A circularity evaluation framework for newly constructed office building design

Muheeb Al-Obaidy

2025

Cover photo: 't Centrum, Kamp C , by Muheeb Al-Obaidy

University of Liège
Faculty of Applied Sciences
Urban and Environmental Engineering Dept.

A circularity evaluation framework for newly constructed office building design

Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Architectural Engineering

By **Muheeb Al-Obaidy**

Supervisor: **Prof. Dr. Shady Attia** (University of Liège)

Jury members: **Prof. Dr. Luc Courard** (University of Liège)
Prof. Dr. Rafael Passarelli (University of Hasselt)
Prof. Dr. Ulrich Knaack (Delft University of Technology)
Dr. Michiel Ritzen (Flemish Institute for Technological Research VITO)

November 2025

بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

﴿ قُلْ إِنَّ صَلَاتِي وَنُسُكِي وَمَحْيَايَ وَمَمَاتِي لِلَّهِ رَبِّ ٱلْعَٰلَمِينَ ﴿١٦٢﴾ لَا شَرِيكَ لَهُۥ ۖ وَبِذَٰلِكَ أُمِرْتُ وَأَنَا۠ أَوَّلُ

ٱلْمُسْلِمِينَ ﴿١٦٣﴾ ﴾

القرآن الكريم، سورة الأنعام، (الآيات ١٦٢-١٦٣)

In The Name of Allah, The Most Beneficent, The Most Merciful

﴿Say, 'Indeed, my prayer, my rites of sacrifice, my living and my dying are for Allah,

Lord of the worlds. (162) He has no partner. And this I have been commanded, and I

am the first of the Muslims. (163) ﴾

The Holy Quran, Surah Al-An'am (Chapter 6, Verses 162-163)

Acknowledgments

I extend my deepest gratitude to my supervisor, Prof. Dr. Shady Attia, for his invaluable guidance, unwavering support, and insightful mentorship throughout my research and personal growth. His expertise and dedication have been a constant source of inspiration, and I am profoundly grateful for his encouragement.

I am also sincerely thankful to my thesis committee members and examiners, Prof. Dr. Luc Courard, Prof. Dr. Rafael Passarelli, Prof. Dr. Ulrich Knaack, and Dr. Michiel Ritzen, whose critical feedback and constructive insights have significantly enhanced the quality of this dissertation. Their dedication to academic excellence and their support of young researchers is truly commendable.

I would like to express my heartfelt appreciation to the University of Liège and the Sustainable Building Design (SBD) Lab for welcoming me into a dynamic and intellectually stimulating research community. This experience has been invaluable in shaping my academic journey.

I am also deeply grateful to the committees of Buildwise/E35001, CEN/TC 350 "Circular Economy in the Construction Sector," NBN/I323, ISO/TC 323, CEN/TC 473 "Circular Economy," COST Action CA20139 (WG4 "Sustainability and Durability"), and COST Action CA21103 (WG3 "Circular KPIs Framework") for allowing me the privilege to contribute to their research initiatives. The knowledge and experience gained from these collaborations have been truly enriching. I also extend my appreciation to all committee members for their dedication and collective efforts.

With deep reverence, I dedicate this work to the cherished memory of my late parents, whose unwavering support and encouragement shaped my academic journey and instilled in me the values of perseverance and commitment.

To my beloved wife, Arch. Fatimah Al-Algaoosh, I am forever indebted to you for your unconditional love, patience, and steadfast support throughout my Ph.D. journey. Your presence has been my greatest motivation, and I am truly blessed to have you by my side.

To my family, my brothers and sisters, I am profoundly grateful for your unwavering love and encouragement. Your belief in me has been a source of strength, especially during challenging times.

I extend my sincere appreciation to my colleagues at the Sustainable Building Design (SBD) Lab for their encouragement, camaraderie, and the invaluable memories we have shared. Their support has made this journey more fulfilling.

Additionally, I am grateful to the Colruyt Group and my esteemed colleagues for their support and expertise throughout the research period. Their contributions have been instrumental in this work.

Finally, I would like to express my deep gratitude to Kamp C, Beneens Construction and Interior, West Architecture, and Cie Architects for their generous support in providing the essential data for the case studies. Their contributions have been fundamental to the success of this research.

To everyone who has been part of this journey, I extend my heartfelt thanks. Your support and encouragement have made this achievement possible.

Table of Contents

Summary

The transition towards a circular economy in the construction sector has become a crucial objective in the pursuit of sustainable development. Given that the built environment is responsible for significant environmental impacts; including high levels of resource consumption, greenhouse gas (GHG) emissions, and waste generation; the integration of circularity principles into building design is imperative. This thesis presents a framework for evaluating circularity in newly constructed office buildings, aiming to provide architects, engineers, and policymakers with an initial framework for assessing and enhancing circularity performance. The thesis is structured into three main parts (Part I, Part II, and Part III). In Part I, the research investigates the regulatory landscape of circular construction by analyzing the role of Northwestern European states in integrating circular economy principles into building regulations. A systematic review of policies in leading EU countries highlights the advancements and challenges in promoting circularity within the construction sector. Additionally, this section examines parametric approaches for optimizing building construction systems, with a focus on their impact on material circularity and carbon footprint. Part II introduces a methodological framework for assessing building disassembly potential, a key aspect of circular construction. Through a review of disassembly calculation criteria and an expert system for evaluating disassembly potential, this section provides a structured approach to designing for deconstruction. The research employs fieldwork, statistical analysis, and case study evaluations to identify key barriers and enablers of building disassembly, ensuring that materials can be efficiently recovered and reused at the end of a building's lifecycle. In Part III, the thesis develops and validates a Building Circularity Evaluation Framework (BCEF), a multi-indicator system designed to quantify circularity in newly constructed office buildings. The BCEF integrates key performance indicators, including Global Warming Potential, Land-Use footprint, Reused Content, Disassembly Potential, Functional Adaptability, and Product-Service Systems. This section applies the framework to three case studies; 't Centrum Building, Green Office, and ABN AMRO Circl Pavilion; demonstrating its applicability in real-world settings. These case studies were specifically chosen because they embody circular building principles, aligning with the objectives of this Ph.D. research. The results underscore the importance of modular construction, design-for-disassembly principles, and material reuse in enhancing circularity performance.

The following key findings and recommendations emerge from the research:

- **Regulatory Support for Circular Construction:** Countries such as Denmark, Finland, and the Netherlands have made significant progress in integrating circularity into building regulations. Policymakers should establish clear and enforceable circularity targets that align with carbon neutrality goals, driving systemic change in the construction industry. While clear and enforceable circularity targets can accelerate uptake, premature or overly prescriptive targets risk regulatory lock-in, rebound, or burden-shifting across life-cycle stages; targets should therefore be adaptive

and evidence-based, accompanied by ex-ante/ex-post evaluation and periodic review under the EU's Better Regulation approach, and by monitoring to detect unintended consequences.

- **Design for Disassembly and Adaptability:** The ability to efficiently disassemble buildings at the end of their lifecycle is crucial for maximizing product recovery. The research highlights the importance of using dry-assembly fastening mechanisms, modular design approaches, and standardized building components to enhance disassembly potential.
- **Parametric Optimization for Circular Design:** By utilizing parametric tools and Life Cycle Impact Assessment (LCIA) methodologies, architects can optimize construction materials and techniques to minimize environmental impact. The research finds that bio-based materials, particularly timber, can reduce the carbon footprint and other environmental impacts of LCIA while maintaining structural integrity and potential for circularity.
- **Implementing a Multi-Indicator Evaluation Framework:** The BCEF provides a standardized framework for assessing building circularity, ensuring that circular economy principles are embedded in early-stage design decisions. The framework enables stakeholders to quantify circularity performance and identify areas for improvement.
- **Case Study Insights:** The comparative analysis of three case studies reveals that buildings designed with circular principles; such as ‘t Centrum, which incorporates modular construction and prefabricated timber elements; demonstrate higher circularity performance compared to conventional designs.

The findings of this thesis emphasize that circular construction is not only an environmental necessity but also a viable strategy for evaluating material waste reduction and GHG emissions, and assessing objectively the resource efficiency in newly designed office buildings. Future research should focus on refining circularity indicators, expanding datasets for material reuse potential, and exploring digital twin technologies for tracking building material flows. Ultimately, achieving circularity in the built environment requires collaboration among architects, engineers, policymakers, and industry stakeholders to drive innovation and systemic change.

Abbreviations and nomenclature

BCEF	Building Circularity Evaluation Framework
BCI	Building Circularity Indicators
BAMB	Building as Material Banks
BIM	Building Information Modelling
CDW	Construction and Demolition Waste
CE	Circular Economy
CEN	European Committee for Standardization
CPR	Construction Products Regulation
DP	Disassembly Potential
DfA	Design for Adaptability
DfD	Design for Disassembly
DfF	Design for Flexibility
DBED	Building Environmental Performance Declaration
EN	European Norm
EPD	Environmental Product Declarations
EU	European Union
FA	Functional Adaptation
GHG	Greenhouse Gas
GRO	Sustainability Assessment Tool (Belgium)
GWP	Global Warming Potential
HVAC	Heating, Ventilation, and Air Conditioning
ISO	International Organization for Standardization
IEA EBC	International Energy Agency - Energy in Buildings and Communities Programme
KPI	Key Performance Indicator
LCIA	Life Cycle Impact Assessment
LU	Land-Use footprint
MR	Materials and Resources
MRQ	Main Research Question
MINERGIE-P-ECO	Swiss Sustainable Building Certification
NSC	Nordic Sustainable Construction
PSS	Product-Service Systems
RC	Reused Content
RE2020	French Energy Regulation 2020
RSP	Reference Study Period
SQ	Sub-question

Introduction

1. Introduction

1.1. Background

1.1.1. Advancing Circular and Sustainable Design in the Built Environment: Embracing Circular Design for Sustainable Development

The built environment should undergo fundamental transformations in response to the imperatives of sustainability and a circular economy. The construction industry consumes around 40% of raw materials and is responsible for 39% of total CO_2 emissions, of which at least 11% comes from manufacturing building materials and products [1]. Over the past few decades, the focus of sustainable building has been primarily on reducing the negative impact of buildings on climate change and the depletion of fossil fuels by improving energy efficiency during the use phase. By the end of 2020, all new buildings in the European Union will need to be nearly zero-energy as a consequence of the Energy Performance of Buildings Directive [2]. However, to address environmental challenges such as climate change, scarcity of land and raw materials, biodiversity loss, waste production, and water problems, the overall environmental impact of buildings throughout their entire life cycle should be considered. In the coming years, a transition towards a life cycle impact assessment (LCIA)- based evaluation of the environmental impact of buildings is expected, and performance-based targets on environmental impact are likely to be established.

Traditional approaches to sustainability aim to reduce, avoid, minimize or prevent the use of non-renewable resources for energy and materials. Within this reductionist paradigm, sustainable building involves attempts to do "less bad" and reduce the negative building impact by improving the efficiency of, for example, energy, materials, and water use. Unfortunately, this "eco-efficiency" approach has limitations and even some unintended consequences. Due to population growth and increased collective wealth, improved efficiency often results in accelerated energy and material consumption on a global scale [3]. The reductionist approach also fails to incorporate the potential of buildings to contribute to positive sustainable development and to restore the Earth's ecological carrying capacity.

Circular design focuses on creating a positive impact through environmentally effective and sustainable buildings, and literature recognizes its potential environmental and economic benefits [4], [5], [6]. Instead of doing less bad, a positive impact is aimed for. Circular architecture is dominated by the ideas of Lyle [4] on Regenerative design, William McDonough and Michael Braungart [7], [8] on Cradle to cradle design and Benyus [9] on Biomimicry. It aims to increase, support and optimize the use of renewable resources and to become as independent as possible from depleting and polluting resources. The linear "take-make-waste" approach is replaced with a cyclical one. Circularity involves sustainable resource management, maintaining the value of resources and materials for as long as possible, and eliminating or avoiding waste, thereby minimizing the environmental impact of material cycles [10].

