2023

A Critical Review of Circularity - ‘design for disassembly’ assessment methods applied in the development of modular construction panels - an Irish case study

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Funder: EU Horizon 2020 project Grant No 841850 e-Prime - Advances in Electrical Engineering, Electronics and Energy 5 (2023) 100252

Contents lists available at ScienceDirect

e-Prime - Advances in Electrical Engineering, Electronics and Energy

journal homepage: www.elsevier.com/locate/prime

A critical review of circularity - 'design for disassembly' assessment methods applied in the development of modular construction panels - an Irish case study

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ARTICLE INFO

Keywords:
Sustainable Buildings
Decarbonisation
Deep Energy Retrofit. Circularity
Modularity
Design for Disassembly
Building Construction
Architectural Technology

ABSTRACT

The construction and operation of buildings has a significant negative impact on the environment and is a major contributor to global warming. The EU has responded with a range of policy measures including targets to decarbonise the existing building stock and to promote circular economy principles in the built environment.

The Drive 0 project aimed to demonstrate potential for such accelerated decarbonisation of the building stock using circular modularised solutions, which necessitated the development and application of circularity - design for disassembly assessment methods, undertaken at key stages during the life of the project, to aid design development and benchmarking of proposed solutions, which is an identified knowledge gap in research.

This paper presents a critical review of the Drive 0 circularity - design for disassembly assessment methods applied in the development of the Irish modularised wall panel, providing case specific insights into the challenges and complexity of implementing and assessing circularity and design for disassembly in buildings, drawing from relevant literature in the field, and contributing to key retrofit, modularity and circularity research needs notably case specific application in construction.

Key findings were limitations of the simplified method in relation to; scope and range of indicators, non-hierarchical consideration, focus and weightings, material aspects and impacts, re-application stages, definitions and terminology, all of which provide theoretical consideration into the complexity of assessing the multi criterion nature of circularity and design for disassembly in practice.

The critical analysis undertaken contributes to this emerging field of knowledge and provides a basis for further research in this field toward developing a more holistic circularity - design for disassembly assessment framework.

1. Introduction

The built environment has significant impacts on the natural environment including operational energy use impacts [41] and significant volumes of construction waste [49]. In the EU there has been a concerted policy and legislative focus on improving the sustainability [24] and energy efficiency of the building stock [23] and more recently a focus on transitioning the economy and building sector toward more circular practices [25], driven by the resource intensity and waste proliferation of the construction sector [5,36].

Circularity is a concept, which broadly aims to retain resources within an economy or supply chain toward limiting resource inputs and waste output at end of life [22]. While circularity has its roots in earlier concepts [53] such as architect, Walter Stahels spiral loops self-replenishing systems and product life factor [55], and is related to Lyles regenerative design [42] and Mc Donoughs & Braungart cradle-to-cradle [45], it is now emerging as a growing area of research in the built environment with an increasing body of literature [46], predominantly focused on strategies, solutions and frameworks [8].

As an evolving research field there is still no standardised definition of circularity, with for example Kirchher et al,. compiling 114 definitions of circular economy in the literature [39], Saidani et al. classifying 55 Circularity Indicators based on several criteria [52] and Parchomenko et al. classifying 63 metrics [51]. However, within the building context, design for disassembly (DfD) is seen as a core aspect of circularity and 'the key to enabling circular processes' [27]; as it facilitates

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https://doi.org/10.1016/j.prime.2023.100252
Received 29 June 2023; Received in revised form 14 August 2023; Accepted 16 August 2023
Available online 27 August 2023

the re-utilization of elements, components, products and materials back into the supply – use chain [4,35,44].

A number of recent built environment circularity literature reviews have given overviews of academic activity and development in the field including identifying knowledge gaps. Bencahio et al., identified from a review of 45 papers that the principle focus of research was on high level consideration of circular economy to the built environment followed by re-use of materials, with tertiary considerations on relationship of circularity to Life Cycle Assessment, design stages and material passports. The review acknowledged growing awareness about circularity and need for change, but identified key issues and knowledge gaps around lack of standardised methods and practices for implementation in construction and specific cases, re-utilisation of material in different levels of construction, (which was identified as a major barrier), material stocks and inventories, implementation in case projects and across design stages, incorporation into LCA, and development of material passports [5].

The work of Gasparri et al. is of particular relevance as they identify and describe some 155 knowledge gap references in 41 recent articles (over 2017 – 2022), which they categorise in terms of economic, environmental, governmental, methodological, societal, sectoral, and technological headings with twenty-six (26) thematic sub-clusters [27].

Of particular interest to this paper is their largest category, methodological, and the sub topic of lack of holistic and comprehensive assessment methods covering the whole building life cycle, which was identified among the most discussed gaps in the literature [3,28,33,48,54], and the related technologies category theme of innovative and integrated design strategies [27].

Relevant methodological – assessment method gaps included the need to develop integrated circularity assessment tools for construction [56], decision making support tools for early design stage [47], and interestingly case specific verification [7,32,60], need for establishing wide-ranging indicators [1,31,32,38,56], as well as quantifying performance, benefits and value [7,60].

Of the technologies category several relevant knowledge gaps were identified notably; the need for further research and innovation on design for disassembly (DfD), facilitating deconstruction, reuse with higher standardisation, fewer components and disassembly of existing construction [30], the need to investigate modular relationship to circularity and off site manufacture and construction including practice examples [43,50], the barriers to developing circular solutions and typologies [21]and the importance to explore circularity in retrofitting of existing buildings, which was noted as largely untapped [3].

In relation to development of assessment methods Drive 0 presented an overview of circular economy indicators many of which apply at higher economic or industrial levels and are not tailored to construction sector with the project developing its own assessment method drawing from a range of sources, that focuses on design for disassembly (DfD), embodied energy and carbon and re-application stages (re-use to recycle) [17].

In this context, this research undertakes a grounded practice-based case study [61], of circularity – DfD assessments applied in a unique and complex case, which combines circularity, modularity and retrofit knowledge gap topics. The research is of an inductive and qualitative nature and aims to examine the challenges, barriers and complexity of applying and assessing circularity in construction explicated from case specific practice knowledge through a detailed critique of four stage cases of the application and testing of a simplified circularity – DfD assessment method applied in the development, testing and production of a novel circular modular retrofit wall panel for application in a deep energy retrofit demonstration case. Utilising both practice case experience and literature review the paper explicates and codifies several issues pertaining to challenges and complexity of implementing circularity DfD in case practice, notably definitions, methods, scope and range of indicators, holism, weighting and value, levels and hierarchy, technical and bio-cycles, metrics and benchmarks, highlighting and discussing from same a range of generic theoretical issues pertaining to the challenges and complexity of applying circularity principles in the construction sector.

The paper presents i) the overall case building and modular circular solution, ii) a bottom up grounded critique of the application of a range of circularity - DfD assessments (sub cases) undertaken during the life of the project, critiquing the scope, indicators, benchmark method, data types and application in case context, iii) drawing from relevant literature in the field the papers provides a synthesis of issues leading to iv) theoretical discussion and v) summarising, concluding and providing recommendations for further research.

The research is responding to identified circularity knowledge gaps in the literature notably the need for research on DfD in construction, assessment methods, with calls for application and testing in case and practice contexts, all relating to modularity and circularity. The paper contributes to the field by providing practice-based perspectives and observations on the challenges and issues involved in implementing circularity DfD principles and assessment methods in real novel case specific construction practice, leading to theoretical consideration and discussion, all of which contribute to both knowledge and practice.

This research is also being used by the author as a foundational basis for further research to develop and test a more holistic DfD assessment framework.

2. The Case Study

Drive 0 is an EU funded 'Horizon 2020' project seeking to demonstrate accelerated decarbonisation of the building stock via deep energy retrofit of dwellings / buildings utilising modularized circular solutions across specific European demonstration cases [13].

The Irish demonstrator proposed a deep energy retrofit, targeting a 65% energy efficiency improvement of two partially retrofitted 1970's semi de-thatched two-story houses of traditional masonry and timber construction. The main project innovation was the development of modularized panels for upgrading of the walls and provision of a simple extension 'pod' both incorporating circular design strategies, and the piloting of associated circularity – DfD assessment methods. See Fig. 1.

Fig 1. LHS photo of existing demonstrator case 1970's two story semi dethatched houses. RHS photo of completed front elevation with circular / modular wall panels and extension 'pod'. Source Author.

The modularized wall panel solution for the Irish retrofit was based on adapting an existing light gauge steel structural wall system to function as a demountable, pre-finished wall panel incorporating circularity principles, notably advanced DfD at all levels in the relevant construction hierarchy and utilising biobased materials where possible in the construction. See Fig. 2.

