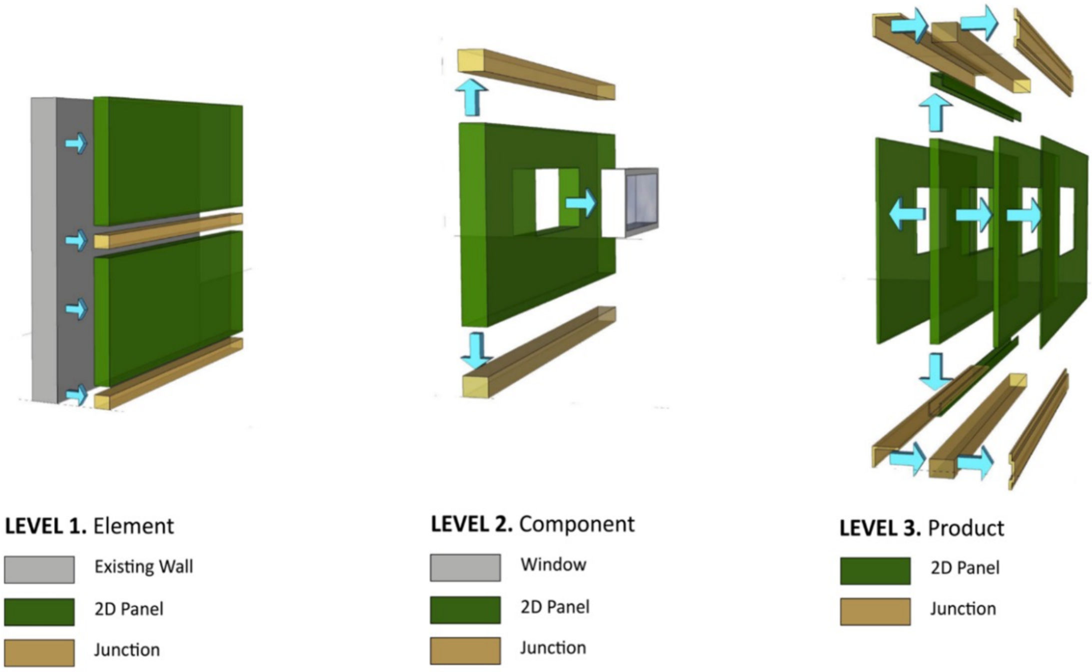

**Figure 4 | Concept graphic showing proposed panel system hierarchical disassembly over three levels, wall, component and product / material**

tion support of the STaMPD method, (Daly & Gallego Barril, 2025). See **Figure 4** for summary overview of method including list of 49 indicators and associated categories.

## Structural and technical design

The panelized/modular wall system was designed to achieve structural integrity, thermal over-cladding, weathering, aesthetics, long-term durability, and disassembly capability in full compliance with relevant European and Irish standards. The frame forms a non-load-bearing over-cladding panelized system, secured to the existing masonry structure using adjustable brackets.

### *Design for disassembly features*

Design workshops focused on supporting disassembly at all construction hierarchy levels. A key detail is shown in **Figure 5**: The horizontal access junction incorporates a steel bracket providing independent gravity support and restraint for each panel, eliminating the need to directly fix the panel to the host wall. A 150mm zone at head junction allows drop-on and lift-off installation and provides clearance under roof eaves. Maintaining space between first-floor window head and eaves was critical to facilitate horizontal studs in upper panels. Vertical junctions were butt-jointed and sealed with neoprene gaskets and elastomeric mastic, facilitating panel movement while ensuring weather-tightness.

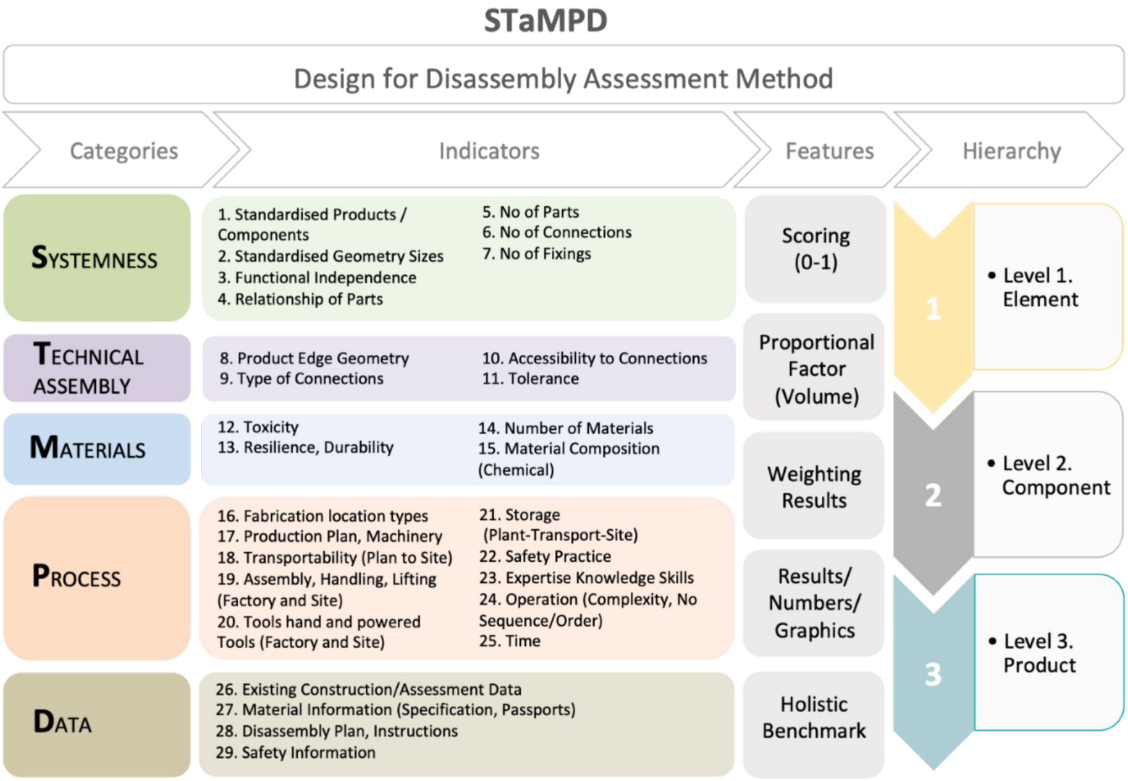

**Figure 5 | Showing overall scope and structure of STaMPD method - main categories, Systems, Technical, Materials, Process and Data, indicators, key features and construction levels** (Daly & Gallego Barril, 2025).

### *Structural compliance*

Although non-load-bearing, panels were designed to support self-weight and withstand wind loads, transferring forces to existing masonry via the bracket and restraint system. Structural design adhered to principles outlined in Eurocodes (0–6) and corresponding Irish National Annexes[1], achieving compliance with Part A of the Irish Building Regulations (Building Regulations 2012 : Technical Guidance Document. A, Structure). Wind forces were evaluated in accordance with Eurocode 1, with Eurocode 0 load and safety factors. Frames and brackets were designed to Eurocode 3 requirements. Steel elements were protected according to EN ISO 12944[2] appropriate to exposure conditions. Existing masonry was assessed to Eurocode 6/SR 325[3], ensuring sufficient capacity of bracket connections.

**Figure 6** illustrates initial bracket design, which enabled drop-on/lift-off action for panel installation and removal from the existing wall, designed and installed according to established best-practice guidance (British Standards Institution (BSI), 2021). Panel lifting straps/anchors were designed to EN 13155[4]. Exposed steel components were hot-dip galvanized for corrosion protection and were redesigned/tested during the mock-up stage to allow greater movement, tolerance, uplift, and deflection.

Although conceived as non-load-bearing elements, the modular panel can function as a load-bearing wall, allowing potential future secondary structural reuse—facilitating circularity objectives through cascading value retention.

## Prototype mock-up

A key requirement of the Drive 0 project was piloting proposed designs in a scale mock-up prior to full realization in case dwellings. This proved invaluable for design refinement and provided opportunity to undertake physical audit of proposed DfD performance. A comprehensive mock-up briefing plan and document was prepared, defining aims and objectives combining technical, aesthetic, and DfD performance auditing requirements.