Maximizing the generation of renewable resources, without ignoring other environmental impacts, and maintaining the quality or value of materials along the lifecycle of buildings for as long as possible by facilitating materials recovery and reuse will reduce material use and environmental impacts associated with our built environment. In the “Roadmap to a Resource Efficient Europe” [11] and the “Closing the loop EU action plan for the Circular Economy” [12], the European Commission emphasizes the importance of sustainable resource management in the built environment and the potential for resource savings during building design. Over the past years, circular positive development has been garnering increasing influence on the evolution of architecture. The progress is dramatic: Energy-plus, earth buildings, healthy buildings, positive impact buildings. Well-known examples include the Cradle to Cradle certified Municipality Building in Venlo [14], the Haarlemmermeer Cradle to Cradle certified Business Office Park [15], and EDGE Südkreuz in Berlin, which is Germany’s largest wooden hybrid office building, a 100% match for Madaster [13]. Additionally, the Powerhouse building in Trondheim, Norway, has achieved BREEAM Outstanding certification [14].

Despite these inspiring projects, the current state of the majority of contemporary designs and realizations suggests an implementation deficit in achieving highly sustainable buildings and environments. Many recently erected buildings perform little better than the lowest standards imposed by building regulations [15]. In addition to critical factors for delivering a successful project, the competency of project team participants [19] plays a central role, with a particular emphasis on the architect [16]. The design of sustainable projects, which had long been “ceded to the specialist engineering profession is now, again, coming under the ambit of the architect and the urban planner [17]. The accumulation of set goals gives rise to ever-increasing intricacy in the implementation of sustainable buildings [22], and architects are directly faced with this intricate task. A generic and rapidly expanding practical approach to sustainable building is the development and application of design-supporting tools, which enable the project team to identify the effects and interactive relationships between the social, economic, and ecological dimensions, and to address these in the planning and/or construction process [18]. A vast number and extensive range of design-supporting tools for sustainability are available, but for architects, the most promising kind are early design generative tools, which hold a guiding methodology [19]. Uptake in practice remains limited; time/fee pressure at the concept stage, steep learning curves, and weak BIM–LCA interoperability reduce the perceived near-term benefit. Persistent labor/skills shortages in EU construction further curtail the capacity to experiment, motivating the development of fast-to-set-up, interoperable, and “architect-friendly” methods [20], [21], [22].

1.1.2. Towards a circular building sector

Assessing the circularity of buildings requires, as a first step, a clear definition of what circularity entails. To date, there is no universally accepted standard, neither within ISO nor CEN frameworks, that provides a comprehensive definition of circularity. Nevertheless, the European literature and several sustainability assessment standards, including ISO 14040 [23], ISO 14044 [24], ISO 21930 [25], EN 15978 [26], EN 15804+A2 [27], prEN 18177:2025 [28] and the Level(s) framework [29], as well as the Construction Products Regulation (CPR) [30], implicitly or explicitly integrate carbon neutrality as a fundamental dimension of circularity. Although this interpretation has not been formally codified or officially adopted in existing regulations, it reflects a growing consensus among European researchers and policymakers that achieving carbon neutrality constitutes an essential component of the circular economy in the built environment.

Accordingly, this Ph.D. thesis adopts the European paradigm that conceptualizes carbon neutrality as an integral part of building circularity, as illustrated in Figure 1.1. This alignment ensures consistency with the current European policy direction and facilitates the integration of circularity assessment within broader sustainability and climate-neutrality objectives.

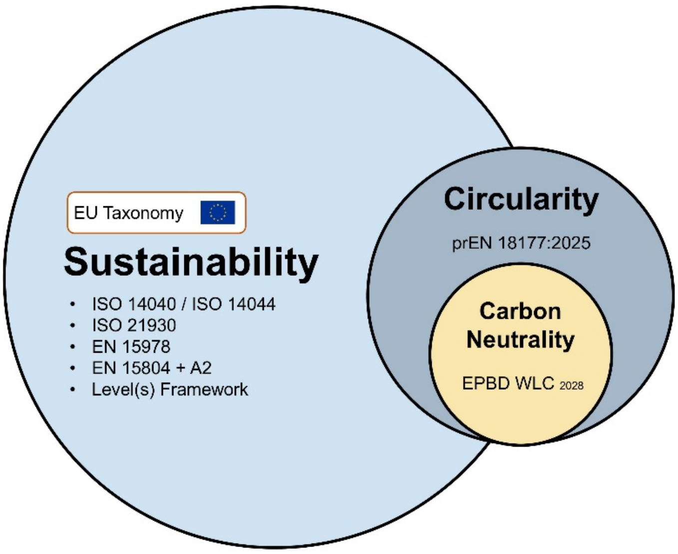


Figure 1.1. Integration of carbon neutrality within circularity and sustainability frameworks in the European context.

Efforts to mitigate the environmental impact of buildings in Europe have predominantly centered on reducing operational energy consumption. This focus has led to the development and implementation of energy-efficient buildings [31]. Consequently, the embodied environmental impacts of building materials; encompassing production, construction, maintenance, and disposal processes; now represent a significant and growing proportion of a building's total life-cycle environmental footprint [32]. For instance, in Denmark, embodied greenhouse gas (GHG) emissions from building materials can account for more than 70% of the building's life-cycle aggregated environmental impacts. This trend highlights the potential contribution of targeted circular/material-efficiency strategies (e.g., design for longevity, reuse, high-value recycling) to mitigating embodied GHG emissions over successive life cycles, alongside continued operational efficiency and clean energy [33], [34].

The circular economy is a restorative and regenerative approach that seeks to minimize emissions, resource use, and waste generation through the principles of narrowing (efficient resource use), slowing (extending product life cycles), and closing (resource cycling) material loops [35]. These principles aim to preserve finite natural resource stocks while maintaining the utility and value of products and materials for as long as possible [36], [37]. CE is operationalized through value retention processes (VRPs), also known as R-imperatives, which include actions such as refusing, reducing, reusing, repairing, refurbishing, recycling, and recovering materials. Certain VRPs result in material re-loops, which can be facilitated by design strategies such as design for disassembly, adaptability, durability, and the use of low-impact materials [38]. Multi-cycling, a critical aspect of CE, emphasizes the sequential implementation of multiple re-loop processes rather than focusing on isolated loops [39]. Re-loops can create cascading systems, enabling building components or materials to be reused in various applications across local and global contexts [40].

In recycling research, “closed loops” refer to recycling materials into the same products, whereas “open loops” involve recycling materials into different products [41]. Within the CE framework, these loops are further differentiated by their supply chain context: open loops are managed by external parties, whereas closed loops are overseen by the original producers [42]. This shift from end-of-pipe solutions, where construction and demolition waste is managed at the end of a building’s life cycle, to a holistic and preventive approach exemplifies the broader CE transition.

The promotion of CE has recently gained significant traction in international policy. At the European level, the European Commission has committed to a CE transition, including initiatives to create a circular built environment and achieve net-zero-emission buildings by 2050 [43]. Supporting these goals, the European Commission has introduced a CE package and action plan [37]. At the same time, nearly €1 billion from the Horizon 2020 Research and Innovation Programme was allocated between 2018 and 2020 to support CE initiatives [44]. Additionally, CE principles have been incorporated into the EU Waste Framework Directive [45]. Overall and at the EU level, updates focused on the fact that from 2028, all member states will be required to report embodied carbon for major projects. This will be extended to all projects from 2030, and new limits will also be introduced [46]. For instance, Nordic Sustainable Construction [47], a program under the Nordic Council of Ministers, published a roadmap, The Nordic Sustainable Construction (NSC) example has been selected according to inclusion criteria were: (i) a public supranational mandate, (ii) an explicit buildings/construction scope with quantified actions or limit-value pathways, and (iii) an open-access, citable figure. The NSC programme under the Nordic Council of Ministers met these criteria and is framed as a contribution to Nordic Vision 2030 as shown in Figure 1.2, that contributes to the Nordic Vision 2030 of becoming a sustainable and integrated region by 2030 in terms of sustainable construction and housing.

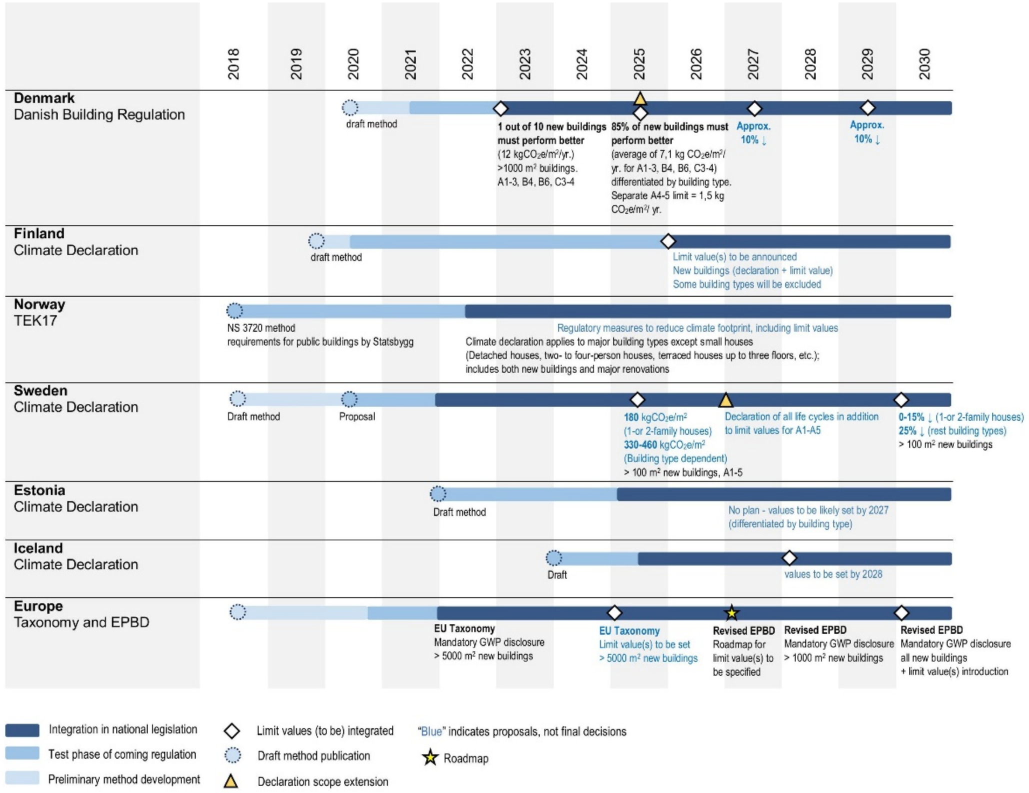


Figure 1.2. Timeline of climate declaration and limit values integration (as of June 2024) [47].

According to Nordic Sustainable Construction [47], Denmark has emerged as a leader in the adoption of CE within the built environment. The UK-based Ellen MacArthur Foundation's case study identified Denmark as a potential CE leader, with construction and real estate sectors offering the greatest opportunities for circularity [48]. This recognition spurred the Danish government to establish an advisory board for CE in 2016, which subsequently presented 27 sector-specific recommendations in 2017. These efforts culminated in Denmark's CE strategy in 2018, which included the introduction of a voluntary sustainable building class in the national building code [49]. Concurrently, the country's first circular social housing project, Circle House, was developed between 2017 and 2020. The project aimed to achieve 90% recyclability and reuse content of building materials, with no value loss, according to Building Social Ecology [50]. Since 1 Jan 2023, all new Danish buildings must submit a whole-life carbon LCA, and new buildings >1,000 m² must comply with a maximum GWP of 12 kg CO_2e/m²·year over 50 years. From July 2025, Denmark tightens and extends the cap: an average limit of 7.1 kg CO_2e/m²·year (with typology-specific values, e.g., 6.7 → 6.0 → 5.4 for single-family houses in 2025/2027/2029) and adds a separate cap for the construction process (A4-A5) of 1.5 kg CO_2e/m²·year; scope is expanded to more building types. These requirements are in place before EU-wide obligations under the revised EPBD [51].