The Irish demonstrator panel solution was developed in the context of ongoing circularity and DfD assessments within the Drive 0 project, which defined circularity based on a '*100% life cycle renewable energy, and all materials used within the system boundaries are part of the infinite technical or biological cycles with lowest quality loss as possible'*, [26]. The application of circularity strategies and assessments in a specific case

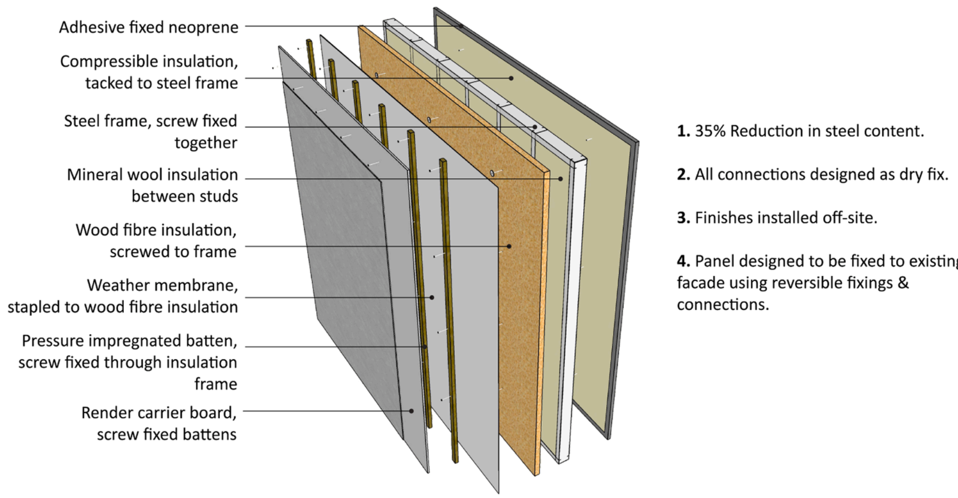

Fig 2. Proposed Irish modular wall panel - showing proposed construction layers, being adapted from conventional 'Vision Built' light gauge steel structural wall panel, toward upgrading the existing masonry cavity wall to U value targets of 0.18 - 0.2 W/m2k. Source of 3D Coady Architects.

Table 1
Summary of Drive 0 circularity – DfD assessments over the design, development and implementation of the project, showing first four stages of assessment with observations on hierarchical level, assessment focus, scope and indictors, data type used and general comments. *Source*: Author.

Summary of Drive 0 Circularity and DfD Assessments							
No	Stage	Hieararchy Levels	Assessment	Scope	Indicators	Data Type	Comments
1	Initial benchmark on existing dwelling (Del 6.1)	Not applied, single level - product / materials	Circ / DfD	Technical Assembly	Durmisivec 4, (Type, Access, Independance, Edge)	Scoring Matrix	Non Integrated, three outputs - Score, EE EC, Mass.
			Materials	Various	Mass, Embodied Energy/ Carbon	ICE Database, Material Spec.	
			Re - Stages	Retrofit elements	7 levels of re-application	Comment	
2	First assessment of propsoed wall modules (Del 3.3, Task 3.3)	Not applied, single level - product / materials	Circ DfD Product / Material	Technical Assembly / Materiality	Durmisevic 4, (Type, Access, Independance, Edge), Materiality (Virgin, Renewable, Biobased)	Scoring Matrix	Non Integrated, Numerious outputs - two seperate benchmark scores, EE EC, various yes/no and qualitative answers.
			Circ DfD Panel Junctions	Technical Assembly / Materiality	Durmisevic 4, (Type, Access, Independance, Edge), Materiality (Virgin, Renewable, Biobased)	Scoring Matrix	
			Questionaires	Various	homogeneity, layering, prefabrication, number and complexity of parts, and standardisation,	Yes/No Anwers	
			Materials	Materials	Embodied Energy/Carbon,	ICE Database	
3	Sample junction detail wall modules (Del 2.5, Task 2.6)	Not applied, single level - product / materials	Circ / DfD	Technical Assembly	Durmisevic 2, (Type, Access)	Scoring Matrix	Single score and graphic output
4	Final assessment of wall panels (Del 2.2, Task 2.3)	Partial application, three levels (element, material, maintenance)	Circ / DfD	Technical Assembly	Durmisevic 4, (Type, Access, Independance, Edge) only 2 at lower level	Scoring Matrix	Irish Adpated for full hierarchy level approach. Single score and graphic output
			Materials Re - Stages	Various Layers	Embodied Energy/Carbon, 5 levels of re-application	ICE Database Selection	

context developed critical insights into circularity - DfD principles and assessment methods both in relation to the specific technical solutions applied in the Irish case and in relation to more general concepts, issues and problems in implementing and assessing circularity.

3. Circularity - DfD Assessment Critique

The concept of circularity in buildings is still an emerging field and there is no definitive standard or method for assessment of circularity as yet with various indicators and methods being currently discussed [9].

Within Drive 0 a simplified circularity assessment method was developed with a focus on some material factors (notably embodied energy and carbon) and core technical DfD aspects, the latter drawn from Alba concepts [58] based on selective indicators from the work of Durmisevic [20], all of which were applied at various stages in the project, to aid design development and benchmarking of the modularised wall panels for application in the demonstration cases.

Circularity - DfD assessments were undertaken at several key stages during the life of the Drive 0 project and showed development in understanding and some method adaptation during same. While embodied energy and carbon were considered at specific key stages, DfD was a core focus of the circularity assessment throughout and hence a focus of this research critique.

Table 1 below represents a summary of the circularity - DfD assessments (sub cases) undertaken during the Drive 0 project, showing how a small selection of Durmisevic's 17 DfD indicators [19] were at the core and common to all assessments, with material assessment, notably initial material embodied energy (EE) and embodied carbon (EC) using data from the University of Bath's Inventory of Carbon and Energy (ICE) [37] being applied in two of the four assessments and that hierarchal analysis was generally ignored being only partially attempted in final assessments. For comparative purposes these assessments were applied to both the modular solution and conventional External Wall Insulation (EWI) systems during particular stages of the Irish case.

Detailed critical review of the Drive 0 assessment methods was undertaken by the author, an experienced architectural, technical and sustainability practitioner / researcher, during application in and reflectively on completion of the Irish demonstrator case and summary of key Drive 0 literature. This highlighted that while the assessments had utility and aided design development of the modularised panels a range of issues emerged such as a narrow and simplified approach, adaptations and changes in scope and indicators during life of project, meaning and use of terms, diversity of data sources, emphasis and weighting (especially in relation to value or quality loss and biobased materials), as well as limitations pertaining to non-consideration of building hierarchy.

The following presents a detailed summary and critique of each of the four assessment sub cases, providing a detailed and rich case description of each expounding the above issues.

i) First Assessments

The first application of circularity - DfD assessment was undertaken on the existing case dwelling and formed the underpinning basis of assessment for the course of the project, albeit with some adaptation. The assessment focused on existing elements effected by the proposed retrofit involving three aspects i) material mass and EE / EC with numeric data outputs, ii) re-application of elements in re-use to recycle stages, and iii) a DfD assessment drawing from Alba Concepts, which was based on four criteria or indicators drawn from Durmisevic's work based on a scoring matrix [19]. The four indicators, selected from Durmisevic's 17 indicators, being core to the Drive 0 circularity / DfD assessment method, where; type of connection, accessibility, functional independence and type of product edge [17].

Critical observations of this assessment method were as follows.

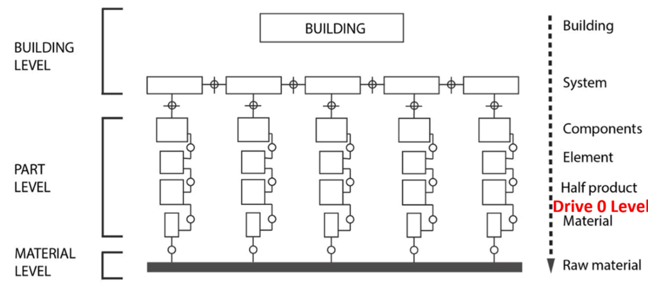

Fig 3. Schematic showing conceptual model of hierarchy in building and construction, with Drive 0 level of assessment (product / material level) noted in RED by author. Original source [19]. Graphically re-worked for clarity.

a) That the scope of assessment was narrow and somewhat simplified, in relation to the complexity of circularity and DfD, focusing mainly on technical connections and energy aspects of materials, with a limited range of indicators being assessed for each aspect. For example, material indicators of toxicity and durability, and indicators such as systems and process were ignored.
b) All indicators were assessed at one level (product / material) without reference to any construction hierarchy. This not only resulted in a lack of clarity as to which level in the construction hierarchy particular connections were being assessed in relation to, but also ignored consideration of differences in DfD at different levels in a building construction hierarchy itself, which is a critical aspect in relation to retention of value or quality in resource recovery and re-application. See Fig. 3.
c) There was some confusion and lack of clarity about terms and their usage, e.g. i) the meaning and inter use of terms such as 'element' and 'component', ii) changes to some of Durmisevic's terms and their meaning and application such as functional independence and type of product edge, and iii) differences in terms, meaning and application of the re-pair, re-furbish or re-manufacture stages.
d) Sources of data in relation to embodied energy and embodied carbon were limited with the assessment using generic data from the ICE database [37], which i) ignored geographic location with manufacture and transport differences, ii) had significant ranges in values, and iii) had limitations in finding appropriate or equivalent material values, especially for some biobased materials.
e) While the consideration of element recovery potential was important, its energy impacts could not be considered or assessed given the diversity of possible re applications in a future scenario.

ii) Second Assessment

The second assessment involved the first circularity - DfD benchmarking of the proposed modularised panel and was broadly based on the initial EE / EC and circularity - DfD assessment method as above, but with additional standalone questions, which while expanding the scope of consideration were excluded from the main scoring matrix. A separate benchmarking of the panel in relation to its various connection details was also included, which was a first attempt to consider the panel as a specific entity beyond its elements [16].