The final mock-up design comprised several wall overcladding panels and extension wall/roof panels—collectively representing all panel and junction types expected in full-scale retrofit. The mock-up was installed on an external wall at the manufacturer's facility and left in situ for weathering exposure during final design stages (**Figure 7**).

## DfD Aufit Results

### Stage 1: Manufacture, transport, and installation

Stage 1 encompassed the manufacture, transport, installation, and initial weather exposure of the modular panels, en-

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[1] I.S. EN 1990-I.S. EN 1996, Dublin: National Standards Authority of Ireland (NSAI, 2010)

[2] EN ISO 12944:2018 – Corrosion Protection of Steel Structures, Geneva: International Organization for Standardization (ISO 2018)

[3] S.R. 325:2013 + A1:2015 Recommendations for the Design of Masonry Structures in Ireland to Eurocode 6 (NSAI, 2015)

[4] EN 13155:2020 Crane — Safety — Non-fixed load lifting attachments (CEN 2020)

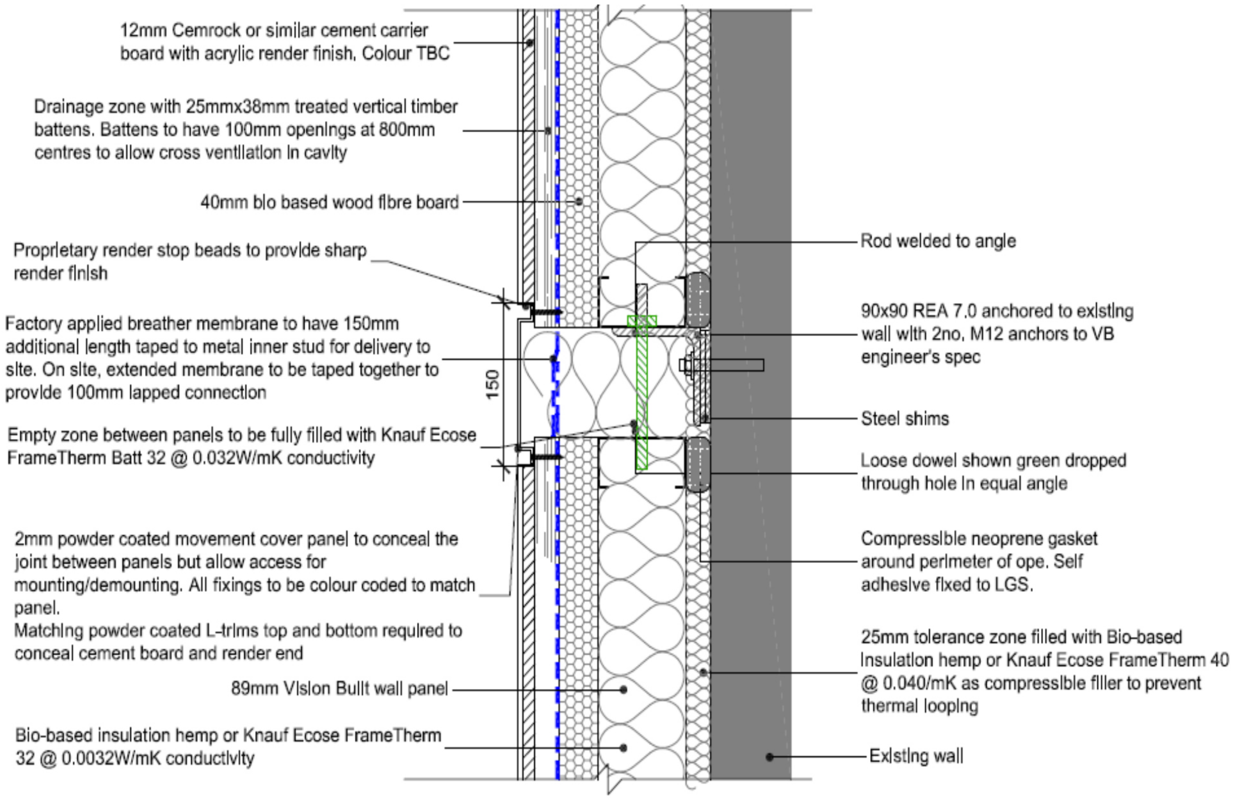

**Figure 6 | Showing the horizontal panel-to-panel DfD connection at floor level that enables independent, non-stacked installation and full panel removal for reuse or further disassembly**

The system uses a gravity-based fixing, with the panel base seated on a bracket bolted to the host wall and laterally restrained by a bolt. The same bracket restrains the head of the lower panel via a restraint bolt. All fixings are accessible within an approximately 150 mm lift-on/lift-off access zone, allowing straightforward installation and de-installation without affecting adjacent panels. Source Coady Architects / Vision Built.

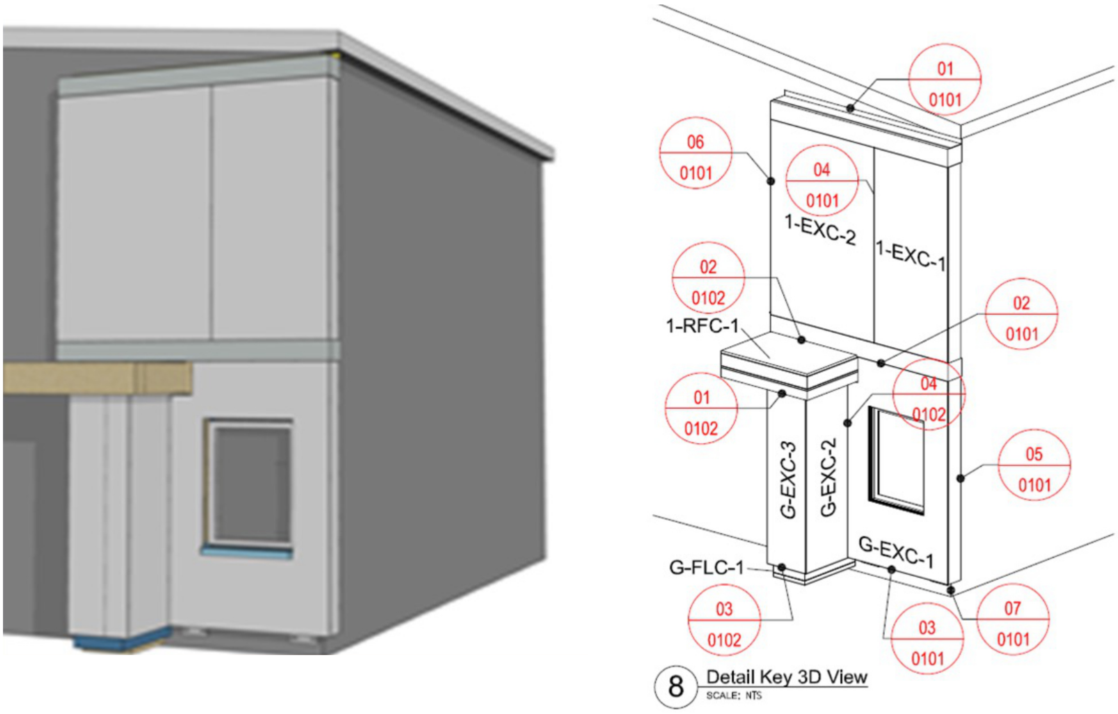

**Figure 7 | Showing schematic drawings of mock-up in 3D, with references to panel types and junction details. Source Vision Built**

**Table 1 | Showing observational / recorded results from Stage 1 across all three levels** (italic - negative impact)

| Stage 1 | Level | Systems | Technical | Materials | Process | Data |
|---|---|---|---|---|---|---|
| Manufacture | L - 1,2,3 | Simple/non-complex.<br>*Number of layers/ fixings.* | Dry reversable with repairable impact.<br>*Jointing tapes/seals.* | No damage.<br>*Number of layers/ fixings/offcuts.* | Factory, simple non-complex, layers, hand tools.<br>*Wet render slow.* | Detail production drawings, bar codes. |
| Transport (Manufacture Reporting, interview and Photos) | L - 1 | | | Minor damages.<br>*Extra plastic required.* | Small panels, light/ hand lift and forklift. | |
| Installation | L - 1 | Functional Separation. Number of parts and fixings low. | Bracket simple & accessible.<br>*Bracket limitations (lack of tolerance).* | *Materials used at joints are considered "sacrificial".* | No scaffold is required / short install time.<br>*Issues with upper panels due to drilled holes mistake.* | Installation drawings / staff training.<br>*No pre-survey wall (Plumbness).* |
| Insitu Inspection | L - 1 | | *Neoprene Gasket too firm and mushroom fixings too numerous.* | *Render quality and roof finishes poor.* | | |

abling observation of design performance, DfD implementation, and assembly logistics. See **Table 1** for summary of observations from Stage 1.