Further advancing its CE agenda, the Danish Climate Council recommended implementing a “polluter pays” CO_2 tax of DKK 1,500 per ton by 2030 to achieve a 70% reduction in CO_2 emissions [52]. This policy provides a strong incentive to reduce embodied GHG emissions from building materials. Additionally, Denmark aims to accelerate the adoption of CE through enhanced collaboration between academia and industry, integrating theoretical knowledge with practical applications [53]. Notably, following the initiation of an industrial Ph.D. program, 15 new industrial Ph.D. projects have been funded to develop circular solutions and business models based on existing and ongoing CE research and initiatives in the building sector [53]. The motivation to implement CE in the European and Danish building sectors remains robust. However, achieving this goal necessitates a concerted effort and fundamental changes across the entire industry.

Despite growing interest, the concept of circularity has yet to gain significant momentum in regulatory frameworks. As illustrated in Figure 1.3, which highlights the most important practical points in the circular economy movement, Denmark leads among EU states in incorporating circular economy principles into the construction sector. Denmark's regulatory landscape is comparatively advanced, characterized by comprehensive policies and tools that aim to promote waste reuse and materials separation. These measures reflect a systematic approach to embedding circular principles in the construction industry [54].

Finland ranks second in adopting circular economy principles in the built environment. The country employs a multi-stakeholder approach to implement its "Circular Economy in the Built Environment" initiative, which is integral to achieving its ambitious target of carbon neutrality by 2035 [55]. Finland’s collaborative strategies underline its commitment to sustainable development in the construction sector [56].

Sweden is positioned third, primarily due to its implementation of climate legislation that supports the transition toward carbon neutrality by 2045 [57]. This legislation, which took effect in January 2022, introduces measures to promote circular practices and mitigate the environmental impact of construction activities. Sweden’s regulatory advancements signify a critical step in aligning national policies with global sustainability goals [54].

France occupies the fourth position, distinguished by its focus on carbon footprint reduction measures [58]. While these initiatives are commendable, the country lags in adopting comprehensive building circularity practices. France’s regulatory focus remains more concentrated on emissions reduction rather than holistic circular strategies [54].

The Netherlands also demonstrates notable progress, ranking alongside France. A key regulatory milestone is the mandatory life cycle impact assessment (LCIA) requirements for all new constructions [59]. These requirements signify a significant commitment to integrating environmental considerations into building practices, thereby fostering a more sustainable construction sector [54].

Belgium’s carbon footprint regulations in construction are regionally driven, with Brussels and Flanders leading in LCIA, material passports, and circular economy policies. Brussels' Building as Material Banks (BAMB) initiative tracks materials for reuse, while Flanders mandates 70% recycling of construction waste by 2030 [60], [61]. However, Belgium lacks a national carbon threshold and uniform regulations, requiring harmonization to align with EU climate goals [62]. Future policies should expand LCIA mandates and enforce carbon limits. Moreover, Belgium developed GRO [63], a sustainability assessment tool in Flanders. It aims to enhance the sustainability of construction projects through an integrated design process that emphasizes circular construction principles. GRO is applicable across various project phases; whether new construction, renovations, or refurbishments; and enables clients and designers to measure and improve sustainability metrics effectively.

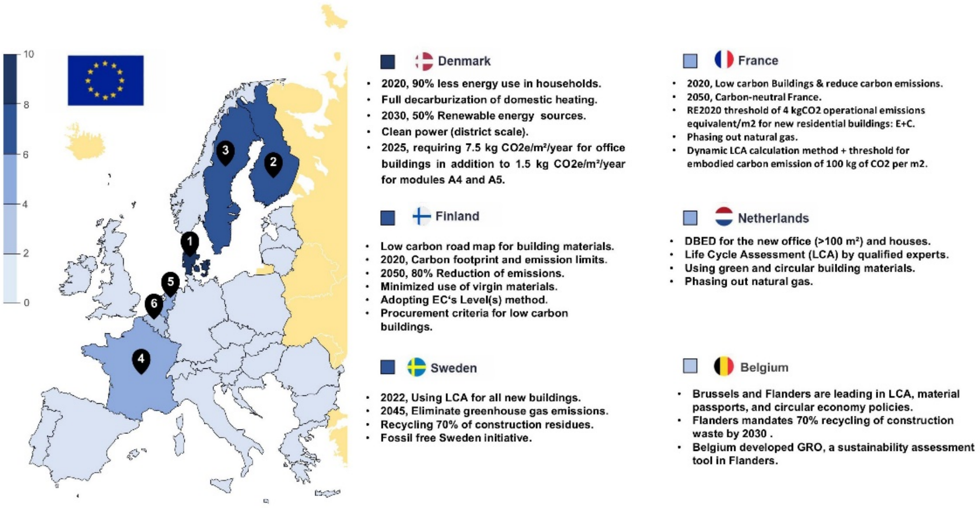


Figure 1.3. Ranking of EU leading member states that couple carbon neutrality and circularity requirements for new constructions.

1.1.3. Challenges of implementing the Circular Economy CE in the construction sector

Despite significant efforts in Northwestern European states, the practical implementation of circular economy (CE) principles in the building sector remains limited in both scale and speed. Numerous challenges hinder this process, among which the lack of readily available environmental CE design tools, decision-making frameworks, and assessment methodologies is a critical barrier. Specifically, three primary issues and knowledge gaps have been identified in relation to developing CE tools and assessment approaches tailored for the building sector.

First, the absence of a universally accepted definition of CE in the building sector creates ambiguity. The CE concept encompasses various strategies [64], which complicates the establishment of uniform guidelines for designing circular buildings, components, and materials. This definitional fluidity has led to disparate interpretations and practices, as highlighted by Hart et al. (2019) [65]. Consequently, this lack of consensus impedes the standardization of CE methodologies across the sector.

Second, there is limited comprehensive knowledge about where the greatest potential exists for reducing the environmental impacts of buildings. Identifying and prioritizing these opportunities remains unclear, which undermines the strategic application of CE principles. Furthermore, while some research exists, the sector still lacks robust methods to quantify the environmental effects of CE initiatives [66]. The Life Cycle Impact Assessment (LCIA), a well-established tool for evaluating environmental impacts in the building sector (EN 15978, 2011) [64], is currently inadequate for CE applications. Among the key limitations of LCIA tools are their data-intensive nature, the lack of relevant data at the design phase, and decision-makers' insufficient understanding of LCIA processes and outcomes [67], [68]. Moreover, conventional LCIA approaches primarily focus on individual products and single life cycles, whereas CE emphasizes a systems perspective involving multiple and potentially diverse use and life cycles [40], [69]. The systems perspective poses additional challenges, particularly in determining how environmental benefits and burdens should be allocated across multiple use cycles and life cycles, a topic on which no consensus exists due to the variety of allocation methods available [70].

Third, while some studies demonstrate the environmental benefits of CE in the building sector [71], [72], knowledge regarding which specific CE design strategies yield optimal environmental performance remains inadequate. For instance, studies on specific CE building cases and their broader implications are limited [73], [73]. Furthermore, CE strategies do not inherently result in reductions of environmental impact, as evidenced by Gallego-Schmid et al. (2020) [74]. Without rigorous evaluation, designers may unintentionally adopt CE strategies with limited or even counterproductive environmental benefits.

Finally, these knowledge gaps pose a significant risk: they may lead building designers to prioritize less effective CE strategies or focus on optimizing building components and materials that hold relatively minor environmental significance. Such misaligned efforts could exacerbate environmental challenges rather than alleviating them [75]. Addressing these challenges through a systematic development of CE-specific tools, methods, and case studies is essential for advancing sustainable practices in the building sector.

1.1.4. Existing frameworks, tools, and platforms, and the positioning of the BCEF

This section provides a concise review of the key European frameworks and tools used by designers and clients, thereby situating the Building Circularity Evaluation Framework (BCEF) within contemporary practice.

The most important framework is Level(s), which is the European Commission’s common reporting framework for building sustainability [29]. Indicator 1.2 prescribes a whole-life Global Warming Potential (GWP) assessment aligned to EN 15978 for buildings and EN 15804 for product data, to be reported across life-cycle stages (A–C, with D as applicable). Level(s) therefore functions primarily as a reporting language rather than a design-time decision method [56].

In Belgium, GRO [63] is an inter-regional public guidance framework jointly developed by the Flemish, Walloon, and Brussels–Capital regions. It provides structure for sustainable construction across project phases; Analysis (Level 0), Concept (Level 1), and Design (Level 2); and across thematic domains, including circular building [76], [77]. Through actionable checklists, performance levels (good, better, excellent), and manuals, GRO supports clients and design teams in integrating sustainability throughout project development [78]. However, it functions as a process guidance tool rather than a quantitative, early-stage design-comparison method and does not generate analytical performance outputs akin to LCA-based frameworks [76], [77].

Belgium has also developed the TOTEM Tool [79] to Optimize the Total Environmental Impact of Materials, which is the Belgian web-based building LCA tool, jointly developed by the three regions and launched in 2018. It quantifies environmental impacts for elements and entire buildings throughout their life cycle, providing a national database and method consistent with European LCA practice [79]. This tool is based on a national LCA method called the "Environmental Profile of Buildings" (MMG), which was developed [80], [81]. The method is in line with the European Standard EN 15804+A2 (CEN, 2019, 2021) but is customized for the Belgian context, considering specific data and scenarios (transport, energy mix, end-of-life). Since 2018, the Belgian MMG LCA method has been available as a web application, called TOTEM (Tool to Optimize the Total Environmental Impact of Materials) [79].

As a certification scheme, BREEAM [82] awards credits for Building LCA under Mat 01 – Life Cycle Impacts, which relies on recognized and approved LCA tools together with Environmental Product Declaration (EPD) data [83]. Its emphasis is placed on documented assessments to support certification scoring, rather than on facilitating early-stage option exploration [84], [85].

Moreover, LEED (v4/4.1) [86] provides Materials and Resources (MR): Building Life-Cycle Impact Reduction credits, including a whole-building LCA option with specified reduction thresholds, as well as an Alternative Compliance Path (ACP) aligned to European practice [87]. Similar to BREEAM, LEED structures evidence for certification purposes but does not constitute a design-time evaluation framework in itself [85].

Additionally, Madaster [88] is a digital materials cadaster that generates material passports from BIM and Bill of Quantities (BoQ) data to document material composition, circularity attributes, and potential residual value. The platform aims to enable circular construction practices by enhancing the transparency of material flows and facilitating reuse and recycling strategies. Beyond its practical applications, Madaster is being positioned as a response to the emerging European requirements for digital product passports under the Circular Economy Action Plan and the Construction Products Regulation [37]. However, Madaster functions primarily as an enabling data infrastructure, supporting asset managers, designers, and policymakers in circularity tracking; it is not itself a design-evaluation method comparable to LCA-based frameworks [89], [90].