In detail this assessment involved the following aspects.

A standalone assessment covering material scope, product scope and multifunctionality, expanded the scope to important factors such as homogeneity, layering, prefabrication, number and complexity of parts, and standardisation, but with limited data quality, (as they were based on yes, no answers), and limited utility, (as they were excluded from the scoring matrix). There were also some minor questions on re-use potential and multifunctionality of products but again these were not integrated into the overall benchmark assessment score.

The core circularity - DfD assessment was based on the initial benchmark assessment utilizing the four Durmisevic indicators applied for each material construction layer, but with an additional material indicator pertaining to virginity, renewability and biobased materials. See Fig. 4

Lastly there was an attempt to examine the panel as an entity itself, using an additional benchmark score based on the core four Durmisevic indicators and an additional 'demountability' indicator applied to a range of junction details rather than construction layers.

In application of this circularity - DfD assessment the Irish study included a comparison of the proposed modularized wall panel to a conventional external wall insulation solution (EWI) achieving equivalent wall U Value, which proved informative.

Additional critical observations from this assessment method were as follows.

a) The expansion of the core circular - DfD study to materials was welcome as the Irish emphasis on biomaterials could be factored, however as there was no weighting given to material or especially to biomaterials in the scoring matrix the proposed biobased specification had minimal influence in the overall indicator due to dominance of the technical indicators at a 4 to 1 ratio.
b) The assessment comprised a range of diverse sub assessments and used different methods of reporting and data such as

2D Façade BIOBASED Insulations

	Element	Type of Connection		Accessibility of connection		Crossings		Form containment		Materials	
1	Connection to existing wall	Mechanical Bracket	0.8	Minor Repairalble damage	0.4	Modular zoning	1	Overlaps on one side	0.8	Mainly virgin material	0.1
2	Buffer Strip Knauf Insulation	Netting	1	Minor Repairalble damage	0.4	Modular zoning	1	Open, no inclusions	1	Recycled material	0.6
3	Vapour Airtight Membrane	Screw??	0.8	Minor Repairalble damage	0.4	Modular zoning	1	Open, no inclusions	1	Mainly virgin material	0.1
4a	Metal Stud Framing	Screw	0.8	No damage	0.8	Modular zoning	1	Open, no inclusions	1	Rycycled Content	0.6
4b	Biosbased Quilt or Batt	Dry	1	No damage	0.8	Modular zoning	1	Open, no inclusions	1	Biobased material	0.8
5	Wood Fibre Board	Screw	0.8	No damage	0.8	Modular zoning	1	Open, no inclusions	1	Biobased material	0.8
6	Wind barrier Membrane	Stapled	0.8	Minor Repairalble damage	0.4	Modular zoning	1	Open, no inclusions	1	Mainly virgin material	0.1
7	Wooden lathing	Screw	0.8	No damage	0.8	Modular zoning	1	Open, no inclusions	1	Biobased material	0.8
8	Facade cladding (fibre cement)	Screw (Open Jointed if no render)	0.8	Freely accessible (depends on use of render or not)	1	Modular zoning	1	Open, no inclusions	1	Mainly virgin material	0.1
9	Render (Optional)	Chemical Bond	0.1	Freely accessible	1	Modular zoning	1	Open, no inclusions	1	Mainly virgin material	0.1
Category average			0.84		0.64		1.00		0.83		0.44
Circularity indicator		0.75		Medium degree of circularity							

EWI STONEWOOL or EPS

	Element	Type of Connection		Accessibility of connection		Crossings		Form containment		Materials	
1	Connection to existing wall	Adhesive / Mech	0.2	Repairable damage	0.4	Modular zoning	1	Open, no inclusions	1	Mainly virgin material	0.1
2	Stonewool or EPS	Chemical	0.1	Accessible with repair damage	0.4	Modular zoning	1	Open, no inclusions	1	Mainly virgin material	0.1
3	Base Coat 5mm	Chemical Bond	0.1	No Access Damage	0.1	Modular zoning	1	Open, no inclusions	1	Mainly virgin material	0.1
4	Acrylic render finish	Chemical Bond	0.1	Freely accessible	1	Modular zoning	1	Open, no inclusions	1	Mainly virgin material	0.1
Category average			0.13		0.48		1.00		0.83		0.10
Circularity indicator		0.51		Medium degree of circularity							

Fig 4. Showing Drive 0 circularity – DfD assessments of Irish Modularised biobased panel (above) compared to EWI (below), showing four technical indicators from Durmisevic and additional material indicator, all applied at single product / material level in construction hierarchy, showing higher number of parts for panel compared to EWI and poorer DfD and material scores for EWI. (Tables from Drive 0 Deliverable 3.3, 2021) *Source*: Author.

commentary, scoring and yes-no answers, and as such the assessment had no holistic benchmark. This gives insight into the challenge of assessing the multi criterion nature of circularity with diverse phenomena and various data types.

c) The comparison between the conventional EWI system and the circular modular wall panel indicated a higher degree of circularity for the modular panel, given that it can be disassembled with minor impact compared to the EWI system, which was clearly reflected in the DfD component score. However, the EE and EC comparisons showed significantly higher values for the modular panel compared to EWI due to the additional materials involved in the modular panel, in part due to its structural nature and in part due to the various additional layers and elements needed to achieve DfD, indicating an EE and EC cost to achieving higher DfD in this case.

iii) Third Assessment Smart Detailing

The third assessment was somewhat bespoke but drew from the selected Durmisevic indicators and focused on the development of 'smart' building details and attempted to apply circular – DfD benchmarking / scoring to some key details with a graphical scoring output [14].

For the Irish modular panel, the study focused on the horizontal panel to panel connection, with the proposed design incorporating an access zone to facilitate independent access and demountability of the entire panel from the host wall, as well as disassembly of the panel itself. This concept facilitated recovery and re-application of the panel in its entirety with potential transport of the entire panel for re use in any location or for factory disassembly both of which would facilitate highest possible value retention and lowest resource and quality loss. See Figs. 5 and 6.

Critical observations during the application of this assessment method were as follows.

a) That the assessment was undertaken at product / material level only, and not on a construction hierarchical basis, proved a limiting factor as it ignored the benefits of the proposed Irish detail facilitating whole panel demounting from the host wall and thereby ignored value and quality retention and reduced resource impacts compared to full disassembly at product and material levels.

b) That the scope of indicators was reduced to only two, which was a further simplification, ignoring a range of other circularity and DfD indicators.

iv) Fourth Assessment

The fourth assessment comprised a detailed reporting on the circularity of the panel and a further circularity - DfD assessment. The reporting included an overview of the demonstration case, the proposed modular system and the circularity design principles involved, which in the Irish case was based on achieving advanced DfD at all levels in the construction hierarchy and a focus on biobased materials. This circularity assessment comprised embodied energy and carbon study with an adapted circularity - DfD study utilizing some of the four selected Durmisevic indicators. The method attempted a first-time hierarchical assessment based on three levels, end of life (element level), end of life (material level) and a poorly defined 'maintenance level'. However, this used only two DfD indicators at element and material level (type of connection and access) compared to four at maintenance level, adding inclusions and piercings, which effected comparison [15].