### *Manufacture (Levels 3–1)*

Five wall panels and associated roof and floor elements were fabricated in accordance with mock-up designs. While not a disassembly process per se, this stage yielded key insights into reversibility and constructibility, as follows;

- System: The modular system was straightforward, comprising an LGS frame with layered build-up. However, bespoke panel sizes and excessive fixings (e.g., 254 screws in one panel) introduced unnecessary complexity.
- Technical: Screw-based mechanical fixings were predominant, offering moderate DfD potential as reversible, "dry" connections, though minor adhesive and sealant applications were sacrificial.
- Material: Bespoke fabrication generated offcuts of insulation, wood fibre, and cement boards. Membrane puncturing by fixings and over-compressed rear insulation indicated potential performance and reuse issues.
- Process: Fabrication followed a structured three-stage process (roll-forming, framing, and layered assembly) using simple hand tools, with rendering and outsourced roofing causing time delays.
- Data: Detailed manufacturing drawings and QR codes (for LGS only) supported traceability and potential future disassembly, though QR visibility was later compromised by subsequent layers.

### *Transport (Level 1) (Manufacturer reporting)*

Panels were transported 100 km between factories using open truck transport. Palletisation, insulation spacers, and plastic wrapping were effective, though minor render damage occurred, requiring repair.

### *Installation (Level 1)*

Installation revealed tolerance and alignment challenges, particularly due to variations in host wall plumpness.

- System: Panel-to-bracket and panel-to-panel junctions were standardized, with clear hierarchy and order of assembly.
- Technical: The bracket system functioned but lacked sufficient adjustability, leading to excessive shimming and misalignment.
- Material: Horizontal joints were partly sacrificial, requiring membrane cutting and seal removal, limiting reuse.
- Process: Installation took three days with minimal equipment, demonstrating good constructibility but limited tolerance to host wall deviation.
- Data: Drawings and sequencing information were available, but absence of a pre-install wall survey caused significant on-site adjustments.

### *In-situ inspection*

Post-installation inspections identified key design deficiencies:

- Bracketry: Lack of multi-directional adjustment led to misaligned joints and necessitated redesign for three-plane movement.
- Backing insulation: Over-compressed neoprene gaskets and excessive fixings were revised to improve thermal performance and compressibility.
- Finishes: Poor render quality and inconsistent jointing prompted a switch to dry board finishes for future stages.
- Roofing: Workmanship issues led to revised detailing between designers and installers.

Stage 2 was reconfigured to test these design refinements and evaluate DfD performance under reassembly conditions.

**Figure 8 | Original mock-up showing - above LHS rear of panel with compressible insulation and perimeter gaskets, RHS original brackets and below - LHS first panel installation in progress, RHS wall panels installed**

See Figure 8 showing key images of initial prototype installation.

## Stage 2: De-installation, disassembly, and re-assembly

Stage 2 tested the revised design through complete de-installation, partial and full disassembly, and subsequent re-assembly with new bracket design. See Table 2 for summary of impacts with negative material impacts in blue/italic.

### *De-installation (Level 1)*

Element level: Panels were removed intact, demonstrating the practical feasibility of design for disassembly (DfD) at the element scale.

- System / Technical: Horizontal joints and bracket fixings performed effectively; however, bonded vertical seals limited full independence during panel removal.
- Material: Membranes and rubber sealing components were irreparably damaged during disassembly, while core panel materials remained undamaged and suitable for reuse.
- Process / Data: Disassembly was carried out efficiently using standard hand tools and forklifts, supported by prior assembly knowledge and straightforward documentation.

### *Disassembly (Levels 2–3)*

Two panels were disassembled—one at the component level (Level 2) and one at the material/product level (Level 3).

- Level 2: Window–cill assemblies exhibited low independence, requiring destructive removal and demonstrating that conventional detailing is not compatible with DfD principles.
- Level 3: Full disassembly confirmed high material recoverability; all major components were separable with minimal damage. Bonding of cement board and render con-

**Table 2 | Showing observational / recorded results from Stage 2 across all three levels,** (italic - negative impacts)

| Stage 2 | Level | Systems | Technical | Materials | Process | Data |
|---|---|---|---|---|---|---|
| De-install | L - 1 | Horizontal joints work well.<br>*Vertical joints bonded.* | *Vertical tolerances very small, affecting panel independency.* | No observed panel impact,.<br>*Joint material impact.* | Quick and non-complicated / forklift / manual lifting and hand tools. | Staff instructed before disassembly<br>*No de-installed drawings.* |
| Disassembly | L - 2 | *Window-Panel not functional independent.* | *Geometry of product edge between window and cill overlaps.* | Cement board repair and re-finishing<br>*Seals and tapes non reusable.* | Hand tools conventional window de-installation.<br>*DfD connections should be included.* | *No disassembly data.* |
| Disassembly | L - 3 | Simple fixing.<br>*High number of layers and fixings.* | *Disassembled process in one direction.* | Core materials can be re-used.<br>*Non weathering at head of panels damaged back insulation and some parts of breather membrane/Cement board and render has limitations in re-use.* | Quick and simple. | No previous data was provided.<br>*Junctions and elements were coded during disassembly to reassembly.* |
| Reassembly | L - 2 | Number of parts and components was simple and easy. | *No DfD considered.* | *Cement board & render damaged.* | | *No reassembly data.* |
| Reassembly | L - 3 | Simple layer.<br>*Excessive number of fixings.* | Same as original / Addition of base channel for panel adjustability on brackets. | Wood fibre board minor impact / fully re-usable. | Simple procedure / Hand tools / New dry cement board. | Mark ups on drawings and products / materials during disassembly aided re-assembly. |

**Table 3 | Showing observational / recorded results from Stage 1 across all three levels**

| Stage 3 | Level | Systems | Technical | Materials | Process | Data |
|---|---|---|---|---|---|---|
| Re-installation | L - 1 | Simple / Functional separation / Hierarchy and order of assembly. | Positive revised bracket detail back insulation fit tighter. | Dry cement board finish changed. | Simple / 1 day / no scaffold required / scissor lift and wheel loaders required / simple hand tools. | Original installation drawings with addition of new bracketry. |

**Table 4 | Summary of Material Impacts, description, scoring and potential re-application**

| Levels | Item | Score | Material impacts | Biobased | Recovery potenial |
|---|---|---|---|---|---|
| L1 Element | Wall Panel | 5 | No impact | Partial | Reuse |
| | | 1 | Membrane tape and Rubber strip damaged beyond repair | | Recycle |
| L2 Component | Window | 5 | No impact | | Reuse |
| | Cill | 5 | No impact | | Reuse |
| | Junction | 5 | No impact | | Reuse |
| | | 1 | Membrane tape cut | | Recycle |
| | | 3 | Cement Board was cut | | Repair |
| L3 Material/Product | Cement board | 3 | Cut to sizes | | Repurpose and Recycle |
| | Wood fibre | 3 | Cut to sizes | Biobased | Reuse, Repair, Recycle |
| | Breather membrane | 3 | Staple holes | | Repair, Repurpose and Recycle |
| | Neoprene gaskets | 1 | Damaged beyond repair | | Recycle |
| | Screws | 1 | 50% damaged | | Recycle |

Overall: Damaged non recoverable materials were limited to sacrificial jointing materials and % of fixings with over 90-90% of materials re-applied following dis-assembly in the re-fabrication of panels for re-installation.

strained reuse potential, while weathering led to minor degradation of gaskets and membranes.

### *Re-assembly (Levels 2–3)*

Both panels were reassembled using predominantly original components.