In Germany, CAALA (Computer-Aided Architectural Life Cycle Assessment) [91] has emerged as a digital tool designed to integrate life cycle analysis into early design stages. The tool enables architects and planning professionals to estimate energy demand, greenhouse gas emissions, and material-related lifecycle impacts at a conceptual level, already during preliminary design [92]. CAALA's strength lies in its immediacy and accessibility. By offering real-time feedback through simplified parametric interfaces, it facilitates the rapid comparison of design alternatives, supporting informed decisions toward climate-neutral buildings, especially in retrofit scenarios and early planning phases [93]. Its user-friendly interface allows practitioners without deep LCA expertise to engage with lifecycle considerations, thereby lowering barriers to adoption in architectural workflows [94]. However, CAALA's reliance on generalized datasets and simplified modelling entails certain limitations. Early-stage tools, including CAALA, typically employ average or generic data, which may introduce uncertainties and limit the precision of results when compared to detailed, project-specific LCA tools [93]. The accessible interface, while advantageous for usability, also reduces transparency regarding methodological assumptions and dataset origins, which can be problematic for rigorous analysis [93]. Therefore, CAALA is best positioned as an exploratory, design-support tool; effective for initial scenario evaluation but not a substitute for comprehensive, full-scope LCA assessments.

This landscape clarifies both the breadth of available support and the persisting gap in integrated, architect-oriented evaluation at the early design stages. This thesis addresses this gap by developing a dedicated framework; however, the precise positioning of the BCEF in relation to these tools; its scope, interoperability, and validation; will be explored in the subsequent chapters of the thesis, where its architecture and application are presented and empirically examined.

1.2. Problem statement

Architects, building designers, and owners seeking sustainable architecture in their practices require valuable information to make informed decisions. Although design typically represents on the order of ~1% of a building's whole-life expenditure, early design choices (form, envelope, systems integration) determine the bulk of lifetime energy demand; established approaches (e.g., Passive House/integrative design) can reduce operational energy by ~80–90%, thereby cutting a very large share of life-cycle energy costs [95]. Currently, to address sustainability issues, most architects follow an ad hoc, problem-solving approach at the end of the design process, rather than designing from a sustainability perspective. However, it has been shown that, during early design phases, 20% of the design decisions taken subsequently influence 80% of impacts and life-cycle costs [96], [97]. Therefore, as the importance of "front-loading" the design process for sustainability is emphasized by many authors (e.g., [18], [99], [100]), sustainability principles should be inherently integrated into the architect's design process from the concept development phase onward.

The main principles of circular design are not new [4], [7], [8], [9], [98], [99]. However, up to now, only vague definitions or general and broad principles exist. No clear criteria, indicators, or hands-on guide to support architects when designing buildings within an integrated circular paradigm have been developed so far [6]. Therefore, several public programmes already provide hands-on guidance and tools for practitioners; notably the EU Level(s) [29] framework (indicator sheets, templates), Belgium's GRO [63] guide and the national TOTEM [100] LCA tool, and the Dutch Het Nieuwe Normaal / Platform CB'23 [101] handbooks (e.g., measuring circularity and material passports) but they still need integration and development. A framework for circularity development is needed, complemented with practical design strategies and measures that are validated for the Belgian context. The accurate and specific determination of circular characteristics of buildings can help designers to make fundamental choices in the design and construction of sustainable architecture.

The concept of circular design encompasses multiple aspects that contribute to positive, sustainable development, including energy, materials, biodiversity, water, and transportation. Within this Ph.D., the focus will be on materials and construction systems, as creating a positive impact through the well-thought-out use of materials and construction systems will be a major challenge for architects in the coming years. Other aspects of circular design offer promising solutions for positive sustainable development too, but often require a multidisciplinary approach and the involvement of several stakeholders, which falls beyond the scope of this Ph.D Concerning energy and materials, architects need information on how to replace fossil fuel-based systems and components with passive or natural/renewable sources on the building and grid level. They need to be stimulated to anticipate evolution and change, and to incorporate strategies and approaches that enhance the building's ability to adapt to various uses over time. In addition, they require information on how to incorporate technical and biological materials that can be safely converted into reusable nutrients, as well as how to design building systems and processes according to their intended use for both building occupants and biological and technical metabolisms [102].

Currently, architects face several challenges when assessing the environmental impact of material choices and the circular nature of building construction systems. The most significant issue is the absence of a clear evaluation framework that supports architects in designing buildings within a circular paradigm. There are three problems related to:

1. Tedious calculation of material quantities (average 3 weeks for a mid-size project, 2000 m^2)
2. Cumbersome use of Life Cycle Assessment software for materials.
3. Complicated evaluation workflow of building materials selection.

Although several of the aforementioned frameworks and tools have been developed, there is currently no practical framework that adopts a methodology combining the aspects above, contains design strategies and components, is complemented by validated practical measures, and provides guidance during the early design stage. Conceptual frameworks for design for change already exist (e.g. [103]); however, they do not yet establish a connection with circular construction techniques or identify building products suitable for their implementation. Existing tools or ratings systems for sustainable buildings are mostly post-evaluation tools, although some early design generative tools (databases, checklists) can be found. However, the methods and formats used in these early design generative tools are not tailored to the specificities of the architect's design process [15], [19], [104]. Furthermore, they follow a rather reductionist approach. In contrast, there is a need for a framework that contributes to introducing a new design thinking paradigm of positive sustainable development through circular design.

Research framework

2. Research framework

2.1. Aim, Objectives, and Research Questions

This Ph.D. research aims to inform and guide architectural students and practicing architects during the design process for achieving circular design outcomes, starting from the early design stage.

The operational objectives of the research project are formulated as follows:

1. Development of an evaluation framework (design principles and strategies, indicators, metrics, measures, etc.) for circular design.
2. Providing an overview of and recommendations for circular building design.
3. Apply the evaluation framework to inform architects' early-stage design decisions within a circular design paradigm.
4. Validation and potential application of the evaluation framework in education.

This Ph.D. research aims to support architectural students and practicing architects in their pursuit of circular design. This evaluation framework will also serve as a starting point in the pursuit of creative and innovative solutions to current environmental challenges by improving indicators in accordance with future standards and legislation.

Regarding innovation and added value, the specific output of this Ph.D. is a multi-indicator evaluation framework with a building circularity index to inform architects during early design within a circular paradigm, which allows them to:

1. Close the knowledge gap in the practical application of circular design in general, and inform architects, producers of building materials, and the construction industry about the potential of circular design and construction techniques and products suitable for achieving circularity.
2. Provides insights into future development in education, research, and practice, as well as knowledge and know-how related to the circular economy.

Currently, no such framework for circular design exists that collects the same indicators. The clear identification of the framework with validated design strategies and applications will unlock this barrier to circular design, allowing architects to follow an integrated design approach within a circular paradigm. Ultimately, the expected outcome visualizations of this research will serve as a guide, setting standards for circular building design for scientific researchers, students, architects, and other relevant audiences. This will provide them with advice on construction techniques and products, as well as inform the design of new software for this purpose.

Accelerating the embracement or uptake of sustainability principles set by the EU in the architectural design practice in Belgium is essential. Sustainability should be brought to the ideation or concept development phase, and the inherent integration of sustainability principles in the architect's design practice should be supported. The circular paradigm holds out a prospect of positive, sustainable development and reversing the ecological carrying capacity. It enables various design processes that aim to strategically select and optimize resources required for building construction and building products within an industrial ecosystem of the circular economy, considering the value chain of building resources.

This Ph.D. research intends to answer the following main research question:

- ***MRQ:*** *How can a Building Circularity Evaluation Framework be developed and validated to guide early design stage evaluation of buildings from a life-cycle thinking approach?*

The main research question can be broken down into several specific Sub-questions that need to be addressed initially. Those questions explore different research gaps that have been identified and addressed in various scientific publications. In total, five publications have been published that form the chapters of this thesis. The specific research questions are as follows:

- ***SQ1:*** *How do carbon neutrality and circularity principles integrate into the building regulations of leading Northwestern European states, and what policy measures are most effective in promoting sustainable construction practices?* ***(Chapter 01)***
- ***SQ2:*** *How can parametric approaches help to evaluate the environmental impact and the building circularity?* ***(Chapter 02)***
- ***SQ3:*** *What are the most effective criteria and methods for evaluating the disassembly potential of buildings to enhance circular construction practices?* ***(Chapter 03)***
- ***SQ4:*** *How can the evaluation of building disassembly potential be enhanced to support circularity and decision-making in the early design and deconstruction stages?* ***(Chapter 04)***
- ***SQ5:*** *How can a building circularity evaluation framework be utilized to assess and optimize circularity and sustainability in the building sector?* ***(Chapter 05 & Chapter 06)***

The focus on newly constructed small- and mid-size office buildings was primarily driven by experimental accessibility, data quality, and methodological validation needs. The proposed circularity evaluation framework (BCEF and DeCon tool) required comprehensive, verifiable datasets on material composition, assembly logic, and connection typologies, conditions that are only attainable in ongoing or recently completed construction projects where full design documentation, BIM models, and site access are available. New office projects such as ’t Centrum, ABN AMRO Circl, and Green Office provided controlled environments enabling systematic measurement of component-level disassembly potential and embodied impact through on-site inspection and bill-of-quantities verification. We are fully aware of the significant share of vacant office stock across Northwest Europe, including Belgium, the Netherlands, and northern France. However, such buildings are typically characterized by heterogeneous vintages, undocumented alterations, and safety or accessibility restrictions, which severely constrain reliable data collection and reproducible analysis. Applying the BCEF framework to these existing structures would introduce high uncertainty in material inventories, contaminant presence, and past renovation layers, undermining methodological consistency and attribution of results. Conversely, new small- and mid-scale office buildings represent a dominant typology in contemporary construction and are the primary focus of emerging EU whole-life carbon regulations (e.g., NL BENG + MPG, DK LCA cap, EPBD Recast 2028). They therefore serve as ideal experimental testbeds to validate early-design decision tools under controlled yet policy-relevant conditions before extending the framework to complex renovation scenarios. This typological focus ensured scientific rigor, regulatory alignment, and the feasibility of extensive parametric experimentation while maintaining the representativeness of market practice.

2.2. Thesis outline

As shown in Figure 2.1, this thesis consists of three main parts: Part I, Part II, and Part III. Part I focuses on the data collection phase, during which two literature review studies were conducted on the principles of carbon neutrality and circularity integrated into the building regulations of leading Northwestern European states, as well as on the use of parametric approaches that evaluate environmental impact and building circularity. In this part, three circularity indicators of the framework were identified and validated through a case study evaluation. Part II focused on the development of an expert system for evaluating the potential for building disassembly, during which two studies were conducted. The first was to review the literature on the most important criteria and barriers used to evaluate the building disassembly potential. The second study was to validate the expert system by evaluating the disassembly potential of a new case study. In Part III, a comprehensive methodology is introduced, and a multi-indicator framework has been developed to evaluate the building's circularity. Each chapter within each section comprises a journal or conference publication that directly contributes to addressing the main research questions of this study. Furthermore, each chapter is structured to examine specific research questions outlined in the corresponding publication.

The chapters in this thesis are correlative and integral. Chapter 01 examines the role of Northwestern European states in developing carbon footprint regulations and promoting circular building design. By conducting a systematic literature review, the paper analyzes policies in Denmark, Finland, France, the Netherlands, and Sweden, highlighting best practices for integrating carbon neutrality and circularity in the construction sector. The findings offer insights into regulatory frameworks that support sustainable building practices and provide recommendations for policymakers to enhance circular economy principles in national and EU-level regulations.

Chapter 02 explores the importance of the parametric approach to optimizing building construction systems and reducing carbon footprints. Using life cycle impact assessment (LCIA) and parametric modeling, four construction scenarios; timber, steel, concrete, and hybrid; on `t Centrum office building in Belgium have been evaluated. This case study was specifically chosen because it embodies circular building principles, aligning with the objectives of this Ph.D. research. Findings highlight the environmental benefits of using bio-sourced materials, such as timber, and emphasize the importance of material reuse and modular construction. The results provide insights for sustainable design strategies, informing policymakers and industry professionals.