At this stage in the Irish project the principle of achieving advanced circularity - DfD at all relevant levels in the construction hierarchy was clearly established and being implemented in the proposed design and

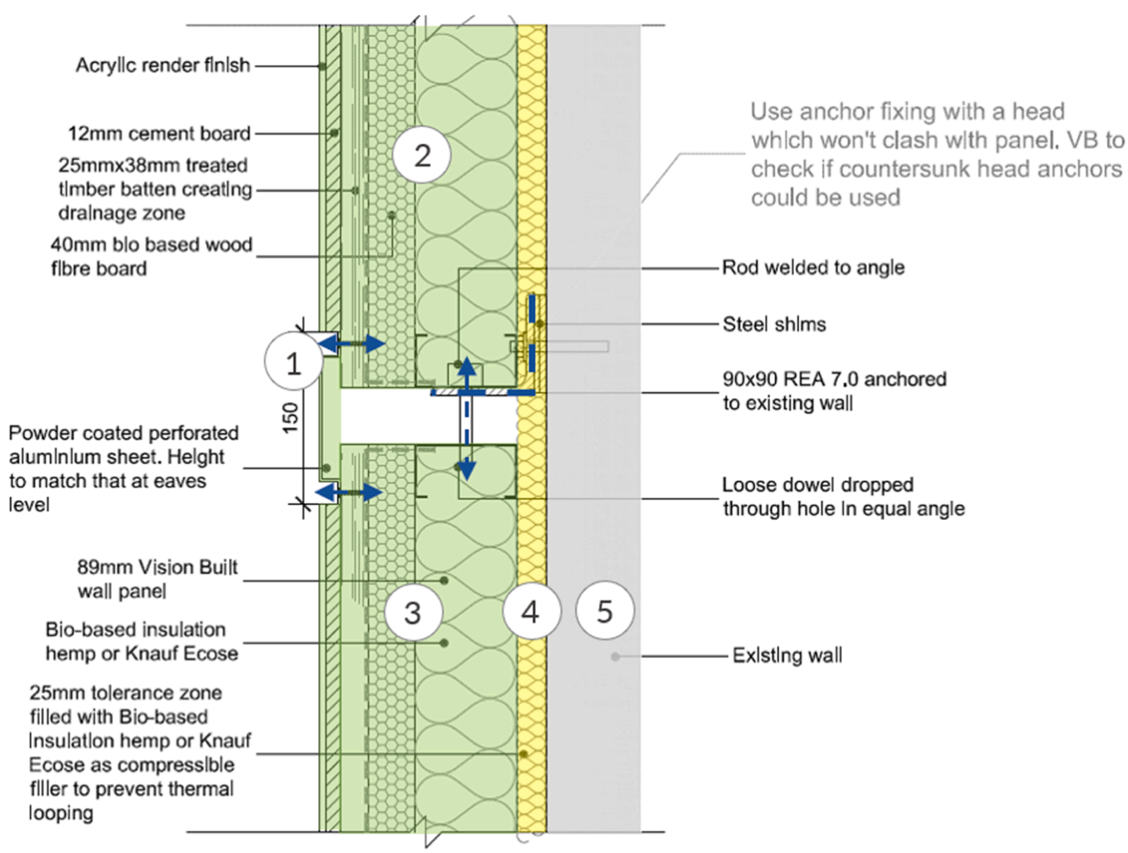

Fig 5. Detail section showing proposed vertical panel to panel construction detail for the Irish modular panel with access zone for independent mounting and demounting of entire panels, with proposed bracket providing combined restraint and gravity anchoring. Original detail Coady Architects [14].

end-of-life	Coady_vertical		0,85		
			score	comment	
1	Powder coated perforate aluminium sheet		0,89		
	on prefabricated façade panels				
		Type of connection	0,80	Screw	Connection with added elements
		Accessibility of connection	1,00	Freely accessible	
2	Top prefabricated façade panel		0,89		
	on existing wall				
		Type of connection	0,80	Connection with added elements	Connection with added elements
		Accessibility of connection	1,00	Freely accessible	
3	Bottom prefabricated façade panel		0,89		
	on existing wall				
		Type of connection	0,80	Connection with added elements	Connection with added elements
		Accessibility of connection	1,00	Freely accessible	
4	Bio-based insulation in tolerance zone		0,75		
	on boarding				
		Type of connection	0,60	Nail	Directe integrale verbinding
		Accessibility of connection	1,00	Freely accessible	
5	Existing wall				
	Existing element; not assessible				

Fig 6. Showing scoring for each layer of construction (product and material) of detail under Drive 0 'Smart Detailing' DFD scoring [14].

this assessment was the first to account for same. A key aspect of the Irish strategy for advanced DfD was a proposed assembly access zone to facilitate individual panels to be installed and demounted in their entirety for full recovery and re-application, enabling transport to another location or disassembly in a factory setting.

The Irish application of this study adapted it to undertake assessments at all its three clearly defined levels in the building construction hierarchy, level 1 major element (wall panel and jointing), level 2 component, (translucent and opaque components) and level 3 product / material level, with both the modularized panel and the conventional EWI system being assessed on this basis to facilitate comparison. See Fig 7

Critical additional observations during the application of this Irish adapted assessment method were as follows.

a) The hierarchical levels-based approach proved insightful and highlighted differences in DfD scores at various levels in the building hierarchy, showing best DfD indicator scoring at the major element level (0.8) and product / material level (0.86) compared to

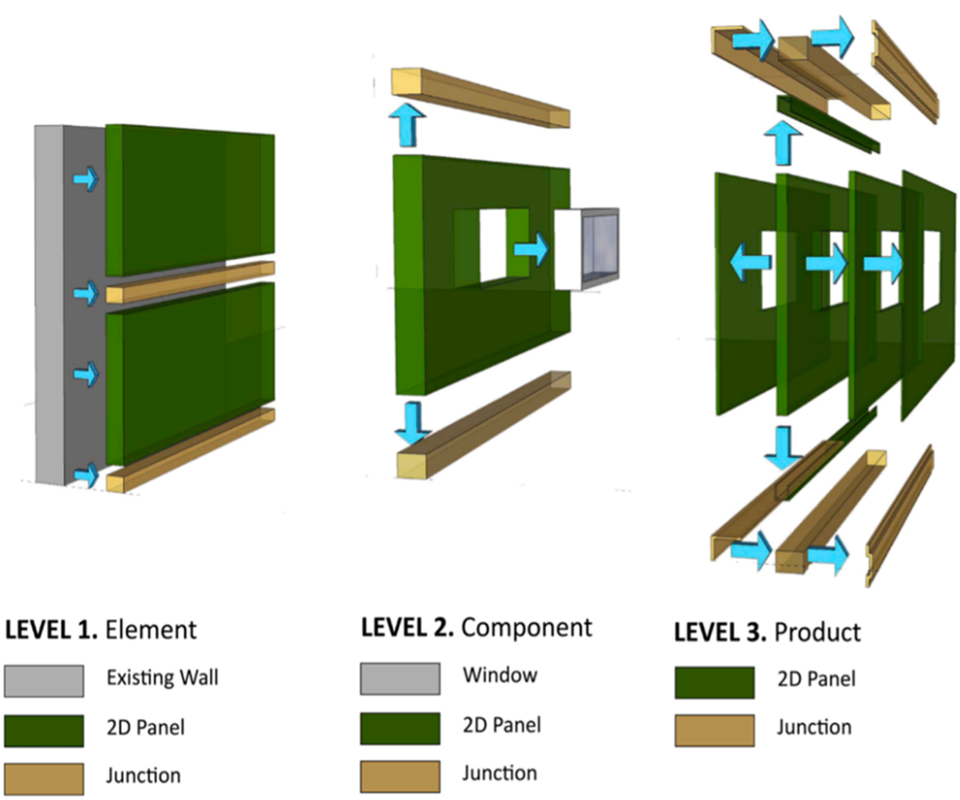

Fig 7. Concept of Irish demonstrator circular modularized wall panel system showing proposed hierarchical breakdown for circularity – DfD assessment. Level 1 Wall element connection to / from host wall, Level 2 components connections, Level 3 the full disassembly of all products and materials. *Source*: Patrick Daly, Paula Gallego TUDublin.

component level (0.62), albeit based on a simple scope and additional indicators at lower levels impacting clear comparison between levels.

b) The comparison of modular solution to EWI in terms of DfD indicates a significantly lower circularity - DfD score for EWI at all three levels in the hierarchy, elemental level (0.45), component level (0.45) and product material level (0.71). The EE and EC comparison resulted in a higher EE and EC for the 2D modularized system than a conventional EWI system, which also had poorer DfD scoring, indicating an embodied energy and carbon cost for achieving this modularised panel solution as per assessment ii) above.

4. Synthesis and Discussion

4.1. Synthesis of Findings

Drive 0 developed and applied a simplified circularity - DfD assessment method that proved useful in examining some core technical aspects of circularity - DfD and supporting circular design solutions for the modularised panels as well as facilitating comparison of conventional versus modular systems. Overall, the approach focused on material EE / EC factors and some technical DfD indicators as core aspects of assessment and benchmarking. It was evident that there was adaptation of the method during the life of the Drive 0 project itself, with clear changes in scope and assessment method occurring.

Fig. 8 below shows a conceptual diagram synthesising the scope and focus of circularity – DfD assessment methods developed and applied during the design and realisation stages of the Drive 0 project (the first four stages / cases of assessment), with DfD and material aspects being the main categories of assessment (shown in circles). DfD indicators contributed to a single benchmark score based on two to four of Durmisevic's technical connection indicators. Material indicators were generally separate to this benchmark focusing on EE and EC with material type being added to the above circularity –DfD indicator in the 2nd assessment, which also included reference to a range of other indicators, but these did not form part of the benchmark score, (main indicators are noted in rectangular boxes and others in text). Across all the assessments, hierarchical levels, shown on the LHS of the diagram, were generally ignored, being assessed at level 3 product and material only, except for assessment four.