- Level 2: Reassembly was straightforward but visually impaired by prior cement board damage; future redesign required to enable reversible window–cill connections.
- Level 3: Reassembly introduced revised dry board finishes and new bracket slots for tolerance adjustment. Approximately 50% of screws were replaced due to wear or mis-

**Figure 9 | Mock-up Stage 2 with LHS revised brackets allowing for minor tolerance in three planes, Centre - revised upper panels with new cement board lining and RHS – revised backing insulation**

**Figure 10 | Showing final mockup full scale panel installation under eaves method being tested**

alignment; most wood fibre and insulation materials were reused successfully.

See Figure 9 showing revised bracket design, with adjustability in two planes, and revised dry cement board test finishing.

## Stage 3a/b: Re-installation and supplemental testing

Stage 3a involved reinstallation of panels incorporating revised bracketry, backing insulation, and dry finishes, as well as a 3b a supplemental under-eaves installation trial. See Table 3 for Stage 3 impacts.

- System/Technical: The new bracket design provided improved tolerance to dimensional variation and enhanced joint quality.
- Materials: The switch to dry cement board finishes eliminated wet trades and reduced damage risk.
- Process/Data: Installation efficiency remained high, requiring one day and minimal equipment. Updated drawings and experience from prior stages supported accuracy.

Stage 3b. A supplementary test successfully demonstrated installation under eaves using a counterweighted hoist, later applied in the real retrofit. See Figure 10 showing test installation of full panel with counterweighted hoist and mock-up of eaves projection. (Manufacturer reporting)

## DfD, material impact, and re-application potential

The DfD audit confirmed strong disassembly performance across all levels, with minimal impact on primary materials and clear potential for reuse, repair, or recycling. See Table 4 showing summary of key material impacts, and reapplication potential.

- Level 1 (Element): Panels could be fully removed intact, retaining economic and environmental value. Only membrane tapes and rubber seals were irrecoverable.
- Level 2 (Component): Window–cill assemblies showed the lowest DfD performance due to conventional detailing and destructive removal, though repair was feasible.
- Level 3 (Material/Product): High material recoverability was achieved, with only minor cosmetic damage to wood fibre boards. Cement boards bonded with render were non-reusable but recyclable; roughly half of fixings were recoverable.

Overall, the DfD audit demonstrated that the modular wall system achieved practical reversibility, high material recovery, and reassembly potential. Damaged non recoverable materials were limited to sacrificial jointing materials and % of fixings with over 90–90% of materials re-applied following dis-assembly in the re-fabrication of panels for re-installation, validating its circularity and reuse objectives within the STaMPD framework.

## Summary of audit findings

The DfD audit demonstrated that the prototype modular wall system achieved advanced disassembly, material recovery, and reassembly performance across three test stages, with minor material impact and identification of areas for further design improvement.

Stage 1 exposed several challenges—particularly in bracket adjustability, joint detailing, and material handling—that restricted functionality, reversibility, and generated material impacts. These findings informed targeted design refinements, including enhanced bracket tolerance, reduced wet trades, and dry finishes.

Stage 2 confirmed DfD performance and provided opportunity to modify and re-test design changes. Panels were fully removable at element level, major components could be disassembled and reused, and most materials were recoverable with minimal degradation. Limitations, such as bonded seals, sacrificial membranes, and conventional window–cill interfaces, highlighted areas where further redesign was required to achieve advanced circular reversibility.

Stage 3 validated the upgraded system in reinstallation, demonstrating improved alignment, faster assembly, and reduced damage risk. Supplemental tests under eaves installation showed adaptability to real-site constraints, reinforcing practical applicability of the modular solution.

The DfD audit verified that the system supports high-value circularity pathways, including reuse at element/component level, repair and repurposing at material level, and integration into future retrofit contexts. While some details still constrain full reversibility, the iterative testing process showed that modular LGS panels can be engineered to deliver robust disassembly performance, maintain integrity of primary materials, and enable meaningful reuse within the STaMPD circular retrofit framework.

# Validation of Stampd

## Validation methodology

The robustness of the STaMPD Design for Disassembly (DfD) assessment method was evaluated through a comparative validation exercise undertaken by two independent researchers. Each assessed both the original design-stage intent and the outcomes of a post-construction physical DfD audit. The purpose was twofold: first, to determine whether the design-stage application of STaMPD could reliably predict actual disassembly performance; and second, to examine the consistency of results across assessors.

The analysis compared the original design-stage scores with revised scores informed by physical audit observations, while also examining interpretive differences between Researcher A and Researcher B. Variations in scoring were attributable to differences in professional judgment and emphasis rather than to any alteration of the method's structure or scoring logic.

## Overall score comparison: Design-stage and post-audit

Across both evaluations, the overall STaMPD scores demonstrated strong alignment between design-stage predictions and post-construction findings. Variations between design-stage and post-audit revised scores are represented as a simple percentage difference.

Researcher A identified only marginal variation, with total score differences remaining below 2% across all system levels. This close correspondence indicates that, when applied by experienced practitioners with in-depth system knowledge, STaMPD can accurately anticipate realized DfD performance. Researcher B recorded more pronounced shifts, with Level 1 decreasing by 11%, Level 2 by 7.6%, and Level 3 improving by 9.75%. These differences stemmed primarily from more conservative initial scoring, improved material-level performance observed during disassembly, and a stronger appreciation of process and data indicators once operational evidence became available. The mean absolute deviation across all system levels was 5.6%. Importantly, both researchers concluded that the DfD design intent was broadly achieved in the constructed prototype. The observed differences reflect interpretive sensitivity rather than methodological inconsistency, thereby reinforcing confidence in STaMPD's predictive validity.

## Category-level analysis

At the system level, both researchers reported comparable performance patterns across Levels 1, 2, and 3. Researcher A identified a minor 3% variation following the audit, confirming stability in the original assessment. Researcher B observed a slightly greater reduction, primarily due to the physical mock-up revealing non-uniform geometries, varied panel functions, and deviations from design-stage assumptions regarding standardization. Both assessments converged in identifying Level 3 as the weakest-performing layer, largely due to the density of fixings and connections—an issue confirmed during physical disassembly and prioritized for optimization.

Technical assembly performance remained strong overall. While Researcher A noted a 4% variation following the audit—attributed to observed fixing density, redundant connections, and minor material damage—Researcher B recorded only a marginal reduction. Practical challenges, particularly during the removal of delicate window panels and rendered finishes, highlighted the difficulty of anticipating interface vulnerabilities through drawings alone.

Material performance was positively evaluated at design stage, reflecting the absence of hazardous materials and theoretical reuse potential. Post-audit reassessments identified modest reductions, primarily due to jointing damage, over-compressed bio-based insulation, and cement board window cills that could not be reused. Both researchers agreed that while strategic material choices aligned with DfD principles, detailing and interface design significantly influence actual reuse outcomes.

Greater divergence emerged within the Process category. Researcher A reported only minor variation, attributing discrepancies to installation duration, sequencing constraints, and tolerance management. In contrast, Researcher B recorded a substantial improvement in post-audit process scores, enabled by direct observation of site practices, safety procedures, and operative workflows that had been uncertain at design stage. This contrast underscores the sensitivity of process indicators to experiential evidence and highlights inherent limitations in early-stage evaluation.

Data performance similarly improved following the physical audit. Initial design-stage scores were low due to limited available information. Post-audit reassessment recognized the effective use of annotated drawings, component marking, and tacit knowledge developed during the mock-up. While the magnitude of improvement differed between researchers, both concurred that data-related indicators benefit significantly from prototyping and cannot be fully resolved through documentation alone.

### Inter-rater reliability

Comparison of both assessments reveals high levels of agreement within the Systems, Technical, and Material categories, particularly at product level, as well as shared conclusions regarding overall design intent achievement. Greater divergence was evident in Process and Data indicators and, to a lesser extent, in component-level material scoring.

These differences were attributable to several factors: variation in assessment timing relative to the mock-up; differing professional judgments when interpreting qualitative criteria; alternative strategies for handling incomplete information; and distinct levels of prior engagement with specific system types.

The findings suggest the need for clearer scoring guidance, standardized approaches to managing missing data, structured assessor training, and potentially staged assessments aligned with project phases to reduce interpretive variability.