Chapter 03 investigates disassembly calculation criteria and methods for circular construction, emphasizing the importance of evaluating building disassembly potential at various scales. Using a hybrid systematic review, the research identifies fragmented criteria and methods for assessing design for disassembly (DfD). The findings highlight key metrics and methodologies that can inform future European standards for circular construction. The study offers valuable insights for researchers and industry professionals, enabling informed decision-making to enhance sustainability and resource efficiency in the built environment.

Chapter 04 presents an expert system designed to evaluate the disassembly potential of buildings, addressing the lack of standardized tools for assessing deconstruction feasibility. By classifying structural connections and analyzing disassembly barriers, the system provides decision support during the early design and pre-demolition stages. The methodology includes standardized inspections of over 2,500 connections in circular buildings, statistical analysis, and inventory measures to enhance disassembly efficiency. The findings contribute to circular construction practices by promoting the recovery and reuse of materials.

Chapter 05 presents the Building Circularity Evaluation Framework (BCEF), designed to assess circularity in newly constructed office buildings. By integrating key performance indicators such as Global Warming Potential, reused content, disassembly potential, and functional adaptability, the framework enables a holistic evaluation of building circularity. The BCEF was validated through a case study of the ABN AMRO Circl pavilion in Amsterdam, demonstrating its applicability. Findings emphasize the importance of standardized circularity assessment methods to enhance circularity in the construction sector.

Chapter 06 presents the implementation of the Building Circularity Evaluation Framework (BCEF) through three case studies: `t Centrum Building, Green Office, and ABN AMRO Circl Pavilion. The study evaluates six key circularity indicators; Global Warming Potential, Land-Use footprint, Reused Content, Disassembly Potential, Functional Adaptability, and Product-Service Systems; quantifying circularity performance. The findings highlight the impact of material selection, construction techniques, and disassemblability on sustainability. The research highlights the applicability of BCEF for assessing and improving circular building practices. It can also be applied to education, where the BCEF can serve as a studio assessment aligned with EN 15978 and mappable to EU Level(s) indicators, which are supported by free educator/learner training modules. These modules enable students to quantify whole-life impacts and compare circular strategies at the conceptual stage.

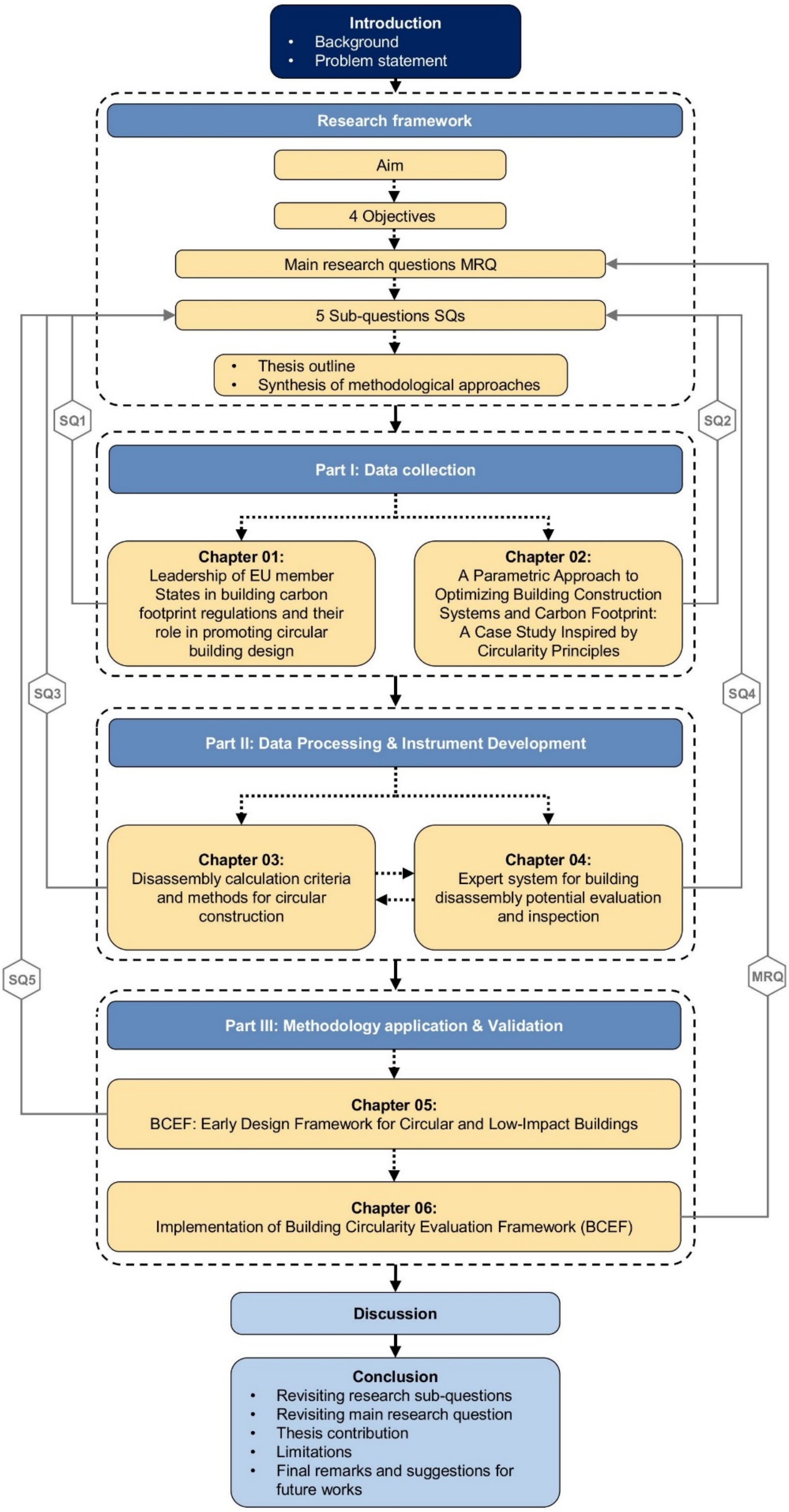


Figure 2.1. Thesis outline

2.3. Synthesis of methodological approaches

Chapter 01. This chapter explores the leadership of EU member states in developing carbon footprint regulations and their role in promoting circular building design. The chapter examines regulatory frameworks and policy measures implemented in five leading EU countries; Denmark, Finland, France, the Netherlands, and Sweden; to integrate circular economy principles with carbon neutrality objectives. By analyzing key performance indicators and legislative measures, this chapter highlights best practices that facilitate the transition toward sustainable building practices. The findings provide a foundation for understanding how regulatory interventions can enhance the implementation of circular design strategies, ultimately contributing to the methodological framework developed in later chapters.

Chapter 02. This chapter introduces a parametric approach to optimizing building construction systems and minimizing carbon footprints, inspired by principles of circularity. Through a case study conducted on an office building in Belgium, the research evaluates different construction scenarios; timber, steel, concrete, and hybrid; using life cycle impact assessment (LCIA) and parametric modeling techniques. The study identifies key parameters influencing the environmental impact of building materials, emphasizing the potential of biosourced materials and demountable construction systems in achieving sustainability goals. The insights gained in this chapter contribute to the broader methodological framework by providing evidence-based recommendations for integrating circularity into early-stage building design decisions.

Together, these two chapters establish the fundamental theoretical and regulatory foundations for this research, equipping the Ph.D. candidate with essential knowledge to advance the implementation of circular and sustainable construction practices. The findings further support the development of robust assessment methods and decision-making frameworks, which are applied and expanded upon in subsequent sections of the thesis.

Chapter 03. This chapter examines the calculation criteria and methods for disassembly in circular construction. This chapter provides a comprehensive framework for evaluating the disassembly potential of buildings at various scales, addressing the fragmented and dispersed nature of existing assessment methods. By conducting a systematic literature review, the study synthesizes key metrics and criteria used in current European regulations and industry practices. The findings contribute to the development of standardized methodologies for assessing design-for-disassembly (DfD) principles, offering valuable insights for researchers and practitioners in circular construction. The methodologies presented in this chapter establish a foundation for quantifying disassembly potential, which informs the decision-making processes in subsequent chapters.

Chapter 04. This chapter introduces an expert system for evaluating and inspecting the potential for building disassembly, addressing the gap in standardized decision-support tools for deconstruction feasibility assessment. This chapter presents a novel framework that classifies structural connections and assesses their impact on disassembly efficiency through standardized inspections of over 2,500 connections in circular buildings. By employing statistical analysis and inventory measures, the system provides actionable insights for improving disassembly practices. The expert system serves as a crucial tool for architects, engineers, and demolition professionals, facilitating more effective material recovery and reuse. The methodologies outlined in this chapter enhance the implementation of circular economy principles in the construction sector.

Together, these two chapters contribute to the methodological framework for circular construction by developing assessment tools and decision-support systems for disassembly evaluation. The findings provide a foundation for advancing research in circular building design, ensuring resource efficiency, and supporting the integration of disassembly principles into regulatory and industry practices.

Chapter 05. This chapter introduces a Building Circularity Evaluation Framework (BCEF) developed to assess circularity in newly constructed office buildings. This chapter addresses the inconsistencies in existing building circularity indicators (BCIs) by proposing a comprehensive and standardized evaluation methodology. The BCEF integrates key performance indicators (KPIs), including Global Warming Potential, reused content, disassembly potential, land-use footprint, functional adaptability, and product-service systems, to provide a holistic assessment of circularity. To validate the framework, the BCEF was applied to the ABN AMRO Circl Pavilion in Amsterdam, a case study demonstrating the practical application of circular economy principles in office building design. The results highlight the critical influence of material choices, construction processes, and service life on circularity performance. The findings emphasize the importance of integrating design-for-disassembly (DfD) principles, modular construction techniques, and service-based business models in the early design stages to enhance circularity outcomes.

This chapter contributes to the broader methodological framework by bridging the gap between theoretical circularity concepts and practical implementation strategies. By offering a structured and scalable assessment framework, the BCEF provides valuable insights for architects, engineers, policymakers, and industry professionals seeking to incorporate circular economy principles into building design and construction practices. The findings reinforce the need for standardized circularity assessment methodologies to support the transition toward sustainable, resource-efficient built environments.

Chapter 06. This builds upon the Building Circularity Evaluation Framework (BCEF) introduced in Chapter 05 by applying and validating the framework through three case studies: `t Centrum Building, Green Office, and ABN AMRO Circl Pavilion. This chapter systematically evaluates the circularity performance of these buildings using six key indicators: Global Warming Potential (GWP), Land-Use footprint (LU), Reused Content (RC), Disassembly Potential (DP), Functional Adaptability (FA), and Product-Service Systems (PSS). The study employs a quantitative methodology to assess circularity using Life Cycle Impact Assessment (LCIA), expert systems, and industry-standard evaluation tools such as One Click LCA. The results indicate significant variations in circularity performance among the three case studies, influenced by material selection, structural design, and construction techniques. The analysis highlights the advantages of modular construction, prefabrication, and disassembly-oriented design, emphasizing their role in improving circularity outcomes. Additionally, the study incorporates an inventory and inspection campaign, systematically analyzing material composition, reuse potential, and adaptability to future modifications. Findings demonstrate that buildings designed for disassembly and adaptability achieve superior circularity performance, while heavy reliance on concrete and non-disassemblable components negatively impacts sustainability metrics.

Through integrating theoretical and empirical insights, this chapter strengthens the methodological framework for evaluating circularity in the construction sector. The results reinforce the BCEF's applicability as a standardized framework for assessing, comparing, and enhancing circular building practices, thereby supporting the transition toward sustainable construction policies and the implementation of a circular economy across the industry.