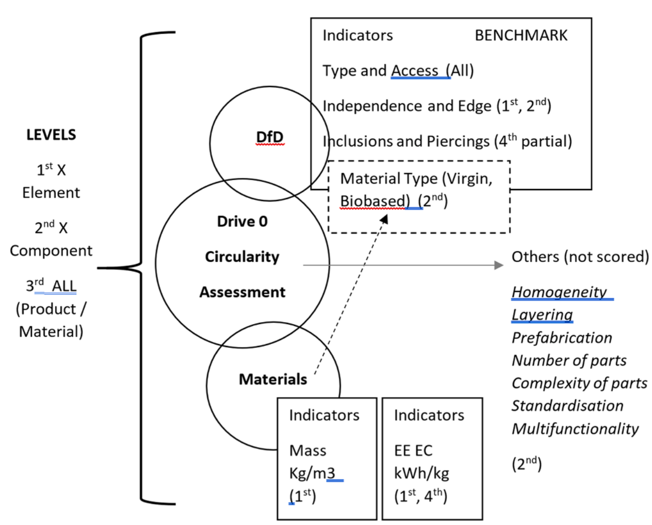

Fig 8. Concept diagram synthesis of Drive 0 circular – DfD assessment method scope and focus development and adaptations over the first four assessments during the life of the project, showing assessments main categories in circles (DfD and Materials), main indicators, benchmark or scoring / data units in rectangles with scored indicators used in assessment and building hierarchal levels applied on LHS. *Source*: Author

The application of these assessment methods in the development of the Irish demonstrator provided important insights, not only in relation to defining and applying circularity DfD principles in design development of the modular panels but also into the complexity and challenges of undertaking circularity – DfD assessment itself, with the method critiqued in relation to method simplicity versus complex reality, limited scope and range of indicators, focus and weighing, hierarchical consideration, re application of resources and a multi criterion method with no overarching representative single benchmark, detailed and discussed as follows.

i) Scope / Range of Indicators

The scope of assessment and range of indicators used in Drive 0 were limited with impacts on results and data. The assessment focused on the embodied energy and carbon aspects of materials principally and a narrow range of DfD indicators as its core circularity benchmark. This contrasts with the scope, categorization and indicators found within the literature, some of which Drive 0 referenced.

For example, Durmisevic's had 17 technical indicators focused exclusively on physical aspects, which it categorised under functional, technical and physical decomposition headings, and including indicators pertaining to the assembly as a system, i.e., the interrelationship of parts, elements, sequence, clustering, etc. [19]. Van Vliet referenced 25 indicators and drew heavily upon Durmisrevic's work, using similar technical indicators, but had a broader scope, including process and financial categories / indicators [57]. Brad and Ciarmboli presented 25 non categorised indicators or factors, which relate to technical, material and process categories [29]. Akinade et al., reports 17 indicators in categories of material, design and human, with alignment of material and design indicators relating to Durmisrevic's technical indicators and human category to van Vliet's process indicators [2]. The International Standard on DfD itself includes 17 principles of DfD grouped in terms of technical, process and financial factors [34].

This literature clearly identifies a broader scope and range of factors that impact upon circularity – DfD than the Drive 0 projects focus, including factors and indicators relating to process such as knowledge, skill, tools, equipment, transport and handling etc., and data / information. Material indicators, which could affect disassembly itself, such as toxicity or durability were identified, that were excluded from Drive 0 assessments.s

ii) Hierarchical Framework

The circularity – DfD assessments in Drive 0 were mainly taken at one level in the building construction hierarchical framework i.e., product and material level, which was a key weakness of the approach, as a hierarchical consideration and assessment is arguably essential to adequately consider the concept of resource use in relation to value retention and quality loss. This is a core circularity principle, as parts or elements that can be – re utilised from and at higher levels in the building construction hierarchy have higher value / quality retention reducing waste and needing less energy input. The first attempted application of a hierarchical approach in the fourth assessment of Irish study highlighted this importance with clear differences in benchmark scoring at different levels in the hierarchy. This aligns with guidance in the recent international standard on DfD,which recommends taking a hierarchical approach [34], and the concept of hierarchy is also argued by Durmisevic & Brouwer who state that the perception of a building a compact and static entity is misleading [20,59]. Verberne also highlights the need for considering buildings as a dynamic structure and refers to the levels type framework developed by Brand or Duffy [6,18,59], which is strongly related to but distinct from hierarchy.

iii) Weighting

The weighting or absence thereof of indicators in the Drive 0 scoring method had consequences, notably that the specification of biobased materials had limited impact on the benchmark and that weighting in relation to construction hierarchy was not accounted for. The application of weighting is an important and complex aspect for consideration in a circularity - DfD assessment method as it can facilitate greater value, focus or emphasis to be placed on certain aspects.

Given the nature of circularity seeking to reduce wastage and retain highest value and quality, there is an argument that weighting should be given to circularity - DfD capability at higher levels in the construction hierarchy to adequately reflect this importance. Similarly, the weighting of biomass materials could also be considered, given it provides not only re-utilization in the technical cycle but also into the alternative biocycle. In addition to these there are also questions about weighting indicators in proportion to mass in a construction as identified by Drive 0 research colleagues [40].

iv) Re-Application Stages

Only the first and last Drive 0 assessments considered the re application of resources in the supply – use chain, which shed light on its importance in relation to facilitating re-application at higher re-application stages such as re use, and complexity in relation to possible resource impacts notably energy resources, as at the point and time in assessment the re application stages are futuristic potentialities that cannot adequately be currently accounted for.

v) Embodied Energy Carbon Impacts

The case study highlights some of the issues with EE and EC assessment in particular relating to use of central data base such as ICE [37] relating to geographic locations, transport, value ranges and limitation in biomass data, which aligns with literature [12,11] and other Drive 0 commentary [9,44].

This case study indicated a higher level of initial EE and EC in the circular modularised wall panel compared to a conventional EWI system, mainly due to the increased number of layers, materials and fixings. However, this has to be considered in context of circularity and possible multiple life cycles – as EE and EC are estimates of energy and carbon over one life cycle only and circularity facilitates possible multiple life cycles.

Therefore, it could be argued, or it may be possible, that relatively higher EE and EC costs of achieving modular advanced circular - DfD solutions may be offset by the multiple life cycles facilitated by the latter. For example, in the Irish case the higher EE and EC modular circular system may, on a longer-term multiple life cycle basis, have lower environmental impact than the conventional EWI solution. That said efforts need to be made to develop lower ‘first life’ EE and EC solutions.

vi) Definitions and Data

There were issues relating to definition and use of terminology across the assessments as well as the complexity of diverse data types in relation to sourcing, utility and integration within an assessment method, which all present challenges in relation to circularity and DfD assessment.

vii) Multi Criterion

The project highlights the challenges of attempting to assess something as complex as circularity - DfD in construction especially in relation to the multiple criteria involved and the diversity of data types they represent, with distinct indicators, units and values including both quantitative and qualitative. Within the Drive 0 project only some of these indicators were grouped into a single numeric benchmark, others were included in some assessments and reported in various ways but not effecting the benchmark and many others ignored, as such there was no single holistic score or benchmark.

4.2. Theoretical Discussion

The challenges and issues encountered and explicated in this practitioner case study highlight a number of generic issues in relation to implementation and development of assessment methods on circularity and DfD in the construction sector.

i) Definitions and Method

Definitions of circularity in general and circularity in construction are diverse and differences in understanding of circularity will likely influence the design agenda and resulting assessment methods. The Drive 0 definition comprised several key elements; 100% renewable energy input across all stages, materials part of an infinite technical or biological cycle, and lowest possible quality loss. However as can be seen in the above critique this was not fully carried into the assessment methods, (which changed and adapted over the course of the project to some degree, perhaps due to differences in interpretation or understanding of what circularity is, or that project members were developing their own understanding on same during the course of the project itself), and can be critiqued for being i) aspirational, with definition representing an unachievable optimal situation, although there is also the argument that it may be useful to have clarity on what full or advanced circularity would mean, ii) technical and biological cycles not equally emphasised, iii) aspects that are difficult to assess or measure (e.g. potential re application stages) and iv) lowest quality loss (or highest value retention), not adequately valued given non-hierarchical consideration.