### Visual comparison of results

Figure 11 and Figure 12 illustrate the comparative outcomes for both researchers. In Researcher A's assessment, design-stage and post-audit scores show minimal variation, supporting the method's predictive reliability. Researcher B's results demonstrate moderate shifts, particularly within Process and Data categories, reflecting enhanced information availability following physical testing.

### Validation summary and implications

Taken together, the validation exercise demonstrates that STaMPD produces stable and credible outcomes at design stage while remaining responsive to empirical evidence from physical disassembly. Design-stage assessments predicted realized DfD performance within a relatively narrow margin, with higher reliability observed in physically measurable categories than in process- and information-based indicators. Both researchers independently identified identical priority areas for refinement, including reduction of fixings, improved interface detailing, enhanced finish protection, and more robust disassembly documentation.

The exercise highlights both strengths and limitations of the method. STaMPD offers a structured, hierarchical framework for comprehensive DfD evaluation, supports identification of targeted design improvements, and facilitates communication within multidisciplinary teams. However, it remains dependent on professional judgment, particularly in process- and data-related categories, and is sensitive to information availability at early design stages.

These insights directly inform the proposed development of STaMPD 2.0, which proposes a streamlined, more practical framework by reducing indicators to four to five per category, introducing detailed scoring descriptors to reduce subjectivity, and incorporating measurable indicators such as ranges for the number of fixings. Material-level indicators will be applied only at the base product or component level, with results aggregated upward, while weighting will prioritizes Technical, System, and Material categories over Process and Data emphasizing higher-level outcomes to reflect value retention. The framework is envisaged to function within a broader circularity or sustainability assessment approaches. Further validation supports could be expanded through measurable indicators, expert review, multi-stakeholder pilots, and case study or deconstruction testing.

Overall, the validation provides strong empirical support for continued refinement and broader application of the method within modular retrofit contexts.

## External Benchmarking

### Rationale for external benchmarking

The STaMPD validation exercise (Section 7) demonstrated internal consistency between design-stage assessment and physical audit outcomes. However, to position these findings within broader circular construction discourse and evaluate performance against established standards and comparable projects, external benchmarking is essential.

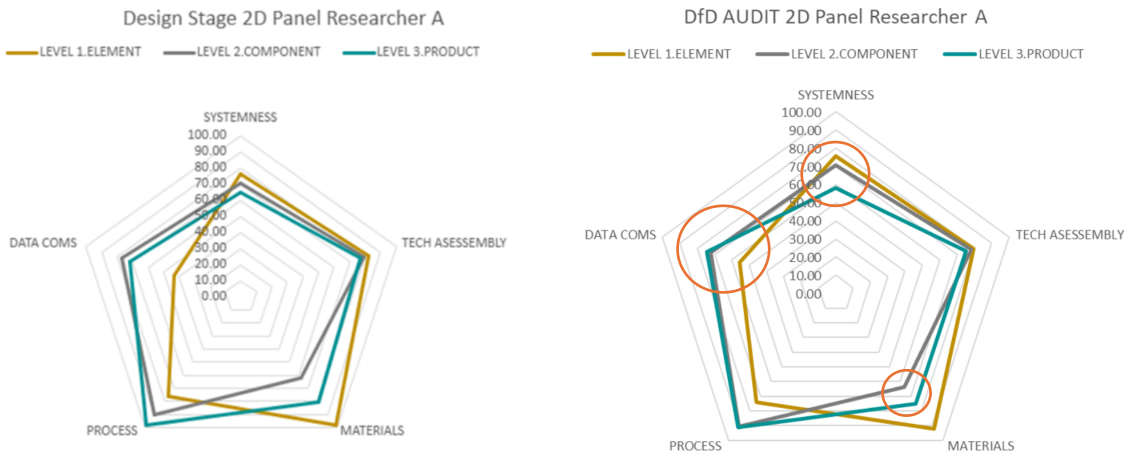

**Figure 11 | STaMPD Results Researcher A**

LHS: Design-stage assessment; RHS: Post physical DfD exercise. Minor variations (<3%) observed, notably in Data Level 1, Systems Level 3 and Materials Level 2 confirming relative predictive reliability. Systems, Technical, and Materials categories showed close alignment, with Process and Data showing slight improvements post-audit

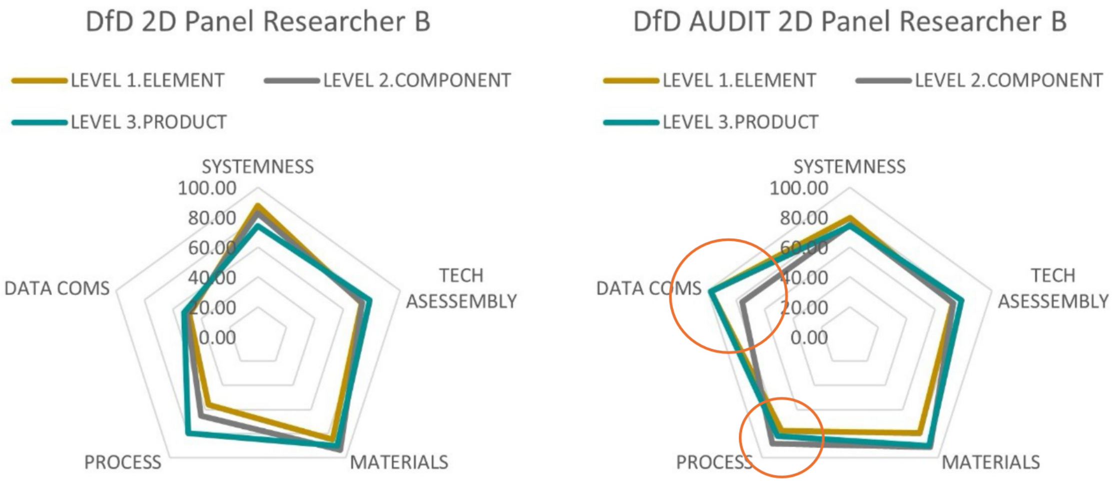

**Figure 12 | STaMPD Results Researcher B**

LHS: Design-stage assessment; RHS: Post physical DfD exercise. Moderate variation observed, particularly in Process and Data categories, reflecting enhanced site observation and improved operational knowledge. Level 2 performance improved for component interfaces, while Level 3 adjustments reflected material reuse insights

External benchmarking serves three critical purposes in this research:

- Normative Validation: Comparing audit findings against ISO 20887:2020 (the primary international standard for DfD) establishes whether the modular system meets recognized industry benchmarks.
- Methodological Triangulation: Cross-referencing with established DfD frameworks (particularly Durmisevic's foundational work) provides additional validation of performance assessment
- Empirical Contextualization: Comparing with European demonstrator projects (CPH Demo 2, B.R.I.C.) that have undergone similar physical testing situates the Irish Drive 0 case within real-world circular retrofit practice

This hybrid benchmarking approach—combining normative standards, research frameworks, and case examples—was adopted to ensure transparency, replicability, and compatibility with physical audit-based study methodology, without reliance on proprietary assessment tools.

**Table 5 | Comparison of observed performance under ISO 20887 principles**

| DfD Metric | Irl Drive 0 Case | CPH Demo-2 (CIRCUIT) | B.R.I.C. (BAMB) |
|---|---|---|---|
| Disassembly potential (% by volume) | (Not quantified by volume; empirically verified as high (element-level 100% reuse potential, other levels . 90%) | 16 % → 89 %<br>(BAU → Optimised) | Not specified (qualitative) |
| Connection type optimisation impact | Accessible, reversible mechanical | High (major effect) | Reversible connections standard |
| Empirical recovery/reuse data | Quantified through audit- strong re-apply potential | Not reported | Window frames 50 % reuse; panels and fasteners labelled |
| Documentation & labelling | Not structured | Not reported | Panels labelled during B.R.I.C. reuse process |
| Modular independence | High | High | High |

## ISO 20887:2020 – Design for disassembly and adaptability

ISO 20887:2020 (ISO, 2020) formed the primary reference benchmark. Key DfD guidance principles were drawn from the standard to establish qualitative criteria for benchmarking (**Table 5**):

- Levels/Hierarchical: Assessment across construction hierarchy
- Accessibility: Access to connections and fixings
- Independence: Functional separation of layers and elements
- Reversibility: Ability to disassemble and reassemble without damage
- Treatment/Finishes: Avoidance of treatments impeding disassembly
- Circular Models: Alignment with circular economy pathways
- Simplicity: Reduction of complexity in assembly
- Standardization: Use of standard products and dimensions
- Safety: Consideration of worker safety during disassembly

The system demonstrates strong alignment with technical DfD principles but weaker alignment with information and data requirements. The use of predominantly mechanical fixings enabled reversibility, and the over-cladding layer could be removed independently of primary structure. Fixings were generally accessible from exterior face, supporting logical reverse-installation disassembly sequence. However, partial non-alignment was identified in relation to procedural and informational requirements. While disassembly was feasible, absence of formalized disassembly documentation, component identification, or material passports limited full compliance with ISO 20887. Minor material damage observed during removal further reduced conformity with the standard's emphasis on damage minimization and reuse optimization.