Journal and conference publications

3. Journal and conference publications

Chapter 01. *Leadership of EU member States in building carbon footprint regulations and their role in promoting circular building design* – *Peer-reviewed conference paper – International Congress*

Abstract: European countries are working towards carbon neutrality of the building sector. Regulations and initiatives, including the European Green Deal, aim at promoting circular buildings and low carbon design. Therefore, this paper seeks to investigate the role of legislation in paving the way towards achieving the circularity of buildings design and construction. A systematic literature review is conducted to compare the current regulations in different EU member states that address carbon emissions and life cycle thinking to achieve circularity. The study aims to demonstrate how the low-carbon emissions regulations in leading countries can lead to making the construction sector's circularity. The research is focused on five leading EU member states in low carbon buildings, including Denmark, Finland, France, the Netherlands, and Sweden. The study compares the performance indicators, metrics, and target thresholds found in the five selected states' regulations and examines them across a circularity assessment framework developed earlier by the authors. This paper provides insights on low emission building regulations state-of-the-art. Moreover, it offers a better understanding of the relationship between low-carbon emissions regulations and building circularity. The article explains the role of the legislative landscape and its impact on circular building design practices. Key findings from the study will assist the European Commission to identify policy options to support the uptake of "Circular economy principles for buildings design" in European, national and local policies.

Role of Ph.D. candidate: As co-author, the Ph.D. candidate led the conceptualization and methodology (Lead), designed the comparative protocol and inclusion/exclusion criteria, conducted the investigation and data curation (Lead) across national sources, performed the formal analysis (Lead) to derive indicators and policy typologies, created all visualization materials (Lead), and drafted the main sections (writing – original draft, Lead). Co-authors contributed supervision and writing – review & editing (Equal), with project administration support.

Conference name, organizers, and location: IOP Conference Series: Earth and Environmental Science (24-25.03.2021), Crossing Boundaries 2021, Zuyd University, Maastricht, Netherlands.

Citations: Google Scholar: 35

Reference: Attia, S., Santos, M. C., Al-Obaidy, M., & Baskar, M. (2021). Leadership of EU member States in building carbon footprint regulations and their role in promoting circular building design. Crossing Boundaries. Maastricht, Netherlands, https://doi.org/10.1088/1755-1315/855/1/012023 & https://hdl.handle.net/2268/258345

IOP Conf. Series: Earth and Environmental Science **855** (2021) 012023 doi:10.1088/1755-1315/855/1/012023

Leadership of EU member States in building carbon footprint regulations and their role in promoting circular building design

S Attia[1], M C Santos[2], M Al-Obaidy[1] and M Baskar[1,3]
[1]Sustainable Building Design Lab, Dept. UEE, Faculty of Applied Science, University of Liege, 4000, Belgium
[2]Faculty of Architecture, University of Lisbon, Lisbon, 1000, Portugal
[3]EPF Graduate School of Engineering, Troyes, 10000, France

Abstract. European countries are working towards carbon neutrality of the building sector. Regulations and initiatives, including the European Green Deal, aim at promoting circular buildings and low carbon design. Therefore, this paper seeks to investigate the role of legislation in paving the way towards achieving the circularity of buildings design and construction. A systematic literature review is conducted to compare the current regulations in different EU member states that address carbon emissions and life cycle thinking to achieve circularity. The study aims to demonstrate how the low-carbon emissions regulations in leading countries can lead to making the construction sector's circularity. The research is focused on five leading EU member states in low carbon buildings, including Denmark, Finland, France, the Netherlands, and Sweden. The study compares the performance indicators, metrics, and target thresholds found in the five selected states' regulations and examines them across a circularity assessment framework developed earlier by the authors. This paper provides insights on low emission building regulations state-of-the-art. Moreover, it offers a better understanding of the relationship between low-carbon emissions regulations and building circularity. The article explains the role of the legislative landscape and its impact on circular building design practices. Key findings from the study will assist the European Commission to identify policy options to support the uptake of "Circular economy principles for buildings design" in European, national and local policies

1. Introduction

On Oct 7 2020, the European Parliament voted to update the EU's climate target for 2030 [1]. The vote is backing the decision of a 60% reduction in greenhouse gas emissions by 2030 compared to the emissions of 1990. Collectively, buildings in the EU are responsible for 36% of greenhouse gas emissions, mainly stemming from construction, operational emissions (heating, cooling, ventilation, and power), renovation, and demolition [2]. Therefore, the building sector has a vital role in responding to the climate emergency, and addressing upfront carbon is a critical and urgent focus [3]. Bringing embodied carbon upfront and the fast energy transition towards carbon neutrality is crucial. Simultaneously, the energy and carbon transition need to be following the principles of the circular economy. The European Commission is looking forward to promoting circular economy principles for buildings' design. However, coupling the carbon neutrality target with the building circularity target is challenging, and there are no established national and local policies within Europe.

Therefore, this study aims to assist the European Commission in identifying policies that support the uptake of "Circular Buildings "and "Carbon Neutral Buildings "to increase buildings' service life and ease the use of secondary materials improve resource efficiency throughout the building lifecycle. The main research questions are: To what extent are carbon neutrality and circularity concepts integrated into mandatory building regulations, and who are the EU leading countries in this regard?

The paper provides an overview of leading EU member states that integrated both concepts in their regulations based on a systematic literature review and expert interviews with relevant circularity and carbon neutrality experts. The research is focused on five leading EU member states in low carbon buildings, including Denmark, Finland, France, the Netherlands, and Sweden. Key findings from the study will be used as an input to define the policies to be implemented in other EU member states. The paper is the audience is mainly scientists and actors involved buildings value chain, namely building engineers, architects, contractors, and builders, including renovators, manufacturers of construction products, and government/regulators, including national, regional, and local municipal authorities.

2. Literature Review

In this section, we focus on two major concepts that are the focus of this study, namely, carbon neutrality and circularity. Both concepts are chosen because they are the most effective concepts that can reduce greenhouse gas emissions and other environmental impacts, such as end-of-life waste.

Several terms are used to express the carbon emissions associated with building construction that depend on the carbon neutrality period's emissions calculation method. From a life cycle thinking approach [4] and based on EN 15978 [5], there are two definitions associated with building carbon neutrality: namely the embodied carbon emissions stage (A1-5) and the carbon emissions in use stage (B1-7) (see Figure 1). Since the European Energy Performance of Buildings Directive (EPBD) introduction, building regulations requirements evolved until we reached nearly zero and net-zero energy building [6,7]. Several studies tried to associate energy neutrality targets with building materials emissions; however, very few countries addressed carbon emissions in the EPBD before the use stage [8]. The Paris agreement emphasized the need for deep decarbonization of the building stock beyond the energy neutrality concept. Carbon emissions from building materials have a significant climate impact. The Incorporated Carbon Review reports indicate that even by de-carbonizing the energy grid, buildings can continue to be a substantial generator of emissions in the long term due to the carbon incorporated in the materials used in emerging countries [9]. Research shows that energy efficiency has decreased fossil energy use and increased renewables; however, the embodied carbon increased [9,10]. The introduction of the Environmental Product Declaration in 2018 for building materials in most EU member states was the first step that was taken to quantify the carbon emissions of buildings [11]. However, the use of EPDs is voluntary in most countries without any emission thresholds. Figure 2 illustrates the European countries driving the demand for EPDs based on the Once Click Life Cycle Analysis (LCA) database.

PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARIES
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	MND	MND	MND	MND	MNR	MNR	MNR	MND	MND	MND	MND	X	MND	X

Figure 1. Description of the stages during the buildings' life, according to EN 15978.

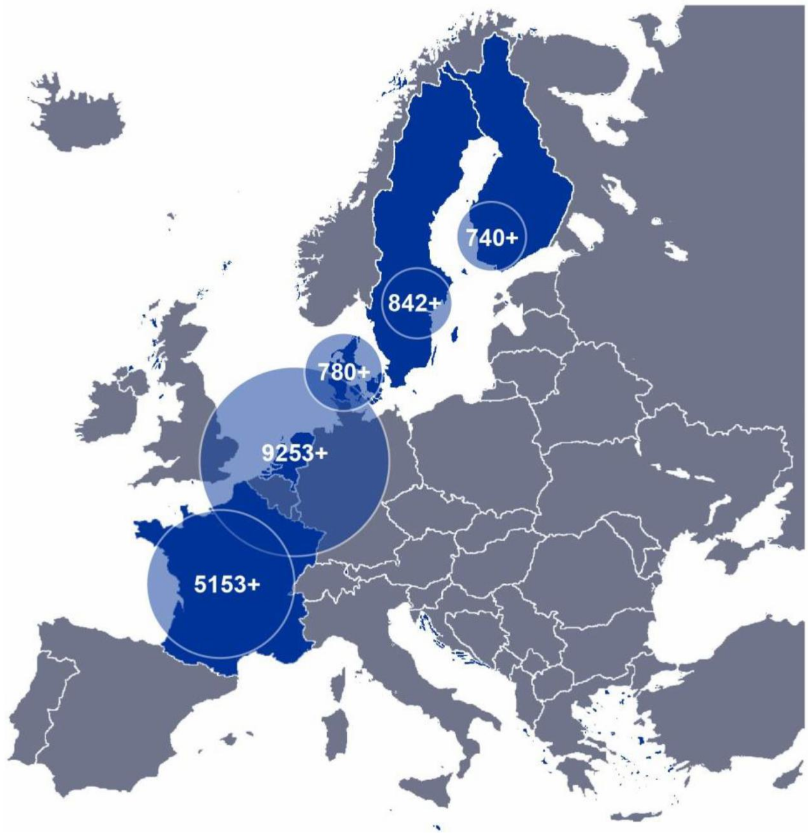


Figure 2. Numbers of European products EPDs available in One Click LCA's database.

The second concept investigated in this study is building circularity. A circular building seeks the highest efficiency in managing combined resources and the maximum generation of renewable resources. It seeks positive development to increase the carrying capacity to reverse ecological footprint [12]. Sustaining the material's value is the key to circular material use, and ways to harvest this value are at the center of the circular buildings. Few studies addressed the concept and definition of building circularity [13]. But several authors like Durmisevic and [14] Antonini et al. [15] tried to develop reliable indicators for reversibility and durability features of circular buildings. Cottafav et al. and Attia addressed the gap between embodied impacts and architectural and structural design aspects [12,16]. The difficulty of defining or building a circular building based on circularity indicators and technologies to enhance buildings' service life while closing material loops is still challenging [17].

Despite the evolution of the carbon neutrality and circular design of building, both concepts are not included in most European building standards and public procurements. The legislative requirements and compliance for circular construction remain excluded from most sustainable business models despite the climate urgency and resource scarcity. This literature review confirms the need to explore both concepts in national and local regulations to collect further insights on the leadership of EU member States in building carbon footprint regulations and their role in promoting circular building design.

3. Methodology

This study conducted a systematic literature review and expert interviews to build legislation concerning the two following concepts: circularity and carbon neutrality. Among the 27 EU member countries, a screening has been done to reduce the study countries to five: Denmark, Finland, France, the Netherlands, and Sweden. The inclusion criteria focused on countries that require a life cycle assessment and environmental product declarations (EPD) for building materials during building permit issuing.

The inclusion criteria included mandatory requirements or measures to increase the service life of buildings. The exclusion criteria included regulations that define circularity on an urban or territorial scale. The search focuses mainly on carbon neutrality and circularity on building scales. Carbon criteria and circularity were assessed based on the building design criteria for circular buildings developed by Attia et al. [12, 17, and 18]. The selected countries were the only countries fulfilling all criteria.

The study is mostly qualitative, based on the literature review of collected documents and articles and short interviews with experts representing the five countries. The principle of "triangulation" for findings was used. Three sources have been used, primary sources, secondary sources, and experts' knowledge to confirm results. Primary sources are official documents such as scientific articles and regulations; secondary sources are constituted by a literature review in the form of articles and magazines, eventually, and experts' short interviews. The texts concerning regulations have been carefully analyzed and summarized in tables and described in the results section. Thus, through this approach, the five countries' relevant regulations and publications are selectively reviewed.