As seen in the literature there is significant diversity of definition of what circularity is in general and in construction specifically, with no agreed definition to date, and as seen in this case critique, definition may not always follow through to design principles or assessment method, as people may interpret or give focus to particular aspects. As such until there is broad agreement on what circularity in construction means and entails, there will likely be some confusion and diversity in how it should be applied and assessed, and there remains a clear need for academics and specialist within the built environment to carefully define what circularity is, its key aspects and features and how these can be applied in construction and assessed during design, construction and other lifecycle stages.

ii) Assessment, Criterion and Benchmarking

The issue of definition strongly relates to the issues of assessment, scope, indicators, criterion and benchmark, as the clarity and scope of definition will impact on the extent and nature of assessment. Within Drive 0 it seems that aspects of the definition were lost or not focused on and others emphasised, and there was changing emphasis and scope during the project itself, albeit the core scope was maintained being materiality - material type, embodied energy content, mass, durability etc. and matters relating to disassembly, re application cycles.

Given the nature of circularity and its scope diversity, the resulting diversity of indicators and indeed metrics can be very broad ranging from diverse numeric values and units to material specification to process aspects and even futuristic potentialities. We are then presented with a complex problem of how these diverse criteria are to be accommodated in an assessment method of multiple indicators and if they can be merged into a holistic benchmark.

iii) Value, Weighting and Hierarchy

The issue of value and weighting is also important and relates to hierarchy, as there are aspects of the circularity – DfD principles that we may wish to, or indeed should be emphasised more and if so how can that be accommodated in an assessment method? Three specific examples of this issue arose in this case study.

Firstly, the non-weighting or proportioning of materials within a construction or particular elements by mass or volume meant that a relatively minor (mass) component with poor score could distort the benchmark in relation to that of a major proportion (mass) component with a better score or indicator. Secondly, although certain bio-materials were specified, which facilitated potential re-application in two (bio and technical) as opposed to just one (technical) cycle, there was no recognition of this within the assessment method. Lastly is the issue of hierarchy and value retention, which was not accommodated in the method.

If by definition circularity is about retaining resources in use or circulation at highest value, be that economic or environmental value, then facilitating the re-application of elements at their highest value is important, meaning that materials and resources are kept as intact as possible at the highest levels of utility and hierarchy and are reapplied at the lowest level of loss and resource need, i.e. re using a building or its wall element is much better than recycling all its components. If this is a key principle of circularity, then assessment methods need to find ways of incorporating this hierarchy and re application principle.

iv) Embodied Energy and Carbon Impacts

This specific case example highlighted that there was an initial embodied energy impact of achieving modular solutions in comparison to the conventional EWI System, due to the modular systems structural frame, increased number of layers and fixings, with the modular system needing further simplification in design and specification to reduce its material energy and carbon impacts. However, while modular solutions may have higher 'first life' energy and carbon impacts, these may be offset in considering potential for further life cycle iterations compared to conventional. The point of debate exemplified here is, do we take a short time lowest impact 'now' single life view versus a potentially higher impact 'now' but ultimately lowest impact over future multiple lifecycles.

v) Centrality of Design for Disassembly

It is clear from the literature and the case experience and assessment that DfD is central and key to circularity in construction, as elements, components and materials need to be able to be deconstructed / disassembled to enter re-use to re-cycle phases.

While DfD was clearly central in the Drive 0 project it is evident from the study that it was mainly focused on full disassembly at product and material levels and insufficient attention was given to disassembly at higher construction and building levels. It is also clear from literature that Drive 0 utilised a rather narrow scope of indicators when assessing DfD mainly relating to physical connection and there may be other issues or factors, such as material and technique, that impact positively or negatively on DfD potential.

As such there is need for research to develop more holistic frameworks and range of indicators for what influences optimal design for disassembly and how they can be incorporated into assessments and is the subject of follow-on research by the author.

4. Summary, Conclusion, Recommendations

Circularity and DfD are complex concepts especially when applied to a complex sector such as the built environment. This case study and critique has met specific knowledge gaps and needs identified in the literature and contributes to the field in explicating from case practice some of the challenges and complexities of implementing and assessing circularity – DfD by providing grounded and practice based detailed insight and perspectives into various issues encountered, many of which also relate to issues identified in the literature.

The approach taken within the Drive 0 project, while having utility and aiding design development of the modularised wall panels, was rather simplified, being based on a limited technical and material focus and range of indicators, considering the range circularity and DfD indicators and categories identified in the literature.

The consideration of building construction hierarchy was clearly identified as a key limitation given its direct relationship to the issue of retention of value and utility and optimal use of resources at higher re-applications levels and building hierarchy and it should form a key part of any circularity – DfD design or assessment method.

The issue of weighting and value was also discussed with potential to focus assessment and design emphasis on retention of resources at highest possible levels on the re-application (re-use to re-cycle) levels and for possible weighting of biobased materials given their ability to be re-applied in both the technical and alternative bio-cycles. Specific indicators could also be weighted in proportion to their application in the construction, by mass for example, to provide a more holistic and balanced assessment.

Attempts to consider the re-application levels were important in terms of facilitating application in the higher stages such as re-use and re-manufacture, but the difficulty to value and assess same was identified, especially in relation to material and energy resource impacts due to potential use in unknown and diverse possible future scenarios. As noted above the alternative bio-cycle needs adequate focus and weighting and at what level it may be applied.

The comparison of the modular wall panel solution to EWI showed a superior scoring for the modular solution in relation to circularity - DfD but with a 'first life' higher embodied energy and carbon impact, which could possibly be offset over a lifecycle or multi lifecycle assessment given the re-application potential of the modular panel and its elements, components, products and materials. This short term single life impact versus long term multiple life impacts is an important point of consideration for circularity and modularity in construction.

Definitions and use of terminology were also discussed as problematic as well as the diversity of data types that circularity and DfD incorporate, which complicates assessment and relates to discussion about muti indicator assessment and or integration to holistic benchmarks.

All the above highlights the complexity and challenges pertaining to implementing and assessment of circularity - DfD in construction, from which several recommendations are made;

There is an urgent need for clarity and consensus on defining what circularity in building and construction is and how it can be implemented and assessed with input required from a range of building design disciplines as well as possible specialists in process or systems fields.

Further research, development and testing needs to be done on developing assessment methods that are more holistic, based on hierarchical building and construction framework, provide for weighting, valuing and proportionality, and that can accommodate diverse multiple indicators and holistic benchmarking. The potential higher embodied energy and carbon aspects of modular circular solutions needs to be examined over single and future lifecycles and given that design for disassembly is very much at the heart of circularity in construction a more holistic consideration and assessment method of same is required, and is the subject of ongoing research interest and activity by the author.

CRediT authorship contribution statement

Patrick Daly: Principal researcher, conceptualisation, methodology, literature review, investigation, analysis, writing original, review, editing.

Declaration of Competing Interest

No potential conflicts of interests are reported by the author.

Data availability

Data will be made available on request.

Acknowledgements

This research was undertaken by the author based on research and design development of the Irish demonstration case, undertaken during the Drive 0 EU Horizon 2020 project Grant No 841850, (See www.Drive0.eu for project details). The development of the Irish modularised wall panel was a collaboration between the research partner Technological University Dublin and the industrial partners Coady Architects (who input on EE and EC assessments), and Vision Built light gauge steel system manufacturers. The author would also like to acknowledge the EU partners in the Drive 0 project who were involved in the development and application of the circularity – DfD assessments in general and in their local cases, which informed this study and the assistance of TUDublin research assistant Paula Gallego Barril.

References

[1] N. Ahn, A. Dodoo, M. Riggio, L. Muszynski, L. Schimleck, M. Puettmann, Circular economy in mass timber construction: State-of-the-art, gaps and pressing research needs, Journal of Building Engineering 53 (2022), https://doi.org/10.1016/j.jobe.2022.104562.

[2] O.O. Akinade, L.O. Oyedele, S.O. Ajayi, M. Bilal, H.A. Alaka, H.A. Owolabi, S. A. Bello, B.E. Jaiyeoba, K.O. Kadiri, Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills, Waste Management 60 (2017), https://doi.org/10.1016/j.wasman.2016.08.017.

[3] S.C. Andersen, H. Birgisdottir, M. Birkved, Life Cycle Assessments of Circular Economy in the Built Environment—A Scoping Review. Sustainability (Switzerland), 2022, https://doi.org/10.3390/su14116887 (Vol. 14, Issue 11).

[4] M.J.M. Bakx, M.J. Ritzen, J.J.N. Lichtenberg, P.R. Beurskens, E. Durmisevic, T. Zero, A Morphological Design and Evaluation Model for the Development of Circular Facades. *Sustainable Built Environment: Transition to Zero 2016, April*, 2016.

[5] G.L.F. Benachio, M.do C.D. Freitas, S.F. Tavares, Circular economy in the construction industry: A systematic literature review. Journal of Cleaner Production, 2020, https://doi.org/10.1016/j.jclepro.2020.121046 (Vol. 260).

[6] S. Brand, How Buildings Learn; What happens after they're built, Penguin Publishing Group, 1994.

[7] F. Bucci Ancapi, K. Van den Berghe, E. van Bueren, The circular built environment toolbox: A systematic literature review of policy instruments. Journal of Cleaner Production, 2022, https://doi.org/10.1016/j.jclepro.2022.133918 (Vol. 373).