The system can be characterized as significantly compliant with ISO 20887, exhibiting strong design intent for disassembly but limited formalization of supporting information.

## Combined DfD frameworks

To enable numerical comparison with published studies, an alternative DfD scoring framework was applied, adapted from established research-based indices drawing from Durmisevic (2006) Seven performance metrics were evaluated on a four-point scale (0 = poor; 4 = excellent), based on direct observations from physical audit (**Table 6**).

The system achieves a total score of 23 of 28, showing broad alignment with combined criterion and high scoring. Particularly strong performance was observed in layer independence and reusability. This result positions the system well above average for façade assemblies, which are frequently constrained by bonded materials, concealed fixings, or non-reversible interfaces.

## Case comparison with European demonstrators

To contextualize performance within contemporary European research, the audit results were compared with two Horizon 2020 demonstrators featuring explicit evaluation of DfD metrics:

### *CPH Demo 2 – Modular façade DfD potential*

The CPH Demo 2 demonstrator evaluated how design adjustments influence DfD potential. Using a volume-based metric: Baseline “Business As Usual” DfD potential: < 16 % by volume; Optimized modular connections (screws replacing nails/staples): ∼ 89 % by volume (CIRCUIT, n.d.) . The improvement was achieved by replacing fixed connections with reversible mechanical fixings and optimizing connection sequencing. This demonstrates that connection strategy alone can dramatically influence DfD performance.

### *B.R.I.C. – Disassembly and reuse outcomes*

The B.R.I.C. pilot building underwent annual construction and disassembly cycles, focusing on reversibility and component reuse:  - 117 interchangeable, self-supporting insulated timber façade cassettes with reversible joints; Recovered components after first disassembly - Window frames: 50 % reusable - Screws recovered and panels labelled for reuse - Cladding boards and structural timber elements reused without damage. B.R.I.C. demonstrates that modular façades with reversible joints and labelling systems can achieve actual material recovery, providing a practical benchmark beyond design-stage projections (BAMB, n.d.) (**Table 7**)

**Table 6 | High-level comparison of observations with combined DfD criterion**

| ISO 20887 Criterion | Evidence from Physical Audit | Performance |
|---|---|---|
| Levels / Hierarchical | Levels based DfD, underperformed L2. | Very good |
| Reversible connections | Bolted / screwed fixings observed, excessive | Good |
| Accessibility of fixings | Majority accessible from exterior face | Very good |
| Independence of layers | Distinct layers / functions, reversible in order | Very good |
| Treatment / Finishes | No treatment or finishes impeding DfD | Very good |
| Circular Models | Strong Re Stage potential minimal impacts | Very good |
| Simplicity | Potential for further reduction in layers | Moderate–Good |
| Standardisation | Standard products used but cutting | Good |
| Safety | Excellent safety consideration | Very good |
| Documentation | Good design data, poor DfD data | Moderate |

**Table 7 | presents a high-level comparative summary of the Drive 0 DfD audit to these case studies**

| Metric | Score | Justification |
|---|---|---|
| Fixing reversibility | 3 | Mostly mechanical, some sacrificial |
| Fixing accessibility | 3 | Removable and minor obstructions |
| Number of disassembly steps | 3 | Multi-step but logical |
| Tool dependency | 3 | Standard tools only |
| Damage risk | 3 | Edge damage observed – one level |
| Layer independence | 4 | Highly independent |
| Reuse potential | 4 | High element re-usability across levels |

## Benchmarking synthesis

The benchmarking exercise highlights the value of physical audit methods in evaluating DfD performance, with several key insights:

### *Design strategy dominates DfD performance*

Both the Drive 0 audit and CPH Demo 2 highlight that mechanical fixings and connection sequencing are primary determinants of disassembly potential. Minor adjustments in connection design can substantially increase DfD performance metrics.

### *Empirical validation is critical*

While CPH Demo 2 quantifies potential DfD gains, B.R.I.C. provides real-world evidence of disassembly and reuse cycles. The Drive 0 audit sits between these, combining practical observation with semi-quantitative scoring to provide actionable performance data.

### *Component recovery and labeling are essential for circularity*

B.R.I.C. demonstrates that labeling and sequence management directly impact reuse rates. Drive 0 currently lacks formalized documentation, representing an area for improvement to maximize circular outcomes.

### *Modular over-cladding systems are inherently adaptable.*

Across all comparisons, systems' layer independence and modularity support disassembly and reuse. Drive 0's performance aligns closely with these benchmarks, indicating robust design for façade-level circularity.

Overall Assessment: The Drive 0 modular over-cladding system achieves high practical DfD performance, comparable to leading EU demonstrators, while identifying opportunities for improved documentation, labelling, and reuse planning. These findings validate the physical audit methodology and provide a framework for future design optimization in modular circular façades.

Methodological Contribution: While several projects, such as Drive 0, assess theoretical circularity DfD performance across project cases, the emerging range of demonstration project and DfD audits presents opportunity for cross project benchmarking. The proposed hybrid external benchmarking approach, combining normative standards (ISO 20887), research frameworks (Durmisevic, 2006), and case evidence (CIRCUIT, B.R.I.C.), provides a pathway for future benchmarking of modular circular and especially DfD performance, future evaluations of façade and envelope systems and supports development of evidence-based circular construction strategies.

# Critical Discussion

## Key findings

This research examined the integration of DfD principles within a prefabricated over-cladding retrofit system through detailed physical auditing. Three principal findings emerge.

First, advanced DfD is achievable in practice. The modular prototype demonstrated that DfD intent can be realized across construction hierarchy levels. Panels were removed intact at element level, components were disassembled with manageable impacts at interface level, and materials were largely recovered without significant damage. These results confirm that circular retrofit strategies can move beyond theoretical aspiration to operational feasibility.

Second, design-stage assessment can reliably predict performance. The STaMPD method demonstrated predictive accuracy within 2–11% of post-audit results, validating its function as both a design guidance framework and an evaluative tool. While interpretive variability occurred between assessors, overall alignment confirms that structured design-stage assessment can anticipate realized DfD outcomes with reasonable accuracy.

Third, performance varied across hierarchy levels and assessment categories. Element-level (Level 1) and material-level (Level 3) performance was strong, whereas component-level interfaces (Level 2), particularly window-to-cill connections and joint detailing, revealed limitations. These findings highlight the importance of interface design in translating modular strategies into full circular performance.

Collectively, the results demonstrate that modular retrofit systems can be engineered to support reuse, repair, and material recovery, while also revealing practical constraints requiring further refinement.

## DfD performance across the construction hierarchy

The audit confirms that DfD performance varies systematically across hierarchy levels.

At element level (Level 1), panels were removed intact, retained structural and thermal integrity, and were reinstalled without difficulty. This confirms that system-level reversibility is achievable in prefabricated retrofits. The adjustable bracket system was critical: gravity-based support with lateral restraint enabled independent lift-on/lift-off removal within a defined 150 mm access zone. Mechanical fixings and clear sequencing contributed to predictable disassembly. These results align with international guidance emphasizing modular independence and accessible connections.