4. Results

The results of the literature review and expert interviews are presented in the section. Firstly, an overall comparative analysis is presented. Secondly, a detailed analysis and facts check is provided individually for each country. Table 1 lists the most important publications that we selected during our review. Each publication is shortly described concerning building carbon footprint and circularity. Moreover, Table 2 compares the five investigated countries against a carbon neutrality and circularity checklist developed by Attia [17].

Table 1. Key publications in the five countries related to carbon neutrality and circularity criteria.

Country	Reference	Description
Denmark	(19,20)	- Denmark outperforms EU28 on most selected resource and innovation metrics, such as share of renewable energy or Eco-innovation index. The improved utilization of assets and better use of waste or by-products as a resource has a potential value as a resource; however, recycled materials should be used in higher-value cycles, such as reuse or remanufacturing [19]. - Denmark has ambitious climate neutrality targets. Energy taxes stand in getting the electrification that can ensure a socio-economically beneficial integration of renewable energy in the total energy system. Even the reduced tax on electricity for space heating is almost twice as high as the energy tax on heating oil and natural gas. That inhibits the electrification of buildings heating and district heating, where heat pumps are both energy efficient and socio-economical efficient technology. [20]
Finland	(21,22)	- The goal is for Finland to build its competitiveness using sustainable material use. The demand for virgin materials will be minimized, the length of material and product life cycles maximized, and products designed so that they can be maintained and reused at the end of their first useful life [21]. - Finland developed a whole life carbon assessment of buildings method. The method is based on the European Commission's Level(s) method and European Standards [23]. A low-carbon building has a low carbon footprint and a giant carbon handprint. The method is intended

		to assess the carbon footprint and carbon handprint of new buildings and buildings undergoing extensive repairs [22].
France	(24)	- The new French Building Regulation RE2020 introduces a new threshold of 4 $kgCO_2$ operational emissions equivalent/m^2 for new residential buildings and set at a level sufficiently ambitious to favor the low carbon-intensive energies [24]. This will eliminate the use of gas for heating. A conversion coefficient between primary energy and final energy of electricity of 2.3 will be used. It corresponds to the expected average value of this coefficient over the next 50 years, thus making it possible to consider the forecast evolution of the French electricity mix -over the life of new buildings. -The new RE2020 is introducing a dynamic LCA calculation method that is ambitious, proposing a threshold for embodied carbon emission of 100 kg of CO2 per m^2, which favors biobased materials and timber [24].
Netherlands	(25,26)	-In the Netherlands, the government and the business community work are currently using a method to measure the building's environmental performance via a life cycle analysis. LCA is used as a criterion for construction procurement. The Dutch recognize the limitation of their method regarding the treatment of demolished materials and their reuse [25,26].
Sweden	(27,28)	-The Nordic construction section is witnessing acceleration towards circular construction. Experts suggest anchoring the requirements in the building regulation in Denmark, Finland, Norway, and Sweden in Environmental Product Declarations (EPD), Construction Products Regulation (CPR), Building Information Modelling System (BIM), and Material and building passports [27,28]. - Sweden has set the goals for achieving a climate-neutral value chain in the construction and civil engineering sector reaching by 2045: Net-zero emissions of greenhouse gases by 2040: 75% reduced greenhouse gas emissions by 2030: 50% reduction in greenhouse gas emissions [28].

4.1. Denmark

Denmark has adopted the German certification system, DGNB (*Deutsche Gesellschaft für Nachhaltiges Bauen*). A large part of the certification system refers to the Life Cycle Assessment (LCA). However, the use of LCA is voluntary. The promotion of sustainable solutions and green products is carried out through the Partnership for Public Green Procurement, a community of municipalities, regions, and public associations. The use of the Environmental Product Declaration (EPD) is voluntary in Denmark, except in Copenhagen, it is mandatory. However, there are strong incentives to use EPDs [19].

The Danes aimed that by 2030, 50% of all energy used in buildings should come from renewable sources, and it wants to reduce buildings total carbon emissions by 9.4 million tons by 2030 [20]. However, there is uncertainty to attain this target. In terms of energy consumption, the legislation provides that new buildings must be built as low-energy houses that consume up to 90% less energy. These requirements are implemented for the 2020 building regulations.

The current state of transition to a circular economy in the Danish construction sector is elaborated on to improve material recycling quality in the construction sector. Preferably, greater direct reuse and removal of hazardous substances in construction materials. The Danes developed their material passport tool, called "*Materialepas*," to improve circular product policies [29]. Denmark is increasing existing building assets by encouraging multifunctional buildings such as schools and building reuse through building components' modular design. The construction industry had shown concerns in the disassembly process to enable the separations of materials after construction [28]. The main innovation area is industrial production processes to reduce waste during construction and renovation, including modular construction and 3D printing construction modules [19].

In terms of construction waste management strategies, the government plans to separate ten waste fractions: 1. natural stone, for example, granite and flint, 2. non-enameled tiles (bricks and tiles), 3. concrete, 4. mixtures of stone materials and unglazed tiles and concrete, 5. iron and metal, 6. plaster, 7. rock wool, 8. soil, 9. asphalt, 10. and mixtures of concrete and asphalt. Currently, 87% of building materials are recycled with low-quality applications, and less than 1% are made into components and materials for new construction [30]. However, large construction companies are going beyond their initiative's requirements - small builders can deliver different construction waste fractions to local recycling centers [31].

Table 2. Mapping of carbon neutrality and circularity criteria regulation landscapes in the five countries.

		Denmark	Finland	France	Netherlands	Sweden
Carbon Footprint Reduction Criteria	Carbon emission threshold	✓	✓	✕	✕	✓
	Green Public Procurement (GPP)	✓	✓	✓	✓	✓
	Embodied carbon in products	✓	✓	✓	✓	✓
	LCA	✓	✓	✓	✓	✓
	EPD & %	✕	✓	✓	✓	✓
	Energy efficiency improvements	✓	✓	✓	✓	✓
Circularity Criteria	Building Materials Passport	✓	✕	✕	✓	✓
	Dismantling Protocol	✓	✕	✕	✕	✕
	Carbon + water footprint	✕	✕	✕	✕	✕
	Competitiveness and innovation industrial	✓	✓	✕	✕	✓
	Waste management	✓	✓	✓	✓	✓
	Adapt Spaces	✕	✕	✕	✕	✕
	Reconfigure \ upgrade structure	✓	✓	✕	✕	✕
	Separate elements material	✓	✕	✕	✕	✕

4.2. Finland

In Finland, the goal for a building's lifespan neighbors 80 years [7]. The plan will be to prolong this lifespan. This is where the idea of circularity comes into account. Construction parts must have net benefits and affect lowering carbon footprint. The first edition of the system for the lifetime carbon assessment of buildings was based on the Level(s) framework developed by the European Commission [23]. A project named "Circular Economy in the Built Environment" was launched by the Finnish Innovation Fund Sitra in early 2018 [21].

Material economics predicts that only cement, steel, aluminum, and plastic used for construction in Finland would result in emissions of 230 Mt CO_2 by 2050 if produced using today's manufacturing processes. The Ministry of the Environment released a plan for low-carbon construction in 2017: by the mid-2020s, a life-carbon assessment of buildings must be included in the building regulations. As Finland intends to achieve carbon neutrality by 2035, estimating buildings' carbon footprint and building-type specific emission limits are introduced in the building regulations of 2020. Furthermore, Finland also plans to reach an 80 percent reduction in greenhouse gas emissions by 2050 under the Climate Change Act, compared to the 1990 baseline figure. The Land Use and Construction Act, a recent reform, embraces low-carbon aspects and a life cycle thinking approach for a low-carbon construction sector [22,32].

4.3. France

The recently updated Energy-Climate Law promises to fight against climate change to reach a carbon-neutral France by 2050 [33]. The future French Environmental Legislation goals within this framework are to reduce the effect of new buildings on the environment by considering all of the building's pollution, right from construction, over its life cycle. A focus and special attention to bioclimatic design is (known as 'Bbio' indicator) is highlighted [34]. In the new building regulation law (RE 2020), new constructions carbon emissions are reduced substantially. Through the promotion of Energy Positive and Low Carbon Buildings, the regulation introduces a new threshold for CO2 emissions [24]. The CO2 emission factor is expressed in kg eq.CO2 /m² [24]. Unfortunately, according to the best available data, French regulations do not address circularity.

Moreover, according to the French Ministry of Energy Transition LCA methodology used to calculate the impact on global warming, buildings mandated by RE2020 will be based on a dynamic LCA methodology. The static LCA method proposed by the E + C- standard is going to be replaced. The calculation of global warming impacts via the dynamic LCA method will widen the gap already present between timber constructions and reinforced concrete construction. The new dynamic calculation will take into account benefits beyond the life cycle of building materials. It will be more adjusted to the reality of the materials integrated in projects, favoring bio-sourced construction solutions.

4.4. Netherlands

The Dutch Building Environmental Performance Declaration (DBED) is mandatory for every environmental permit [35]. The declaration indicates the environmental impact of the materials used in a building. This concerns new office buildings (larger than 100 m²) and new-built homes. As of Jan 1, 2018, a maximum limit value of 1.0 applies to the Building Environmental Performance Declaration. The DBED is an essential measure of the sustainability of a building. The lower the declaration value the more sustainable the use of materials. The DBED is a tool that should be used during the design process, and it can be used in a Design Brief to record the result of a design process [26]. For example, recycled floor covering gives a sustainable value and is an essential means of communication. However, the DBED calculation shows that the floor slab's sustainability has a much more significant effect on the environmental impact than the floor finishing.

To determine the material's environmental impact, an LCA is performed. A qualified expert must perform the LCA. The LCA results are reported for 11 environmental indicators of a product. These 11 indicators are combined into one value: the environmental cost per unit of the product (kg, m3, m2, etc.). It is not necessary to perform an LCA of the same product/material over and over again. For the Netherlands, the characteristics of materials from the LCAs are collected in the National Environmental Database (NMD). The Building Quality Foundation manages this database (SBK). A producer or supplier must ensure that a product is included in the NMD.

Regarding circularity, no enforced building regulations exist. However, many guidelines and initiatives taken by municipalities and companies encourage green and circular building materials procurement. The Design for Modularity (DfM) or Design for Disassembly (DfD) concepts are implemented in several pilot projects. The renovation and adaptation of existing buildings, such as churches, and their transformation into dwellings, are examples of layouts circular design strategies in the construction, including adaptively, modularity, and design for reuse [25]. In 2019, 12.5 thousand homes were created by transforming existing buildings, such as offices, schools, and shops [36]. Netherlands is seeking to have a circular economy by 2050 and reduce the materials used by 50% [37].

4.5. Sweden

Under the Paris Agreement requirement, Sweden aims to eliminate its greenhouse gas emissions until 2045 [28]. The climate program legislation is made according to Ordinance (2015: 517) and is supported by local climate investors (Klimatklivsförordningen) [38]. Starting in 2022, all new buildings must reduce carbon emissions to meet a specific threshold. The approach is based on the LCA of buildings.

To ensure that the national energy target is 50% more efficient by 2030, Sweden has created several instruments that provide incentives to promote carbon efficiency and circularity. For waste management of the construction industry, Sweden aims to recycle 70% of materials [39]. The Swedish, Environmental Protection Agency requires recycling large amounts of construction residues guided through a manual to facilitate recycling in an environmentally safe and health-friendly manner. The Swedish Public Procurement Act states that contracting authorities should follow green procurement for public-funded projects [40].