[8] R. Charef, W. Lu, Factor dynamics to facilitate circular economy adoption in construction, Journal of Cleaner Production 319 (2021), https://doi.org/10.1016/j.jclepro.2021.128639.

[9] D. Cottafava, M. Ritzen, Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects, Resources, Conservation and Recycling 164 (2021), 105120, https://doi.org/10.1016/J.RESCONREC.2020.105120.

[10] D. Cottafava, M. Ritzen, Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects, Resources, Conservation and Recycling 164 (2021), 105120, https://doi.org/10.1016/J.RESCONREC.2020.105120.

[11] M.K. Dixit, C.H. Culp, J.L. Fernández-Solís, System boundary for embodied energy in buildings: A conceptual model for definition, Renewable and Sustainable Energy Reviews 21 (2013) 153–164, https://doi.org/10.1016/J.RSER.2012.12.037.

[12] M.K. Dixit, J.L. Fernández-Solís, S. Lavy, C.H. Culp, Identification of parameters for embodied energy measurement: A literature review, Energy and Buildings 42 (2010) 1238–1247.

[13] *Drive 0*. (2023). https://www.drive0.eu/.

[14] Drive 0, Alders, N., & van der Kooij, D. (2022). *Deliverable 2.5 A set of smart building and installation details for mounting and demounting*. https://www.drive0.eu/wp-content/uploads/2023/02/Drive-0_D2.5-Improved_1-Jul-2022.pdf.

[15] Drive 0, Bergmans, I., van Oorschot, J., Binow Bitar, A. L., & Ritzen, M. (2022). *Deliverable 2.2 A set of circular prefab 2D building envelope elements with case specific solutions*. https://www.drive0.eu/wp-content/uploads/2023/02/DRIVE-0_D2.2-Improved.pdf.

[16] Drive 0, TalTech, Zuyd, IVE, Unibo, IRI UL, NKUA, TUDub, WEBO, KI, ALIVA, SALFO, Timbeco, Fact0, PICH, COADY, & UIPI. (2021). *Deliverable 3.3 Tailor made holistic and circular renovation packages for the 7 demonstration cases*. https://www.drive0.eu/wp-content/uploads/2022/07/Tailor-made-holistic-and-circular-renovation-packages.pdf.

[17] 0. Drive, D. Cottafava, M. Ritzen, J. van Oorschot, Zuyd University of Applied Sciences, SURD research team. Deliverable 6.1 Report on benchmarking on circularity and its potentials on the demo sites, 2020. https://www.drive0.eu/wp-content/uploads/2020/08/DRIVE0_D6.1.pdf.

[18] F. Duffy, Measuring building performance, Facilities 8 (5) (1990) 17–20.

[19] E. Durmisevic, Transformable building structures: Design for dissassembly as a way to introduce sustainable engineering to building design & construction, TUDelft, 2006.

[20] E. Durmisevic, J. Brouwer, Design Aspects of Decomposable Building Structures, in: *Proceedings of the CIB Task Group 39-Deconstruction Meeting, January*, 2006.

[21] L.C.M. Eberhardt, M. Birkved, H. Birgisdottir, Building design and construction strategies for a circular economy, Architectural Engineering and Design Management 18 (2) (2022), https://doi.org/10.1080/17452007.2020.1781588.

[22] Ellen MacArthur Foundation, Towards the Circular Economy: Vol. 1: Economic and business rationale for an accelerated transition, Ellen MacArthur Foundation 1 (2014).

[23] European Commision, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Energy Roadmap 2050, Brussels COM 885 (2011) *final*.

[24] European Commission, Communication from the Commission to the European Parliament and the council. Strategy for the Sustainable Competitiveness of the Construction Sector and its Enterprises, Brussels COM 66 (3) (2012).

[25] European Commission, Communication from the Commission - Towards a circular economy: A zero waste programme for Europe, European Commission 398 (2014) 1–14. https://ec.europa.eu/environment/circular-economy/pdf/circular-economy-communication.pdf.

[26] European Commission. (2018). Horizon 2020 Proposal Submission 2018, Call: H2020-LC-SC3-2018-2019-2020 (Building a Low Carbon, Climate Resilient Future: Secure, Clean and Efficient Energy). *EN Horizon 2020, 841850*.

[27] E. Gasparri, S. Arasteh, A. Kuru, P. Stracchi, A. Brambilla, Circular economy in construction: A systematic review of knowledge gaps towards a novel research framework, Frontiers in Build Environment (2023).

[28] P. Ghisellini, M. Ripa, S. Ulgiati, Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review, Journal of Cleaner Production 178 (2018), https://doi.org/10.1016/j.jclepro.2017.11.207.

[29] Guy, B., & Ciarimboli, N. (2007). *Design for Disassembly in the built environment. A guide to closed-loop design and building.*

[30] R. Hartwell, S. Macmillan, M. Overend, Circular economy of façades: Real-world challenges and opportunities, Resources, Conservation and Recycling 175 (2021), https://doi.org/10.1016/j.resconrec.2021.105827.

[31] M.U. Hossain, S.T. Ng, Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review, Journal of Cleaner Production 205 (2018), https://doi.org/10.1016/j.jclepro.2018.09.120.

[32] M.U. Hossain, S.T. Ng, P. Antwi-Afari, B. Amor, Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. Renewable and Sustainable Energy Reviews, 2020, https://doi.org/10.1016/j.rser.2020.109948 (Vol. 130).

[33] M.U. Hossain, S. Thomas Ng, Influence of waste materials on buildings' life cycle environmental impacts: Adopting resource recovery principle, Resources, Conservation and Recycling 142 (2019), https://doi.org/10.1016/j.resconrec.2018.11.010.

[34] ISO. (2020). *ISO 20887 'Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements and guidance'*.

[35] ISO. (2021). EN ISO 14021:2016/A1. *I.S. EN ISO 14021:2016&A1:2021 Is the Adopted Irish Version of the European Document EN ISO 14021:2016, Environmental Labels and Declarations - Self-Declared Environmental Claims (Type II Environmental Labelling) (ISO 14021:2016), 7.4 Designed for disassembly*.

[36] T. Joensuu, H. Edelman, A. Saari, Circular economy practices in the built environment, Journal of Cleaner Production 276 (2020), https://doi.org/10.1016/j.jclepro.2020.124215.

[37] Jones, C., & Hammond, G. (2019). Inventory of Carbon and Energy (ICE database). In *2019*. https://greenbuildingencyclopaedia.uk/wp-content/uploads/2014/07/Full-BSRIA-ICE-guide.pdf.

[38] N. Khadim, R. Agliata, A. Marino, M.J. Thaheem, L. Mollo, Critical review of nano and micro-level building circularity indicators and frameworks, Journal of Cleaner Production 357 (2022), https://doi.org/10.1016/j.jclepro.2022.131859.

[39] J. Kirchherr, D. Reike, M. Hekkert, Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling, 2017, https://doi.org/10.1016/j.resconrec.2017.09.005 (Vol. 127).

[40] K. Kuusk, M. Ritzen, P. Daly, D. Papadaki, C. Mazzoli, G. Aslankaya, J. Vetršek, T. Kalamees, The circularity of renovation solutions for residential buildings, in: 2022: CLIMA 2022 The 14th REHVA HVAC World Congress, 2022, https://doi.org/10.34641/clima.2022.333.

[41] O. Lucon, D. Ürge-Vorsatz, A. Zain Ahmed, H. Akbari, B. P, L.F. Cabeza, N. Eyre, A. Gadgil, L.D.D. Harvey, Y. Jiang, E. Liphoto, S. Mirasgedis, S. Murakami, J. Parikh, C. Pyke, M.V. Vilariño, 2014 Buildings, in: O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel J.C. Minx (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014, pp. 671–723.

[42] Lyle, J. T. (1996). *Regenerative Design for Sustainable Development.*

[43] N. Machado, S.N. Morioka, Contributions of modularity to the circular economy: A systematic review of literature, Journal of Building Engineering 44 (2021), https://doi.org/10.1016/j.jobe.2021.103322.

[44] C. Mazzoli, R. Corticelli, L. Dragonetti, A. Ferrante, J. Van Oorschot, M. Ritzen, Assessing and Developing Circular Deep Renovation Interventions towards Decarbonisation: The Italian Pilot Case of "Corte Palazzo" in Argelato, Sustainability (Switzerland) 14 (20) (2022), https://doi.org/10.3390/su142013150.