At component level (Level 2), performance was constrained by interface detailing. Disassembly of window–cill–cladding assemblies required cutting of cladding layers, limiting immediate reuse. Vertical joints sealed with butyl rubber and taped membranes generated additional material impacts. These findings reinforce that modularity alone does not guarantee circularity; detailing, tolerances, and joint systems strongly influence realized performance. While panel independence was achieved, sub-element interfaces require further rationalization and redesign.

At material/product level (Level 3), core materials, including insulation, wood fibre boards, and structural steel, showed high recoverability with minimal damage. Recovery exceeded 90% for primary materials (Section 6.4, Table 4). Losses were concentrated in jointing components, membranes, and sacrificial sealing elements, and approximately half of screws required replacement. This indicates strong material-level circular potential but also highlights opportunities to optimize fixing strategies and minimize consumable components.

The hierarchical variation validates the importance of multi-level assessment. System-level modularity enables reversibility; interface detailing constrains component performance; and material specification determines recovery outcomes. Comprehensive DfD therefore requires coordinated design attention across all scales.

## STaMPD as design and assessment tool

STaMPD functioned both as a design framework during prototype development and as a performance evaluation method during the audit.

### *Predictive accuracy*

The close alignment between design-stage and post-audit scores demonstrates that STaMPD can reliably predict DfD outcomes when applied by informed professionals. Predictive accuracy was strongest in physically measurable categories—Systems, Technical, and Materials—where documentation and specifications provided sufficient clarity. Greater variability occurred in Process and Data categories, reflecting the difficulty of anticipating operational practices and information flows during early design stages.

**Category-Level Insights.** The category structure proved effective in identifying targeted optimisation areas:

- Systems assessment highlighted excessive fixings and layering at Level 3 as avoidable complexity, establishing clear design priorities for simplification.
- Technical indicators confirmed the effectiveness of the bracket and lift-on/lift-off strategy while identifying window and joint interfaces as constraints.
- Materials assessment demonstrated alignment with DfD principles at strategic level, though it underscored the importance of detailing and protection to preserve reuse potential.
- Process findings showed benefits of factory prefabrication—improved quality control and reduced on-site time—while revealing ongoing challenges in tolerance management.
- Data indicators were weakest at design stage but improved during audit as ad-hoc documentation and experiential knowledge emerged, highlighting the role of structured information systems in enabling circularity.

### *Inter-rater reliability*

Differences between Researcher A and Researcher B, particularly in Process and Data categories, reveal that STaMPD requires professional judgment and is sensitive to information availability. Interpretive variability reflects methodological comprehensiveness rather than instability but suggests refinement is needed.

Improvements may include clearer scoring thresholds, protocols for handling incomplete data, staged assessment aligned with design phases, and assessor calibration exercises. These insights inform the proposed STaMPD 2.0 development, balancing rigour with practical usability.

### *Validation summary*

Overall, STaMPD proved effective as both design guidance and evaluation framework. It provided structured, hierarchical assessment capable of identifying optimization opportunities and predicting realized performance within acceptable margins. However, refinement is necessary to reduce data intensity and minimize subjectivity before broader industry adoption.

## Modularity, calability, and structural considerations

Although demonstrated on a limited dwelling typology, the prototype was conceived for broader application.

### *Modular benefits and circular preconditions*

The audit confirmed recognized benefits of prefabrication: factory-controlled quality, shortened installation time (three days for Stage 1; one day for Stage 3), reduced occupant disruption, and flexibility to accommodate windows and junctions within a standardized framing logic.

However, modularity alone did not guarantee circularity. Specific DfD-enabling features were essential: independent brackets avoiding panel stacking, accessible fixing zones, mechanical (not adhesive) connections, and tolerance management through adjustable supports. Circular performance required deliberate integration rather than passive reliance on modular construction.

### *Structural and typological considerations*

Scalability depends on structural and contextual factors. Panel weight was manageable using mechanical assistance; alternative framing systems may alter load paths and fixing requirements. The bracket system accommodated ±15 mm dimensional variation, but larger or multi-storey buildings may require rail systems or alternative adaptive fixings.

Host wall diversity—solid masonry, cavity walls, framed structures—will necessitate site-specific structural assessment. Hollow block or variable substrates may require modified bracketry to ensure adequate load transfer. Trade-offs between ease of disassembly and long-term structural robustness must be carefully managed.

### *Economic and industrial dimensions*

While technical feasibility was demonstrated, economic analysis was beyond the study's scope. Nevertheless, DfD influences cost through factory fabrication, reduced on-site labour, potential material value retention, and lifecycle adaptability. Industrial scalability requires sufficient market volume, simplified component systems, and coordinated supply chains.

The Drive 0 collaboration between academic, architectural, and manufacturing partners illustrates the integration required for modular retrofit scaling, but also the coordination complexity involved. Insights from manufacturing sectors—particularly part reduction, standardization, and sequencing optimization—offer potential pathways to improve cost-efficiency and circular outcomes.

Further research is required to examine scalability across diverse building archetypes, optimize joint systems, integrate economic evaluation, and assess long-term durability and reuse pathways. Economic scalability requires further life-cycle cost analysis, a key future research priority outlined in Section 10.4.

## Methodological limitations and future research

Several limitations shape interpretation of results.

The prototype represents a single façade typology at limited scale, restricting generalizability. Broader validation across building types, heights, climates, and construction methods is necessary. The STaMPD method is focused on generic DfD performance and not a particular construction method or application context and should be applicable across construction types and scales, with findings on utility having wider relevance and utility.

Certain audit stages, notably transport and supplemental Stage 3b relied partially on manufacturer reporting due to access constraints, introducing potential observational bias. However technical researcher was present for all key DfD actions - manufacture, assembly, disassembly and reassembly stages. Continuous researcher presence in future studies would strengthen evidence reliability.

STaMPD, while effective, remains data-intensive and interpretively sensitive. Further refinement is required to streamline indicators, clarify scoring, and improve usability for industry practitioners. Additionally, economic performance was not assessed; lifecycle costing and material value retention modeling are essential for commercial viability.

Future research priorities include expanded case applications, integration of economic metrics, long-term monitoring of installed systems, comparison across alternative structural systems (e.g., timber and concrete), and exploration of regulatory alignment with circular economy policy frameworks.

## Recommendations for research and practice

For Research: Future development should prioritize STaMPD 2.0 refinement through streamlined indicators, measurable sub-criteria, and staged assessment protocols. Broader multi-stakeholder validation is necessary to test reliability across disciplines. Integration of lifecycle cost analysis with DfD performance metrics will strengthen decision-making frameworks. Expanded application across typologies and climates will improve generalizability, while knowledge transfer from manufacturing engineering may enhance efficiency. Finally, exploration of regulatory integration could support market adoption.

For Practice: DfD thinking should be embedded from early design stages, simultaneously addressing element, component, and material levels. Physical prototyping is recommended to validate assumptions and reveal interface challenges before full deployment. Designers should prioritize simplification—reducing fixings, rationalizing part counts, and standardizing components. Factory prefabrication should be leveraged for quality control and systematic documentation. Comprehensive disassembly information, including sequencing guidance and component identification, should be developed. Particular attention must be paid to interfaces and tolerances, recognizing these as primary determinants of practical disassembly. Adoption of material passports and collaborative, multi-disciplinary design processes will further strengthen circular outcomes.

# Conclusion

## Summary

This research presents a hovel comprehensive physical audit of hierarchical design-for-disassembly (DfD) performance in a modular retrofit system, addressing critical gaps in circular construction practice. Through detailed examination of a prototype modular wall system across manufacture, assembly, installation, disassembly, and reassembly, the study provides empirical evidence that advanced DfD principles can be realized in retrofit applications. Key contributions include:

- Empirical Validation of Hierarchical DfD: Confirms DfD intent can be achieved at element, component, and material levels, with differentiated performance across scales.
- Method Validation: Demonstrates predictive accuracy of STaMPD design-stage assessment (within 2–11%) through physical testing.
- Practical Implementation Insights: identifies key technical enablers (adjustable brackets, mechanical fixings, accessible lift-on/lift-off zones, factory prefabrication) and constraints (bonded joints, sacrificial membranes, conventional window-cill detailing, excessive fixings, limited formalized documentation), providing concrete guidance for design optimization.
- Benchmarking Framework: Establishes a hybrid evaluation approach combining ISO 20887, academic frameworks, and European demonstrator case evidence for comparative DfD assessment.