[45] McDonough, W., & Braungart, M. (2002). *Cradle to Cradle: Remaking the way we make things* (S. and G. Farrar, Ed.).
[46] P. Mhatre, R. Panchal, A. Singh, S. Bibyan, A systematic literature review on the circular economy initiatives in the European Union. Sustainable Production and Consumption, 2021, https://doi.org/10.1016/j.spc.2020.09.008 (Vol. 26).
[47] M.R. Munaro, S.F. Tavares, Materials passport's review: challenges and opportunities toward a circular economy building sector, Built Environment Project and Asset Management 11 (4) (2021), https://doi.org/10.1108/BEPAM-02-2020-0027.
[48] D.A. Ness, K. Xing, Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model, Journal of Industrial Ecology 21 (3) (2017), https://doi.org/10.1111/jiec.12586.
[49] OECD. (2018). *Global Material Resources Outlook to 2060 Economic drivers and environmental consequences*.
[50] O.A. Osobajo, A. Oke, T. Omotayo, L.I. Obi, A systematic review of circular economy research in the construction industry. Smart and Sustainable Built Environment, 2022, https://doi.org/10.1108/SASBE-04-2020-0034 (Vol. 11, Issue 1).
[51] A. Parchomenko, D. Nelen, J. Gillabel, H. Rechberger, Measuring the circular economy - A Multiple Correspondence Analysis of 63 metrics, Journal of Cleaner Production 210 (2019), https://doi.org/10.1016/j.jclepro.2018.10.357.
[52] M. Saidani, B. Yannou, Y. Leroy, F. Cluzel, A. Kendall, A taxonomy of circular economy indicators, Journal of Cleaner Production 207 (2019), https://doi.org/10.1016/j.jclepro.2018.10.014.
[53] Shooshtarian, D. S., Hosseini, D. M. R., Kocaturk, P. T., Ashrad, A. P. M., Arnel, P. T., & Doerfler, P. J. (2021). *The Circular Economy in the Australian Built Environment: The State of Play and a Research Agenda*.
[54] S. Singh, C. Babbitt, G. Gaustad, M.J. Eckelman, J. Gregory, E. Ryen, N. Mathur, M. C. Stevens, A. Parvatker, R. Buch, A. Marseille, T. Seager, Thematic exploration of sectoral and cross-cutting challenges to circular economy implementation. Clean Technologies and Environmental Policy, 2021, https://doi.org/10.1007/s10098-020-02016-5 (Vol. 23, Issue 3).
[55] Stahel, W. R. (1982). Chapter 4 The Product Life Factor. *An Inquiry Into the Nature of Sustainable Societies: The Role of the Private Sector*.
[56] G. Tokazhanov, O. Galiyev, A. Lukyanenko, A. Nauyryzbay, R. Ismagulov, S. Durdyev, A. Turkyilmaz, F. Karaca, Circularity assessment tool development for construction projects in emerging economies, Journal of Cleaner Production 362 (2022), https://doi.org/10.1016/j.jclepro.2022.132293.
[57] van Vliet, M. (2018). *Disassembling the steps towards building circularity redeveloping the building disassembly assessment method in the building circularity indicator.* https://research.tue.nl/en/studentTheses/disassembling-the-steps-towards-building-circularity.
[58] van Vliet, M., van Grinsven, J., & Teunizen, J. (2021). *Circular buildings disassembly potential measurement method*.
[59] Verberne, J. J. H. (2016). *Building circularity indicators an approach for measuring circularity of a building* [Student thesis: Master, TUDelft]. https://research.tue.nl/en/studentTheses/building-circularity-indicators.
[60] I.Y. Wuni, Burden of proof beyond the triple bottom line: Mapping the benefits of circular construction. Sustainable Production and Consumption, 2022, https://doi.org/10.1016/j.spc.2022.10.006 (Vol. 34).
[61] R.K. Yin, Case study research and applications: Design and methods, Sixth Edition, SAGE Publications, 2018 (Vol. 53, Issue 5).

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Patrick has a background in Architectural Technology and Project Management and in design technology education, and has masters qualifications in Architecture / Environmental Studies and in Research Methods and Sustainability.

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CONCERTO – Technical advisor and consultant to the Irish energy authority on the HOLISTIC Dundalk 2020 Sustainable Energy Zone

IEE – Bioregions – toward developing a sustainable bioregion and sector in the midlands of Ireland.

FP7– Rockwood – promoting sustainable development of SRC in Ireland

H2020 – Drive 0 – demonstration low carbon deep energy retrofit via modular circular solutions.

Patrick has written a chapter on sustainability in an edited book on the future of Dublin has published a number of peer reviewed conference papers and numerous articles as well as project reports.

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Publications, Papers, Articles

Books

Daly P (Ed Lorcan S) 'From Dependent City to Sustainable City' in Dublin's Future New visions for Irelands Capital City, Liffey Press, Dublin, 2011

Reports and Studies

EPA Hemp Lime Study

Daly P, Ronchetti P, Wooley T 'Hemp Lime Biocomposite as a Building Material in Irish Construction EPA Ireland STRIVE Report 2009

Bioregions IEE Project

Daly P 'Case Studies Biomass Domestic Stove Boilers in Co Westmeath' Bioregions EU Project 2010 -2013

Daly P 'Proceedings of the Workshops in Ireland ' Bioregions EU Project 2010 -2013

Daly P, 'Bioenergy Action Plan, Target Region Co Westmeath Ireland', Westmeath Community Development Bioregions EU Project 2010 -2013

Joint Publication 'Proceedings of the Networking Workshops in the Target Regions' Bioregions EU Project 2010 -2013

Joint Publication 'Fuel Quality and Sustainability Issues in the Target Regions' Bioregions EU Project 2010 -2013

Joint Publication 'Biomass Trading Centre Applicability in the Target Regions' Bioregions EU Project 2010 -2013

ROKDOOD FP7 EU Project

Joint Publication 'Energy Crops in Europe Best Practice in SRP Biomass from Germany, Ireland, Poland, Spain, Sweden and UK' ROKWOOD FP7 EU Project 2013 - 2015

Joint Publication 'ROKWOOD Resource Efficient production and utilization of woody biomass from SRPS – European Best Practice and Key Findings' ROKWOOD FP7 EU Project 2013 - 2015

Journal Papers

C Parra-Lopez et Al 'Strengthening the development of the short-rotation plantations bioenergy sector: Policy insights from six European countries' Renewable Energy Elsiever 2017

Conference Papers

Daly P 'Integrating Energy Rating and Carbon Limitation in Irish Building Regulations a Comparative Analysis of Ireland and UK / (Eng/Wales)' PLEA Passive Low Energy Architecture conference, Singapore, Nov 2007

Shanks K, Daly P 'Strategic Energy Planning Decision-Making from Early Design to Detailed Design Stages', PLEA Passive Low Energy Architecture conference, Singapore, Nov 2007

Daly P 'Crossing Tresholds', A Zero net Energy Demonstration House in Ireland. PLEA Passive Low Energy Architecture conference, Dublin Ireland, Oct 2008.

Daly P, Stevens C, Achieving Passive Refurbishment in a 19^{th} Century traditional Irish Cottage, Passive Haus Conference Germany 2010

Daly P Hemp Lime Bio-composite in Construction - A study into the performance and application of hemp lime bio-composite as a construction material in Ireland. PLEA Passive Low Energy Architecture conference, Louvain-la-Neuve, Belgium, 2011

Daly P Achieving Low Energy and Environmental Impact in Ireland's First Energy Positive House, Sustainable Building, Helsinki, Finland 2011

Daly P Undertaking Social Housing Energy Refurbishment in Ireland, Sustainable Building, Helsinki, Finland 2011

Magazine articles

Daly P, 'DEAP Impact, Irish Home Energy Rating Software to Challenge Designers' Construct Ireland, Temple Media, Dublin, June 06

Daly P, 'Lime Hemp, Mainstreaming Bio-composite Construction' Construct Ireland, Temple Media, Dublin, Aug 06

Daly P, 'Laughing Stock, Ireland Pre Building Regulation Housing Stock, Construct Ireland, Temple Media, Dublin, Sept 06

Daly P, 'Part L 2006, Carbon Compliance – UK V's Ireland' Construct Ireland, Tem *ple Media, Dublin, Aug 07*

Daly P, 'Airitight, airtightness in Irish buildings' Construction Property News, Dublin, May 07

Daly P, 'Green Future, prediction for new Part L' Construction Property News, Dublin, June 07

Daly P. 'Up the Scale, optimal energy ratings' Construction Property News, Dublin, Oct 07

Daly P, 'Going Passive, design issues for Passive Housing' Construction Property News, Dublin, Nov 07

Daly P, 'Part L Not costing the earth, compliance costs study' Construction Property News, Dublin, Jan 08

Daly P, 'New Part L – improvements welcome,' Construction Industry Magazine, Dublin, Oct 07

Daly P, 'New Part L – UK Comparison,' Construction Industry Magazine, Dublin, Feb 08

Daly P, 'Change – Sustainable Overview 2008,' Construction Industry Magazine, Dublin, Jan 08

Daly P, 'Building Energy Rating,' House Magazine, Dublin, May 07

Daly P, 'Houses with Holes – Ventilation,' House Magazine, Dublin, Oct 07