## Key findings

The audit revealed advanced disassembly, material recovery, and reassembly performance, with three principal observations:

- Hierarchical Performance Variation: Element-level DfD (Level 1) was strong, with panels removed intact and reinstalled fully. Material-level DfD (Level 3) achieved >90% recovery. Component-level DfD (Level 2) was constrained, particularly at window-cill interfaces, highlighting the need for design refinement.
- STaMPD Validation: Physical categories (Systems, Technical, Materials) were predicted accurately, confirming STaMPD as both design guidance and evaluation tool. Process and Data categories were more variable, reflecting early-stage information limitations and the need for clearer assessment criteria.
- Enablers and Constraints: Enablers included independent adjustable brackets, mechanical fixings, accessible lift-on/lift-off zones, and factory prefabrication. Constraints included bonded joints, sacrificial membranes, conventional window-cill detailing, excessive fixings, and limited formalized documentation.

External benchmarking shows Drive 0 performance aligns with leading European modular façade systems (CPH Demo 2, B.R.I.C.), while identifying areas for improvement in labelling, documentation, and reuse planning.

## Implications for research and practice

For Research: Physical auditing is essential to validate design-stage assessment and circular design claims. Hierarchical assessment is critical, as performance varies across levels. Future research should refine STaMPD into a streamlined, practical tool with clearer criteria, staged protocols, and reduced subjectivity. Broader validation across building types, integration of economic analysis, and long-term performance monitoring are recommended. The methodology provides a replicable framework for evaluating circular construction systems.

For Practice: Modular prefabricated retrofit systems can deliver advanced DfD when deliberately designed for disassembly. Key actions include early hierarchical DfD integration, physical prototyping, simplification and standardization of components, factory prefabrication, and systematic documentation. Interface design—junctions, connections, and tolerances—is critical for practical disassembly, while adjustable fixing systems accommodate real-world variations. Material passports and component labeling support future material recovery and circular value retention. Iterative design, prototyping, and hierarchical assessment are central to achieving circular outcomes. Scaling requires addressing economic viability, supply chain coordination, and regulatory integration.

## Future directions

STaMPD 2.0 Development: Harmonize indicators (4–5 per category), define measurable criteria, provide scoring guidance, and implement staged protocols. Pilot multi-stakeholder studies to refine reliability and training requirements. Integrate with lifecycle and circularity assessment frameworks.

- Broader Case Applications: Test across diverse building types, climates, retrofit scales, and alternative modular systems (timber, concrete, hybrid). Assess disassembly of non-circular existing structures to inform retrofit strategies.
- Economic and Lifecycle Integration: Develop frameworks linking DfD performance with lifecycle costs, material value retention, and business models (leasing, material banking, performance contracts). Assess economic impacts of simplification, standardization, and documentation on industrialization potential.
- Regulatory and Industry Integration: Align DfD assessment with building codes, circular economy legislation, and certification schemes. Apply manufacturing sector knowledge including design for robotic assembly lines, automated prefabrication sequencing, and standardization of modular interfaces to improve construction efficiency and repeatability. Develop guidance, training, and case repositories to support adoption.

**Closing Statement:** This research demonstrates that circular retrofit is technically feasible, empirically verifiable, and directly informs policy and practical implementation, providing a foundation for scaling DfD solutions across the building stock. Physical auditing establishes a rigorous approach to validating circular design claims. Transitioning to circular construction requires integrating design innovation, assessment methodology, industry collaboration, and supportive policy frameworks. Advanced DfD can be achieved in real-world modular retrofits through hierarchical design thinking, iterative prototyping, and comprehensive performance assessment. As the building sector confronts decarbonization and resource efficiency imperatives, modular retrofit systems incorporating circularity principles offer a promising pathway. These findings provide actionable insights for regulators, designers, and contractors, supporting broader adoption of circular retrofit strategies and a truly circular built environment.

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### Appendix 1 | Showing “Impact and Re-application” assessment framework, scoring and guidance

| Ranking of impact | Score | Description | Example |
|---|---|---|---|
| None | 5 | No damage has been caused at any stage. Component/material can be REUSED without any modification. | Brackets |
| Minor | 4 | Minor damaged has been caused at any stage. Component/ material has to be modified on site to be reused. | Cement Board (Remove the render coat to be reused or fix a small crack in render) |
| Moderate | 3 | To be able to reused the component/material has to be modified on factory and be reused for any other purpose. | Fibre Board (Cut the damage area and reuse it for another small panel); Compressible Gasket (Bring it back to the factory and add a new adhesive for being reuse) |
| Significant | 2 | If the damaged caused into the component/material required to bring it to the manufacture process to be reused. | Window components |
| Severe | 1 | Severe damaged has been caused at any stage. Component/ material can NOT BE REUSED after any of the process below described. | Steel studs waste after being cut (Bring to Recycling factory to create new roller steel) |

| Restages | Description |
|---|---|
| Reuse | Use of products or components more than once for the same or other purposes without reprocessing. |
| Reprocessing | Preparation for re-use such as removal of connectors, cleaning, trimming, stripping of coatings, packaging, etc. |
| Repair | Returning a product, component, assembly, or system to an acceptable condition by renewal or replacement of worn, damaged or degraded parts. |
| Remanufacture | Ability of a product to be disassembled and refabricated at the end of its useful life in a manner that provides restoration to a condition suitable for resale. |
| Recycle | Product or associated component that can be diverted from the waste stream through available processes and programmes and can be collected, processed and returned to use in the form of raw materials or products. |

### Appendix 2 | Showing KPIs and Data sources

### Table A | High Level KPI’s and Dara Sources

| KPI Category | Indicator | Measurement | Value / Result | Data Source | Notes |
|---|---|---|---|---|---|
| Design Performance | Target U-value | Thermal transmittance (W/m$^2$K) | 0.18–0.20 | Design specifications | Exceed Irish Building Regulations |
| DfD Assessment | Element Level | % of components reusable | 100% | Physical audit | Stage 1 audit, Table 1 |
| | Material Level | % of material suitable for reuse | >90% | Physical audit & Table 4 | All Stages |
| Biobased | Biocycle Integration | % materials renewable / compostable | 25-30% | Specification / Audit - Woodfibre board, studs | Table 4 |
| Process Efficiency | Installation Time | Hours per façade module | 1.5 days | Direct observation | Stage 1 assembly |
| STaMPD Validation | Overall Score Variation | % difference vs benchmark | 2–11% | STaMPD scoring & comparative analysis | Table 7 & Section 7.2 |
| External Benchmarking | Drive 0 Disassembly Potential | 90 % by volume | empirically verified as high | Case study benchmarking | Element-level 100% reuse potential |

### Table B | Categories and Indicators used as basis for observation, recording reporting and data sources

| Category | Indicators (Grouped) | Data Source - researcher | Notes |
|---|---|---|---|
| Systems | Standardisation of products, Geometry, Functional independence, Relationship of parts, Number of parts, Connections & fixing | Physical audit, design drawings | Measures interrelation of parts; high standardisation improves disassembly efficiency |
| Technical | Edge connection, Type of connection, Accessibility, Tolerance | Physical audit, manufacturer data | Evaluates core DfD connections; lower accessibility or tight tolerances reduce efficiency |
| Material | Toxicity, Resilience, Durability, Number of materials, Chemical composition | Material datasheets, site observation | Materials with low toxicity and high resilience support reuse and recycling |
| Process | Fabrication location, Production, Transport, Assembly, Tools, Storage, Safety, Knowledge & skill, Operation complexity, Time | Site observation, interviews, time studies | Captures assembly/disassembly workflow and operational efficiency Note - Transport and Final Stage 3b recorded by Manufacturer |
| Data / Information | Construction information, Material information, Disassembly instructions, Safety information | Manuals, BIM files, manufacturer guidance | Ensures correct execution; higher quality documentation facilitates safe and efficient DfD |

Note: The collated observations, photos, sketches, drawings, material data and interview notes, comments and feedback were collated by Researcher in a comprehensive DfD Auditing Report, utilising the STaMPD framework as a reporting mechanism, which also facilitated re-scoring (Post DfD Audit) for comparison to design stage pre works Audit.