5. Discussion

This research presented a literature review and expert interview results of five countries regarding building regulations associated with carbon neutrality and circularity. The five leading European countries are slowly increasing wood and biobased materials in construction to sequester carbon emissions. The use of EPDs and LCA with performance thresholds for carbon emissions is transforming the construction industry. However, the circularity concept is still not gaining momentum in regulations. As shown in Figure 3, our study indicates that Denmark is the most leading EU state to incorporate the circular economy's principles in the construction sector. The regulations landscape in Denmark is almost mature, with policies and tools that aim to waste reuse and materials separation. In second place comes Finland, with a multi-stakeholder approach to adopt "Circular Economy in the Built Environment" in the construction sector and achieve carbon neutrality by 2035. Sweden comes in third place by implementing a climate legislation that introduces and favors the execution of measures and supports the transition toward carbon neutrality in 2045, entering into effective January 2022. France is in fourth place in the qualification, leading to carbon footprint reduction measures and lagging regarding building circularity. The Netherlands comes forth with the mandatory LCA requirements for all new constructions.

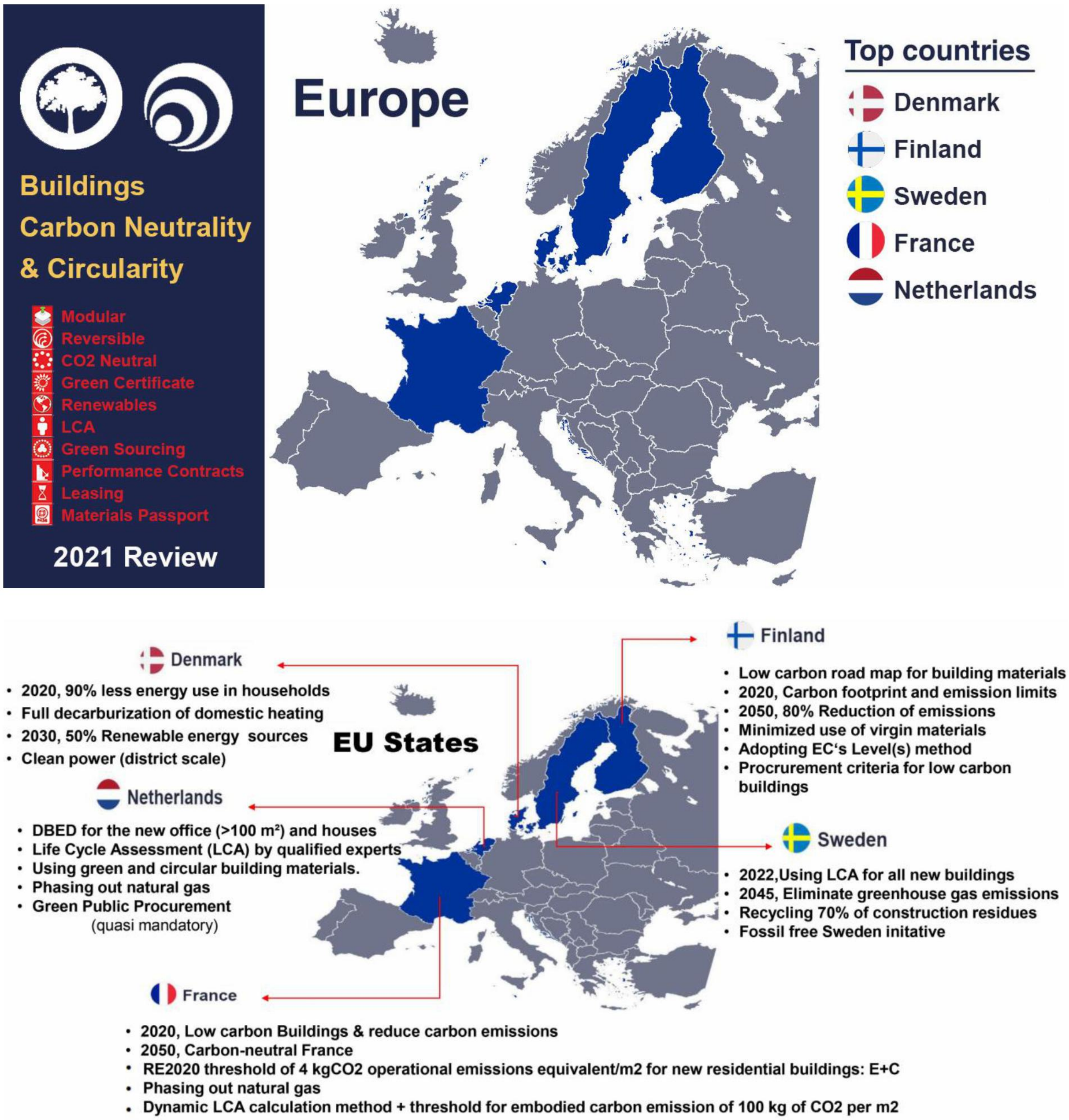


Figure 3. Ranking of EU leading member states that couple carbon neutrality and circularity requirements for new constructions.

Based on our review and analysis, we provide three main recommendations. Firstly, EU member states must adopt measures to limit carbon emissions and the carbon incorporated in products based on European standard EN 15978 and Level(s) framework [5, 25, 41]. The use of wooden buildings as carbon sinks or carbon sequestration is gaining momentum in the five investigated countries based on the evolving regulatory landscape [42]. Carbon emissions from heating are already very low in Sweden, Denmark, the Netherlands, and Finland due to district heating and heat pumps. France has recently adopted a new regulation that prohibits using gas as a source of heating in new households and is encouraging reversible heat pumps across the country.

Secondly, circularity criteria for buildings should not be treated in isolation from carbon neutrality. The circularity criteria must be coupled to carbon footprint reduction measures. As a consequence, timber construction materials and biosourced insulation materials will be in great demand. The current supply chain of timber is already under pressure, and the availability of wood sourced from sustainably managed forests will not be enough to meet the European demand. Moreover, the number of trained workers who can deliver timber construction projects is not enough. The training of professionals, including architects, masons, electricians, and plumbers, will require significant investments to prepare them to design and build timber constructions.

Thirdly, the EU member states must increase the share of recycled and reused construction waste and the possibility of separating the materials for future reuse. Timber and biosources materials will not cover the demand/supply during the coming 20 years. Also, none of the investigated countries addressed this matter thoroughly. Therefore, increasing the share of recycled and reused construction materials can help during the transition towards timber constructions. EPDs can facilitate the decision-making of architects and design teams while keeping the embodied carbon low.

Finally, this research's strengths are centered on reviewing carbon neutrality and the circularity of buildings together. The exhaustive analysis of the state of the art, regulation, and legislation resulted in selecting and ranking five leading member states incorporating the circular economy in buildings. At the same time, the research provides a snapshot and status quo analysis of a very dynamic field. The European housing market is under pressure to produce more and more housing units. There is already a housing supply gap in Europe. Most leading EU states are stopping the urbanization of land and setting limits for urban sprawl. The circularity and carbon neutrality paradigms will intensify this challenge of building sustainably.

We imagine it will be outdated very soon once this paper is published. Besides, the analysis is mainly quantitative and is not based on case studies or quantitative research approaches. However, this article aims to help researchers, the EU commission, and member states take the lead in legislation and regulation to embed circularity and carbon neutrality in buildings. The paper brings perspectives regarding the regulatory landscape of the construction sector in Europe. Future research should update our review and focus on case studies and a detailed dynamic LCA approach to assess carbon neutrality and circularity.

6. Conclusions

The three Nordic countries (Denmark, Finland, and Sweden) are leading the way in implementing policies and regulations that reduce the carbon footprint and incorporate the circular economy principles in the building construction sector. The five investigated countries implementing ambitious measures to reduce the environmental impact of buildings operation and materials use. However, our study found a separation between carbon neutrality targets and circularity targets. Integrating both targets in future building regulations is fundamental to reducing buildings' overall carbon and environmental footprint. The quantification of carbon neutrality and circularity targets through measurable indicators and critical performance thresholds is the key to accelerate the market uptake and inform policies and decision making.

7. Acknowledgments

The authors would like to express their thanks to Greg Vendena, Architect, and Danish Collaborative at the International Living Future Institute, for sharing his insights on Denmark's policies and best practices. Also, we acknowledge the Sustainable Building Design (SBD) Laboratory at the University of Liege for the operationalization of study variables and systematic reviews. The lab provided valuable support during the data collection and data analysis.

8. References

[1] eceee. EU Parliament votes in favour of cutting emissions 60% by 2030 [Internet]. European

Council for an Energy Efficient Economy. 2020 [cited 2020 Oct 23]. Available from: https://www.eceee.org/all-news/news/news-2020/eu-parliament-votes-in-favour-of-cutting-emissions-60-by-2030/

[2] EC. In focus: Energy efficiency in buildings [Internet]. European Commission; 2020 [cited 2020 Oct 23]. Available from: https://ec.europa.eu/info/news/focus-energy-efficiency-buildings-2020-feb-17_en#:~:text=Collectively%2C%20buildings%20in%20the%20EU,%2C%20usage%2C%20renovation%20and%20demolition.

[3] WGBC WGB. Bringing embodied carbon upfront: Coordinated action for the building and construction sector to tackle embodied carbon [Internet]. London: World Green Building Council; 2019 [cited 2020 Aug 25] p. 1–35. Available from: https://www.worldgbc.org/sites/default/files/WorldGBC_Bringing_Embodied_Carbon_Upfront.pdf

[4] Pombo O, Rivela B, Neila J. Life cycle thinking toward sustainable development policy-making: The case of energy retrofits. J Clean Prod. 2019 Jan; 206:267–81.

[5] EN 15978. Sustainability of construction works–Assessment of environmental performance of buildings–Calculation method. Bruss Belg Eur Comm Stand. 2011;

[6] Attia S. Net zero energy buildings (nzeb). 1st edition. Cambridge, MA: Elsevier; 2018.

[7] Belussi L, Barozzi B, Bellazzi A, Danza L, Devitofrancesco A, Fanciulli C, et al. A review of performance of zero energy buildings and energy efficiency solutions. J Build Eng. 2019 Sep;25:100772.

[8] Tallini A, Cedola L. A review of the properties of recycled and waste materials for energy refurbishment of existing buildings towards the requirements of NZEB. Energy Procedia. 2018 Aug;148:868–75.

[9] Pasanen P. The embodied carbon review Embodied carbon reduction in 100+ regulations & rating systems globally. 2018; Available from: https://www.oneclicklca.com/embodied-carbon-review/

[10] Tagliapietra S, Zachmann G, Edenhofer O, Glachant J-M, Linares P, Loeschel A. The European union energy transition: Key priorities for the next five years. Energy Policy. 2019 Sep;132:950–4.

[11] Passer A, Lasvaux S, Allacker K, De Lathauwer D, Spirinckx C, Wittstock B, et al. Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries. Int J Life Cycle Assess. 2015;20(9):1199–1212.

[12] Attia, S. (2018). *Regenerative and positive impact architecture: Learning from case studies*. Springer International Publishing, New York, USA. ISBN 978-2930909004, https://doi.org/10.1007/978-3-319-66718-8.

[13] Cambier C, Galle W, De Temmerman N. Research and Development Directions for Design Support Tools for Circular Building. Buildings. 2020;10(8):142.

[14] Durmisevic, E. Reversible Building Design: Reversible Building design guidelines [Internet]. University of Twente; 2018 [cited 2020 Oct 26]. Available from: https://www.bamb2020.eu/wp-content/uploads/2018/12/Reversible-Building-Design-guidelines-and-protocol.pdf

[15] Antonini E, Boeri A, Lauria M, Giglio F. Reversibility and durability as potential indicators for

Circular building Technologies. Sustainability. 2020;12(18):7659.
[16] Cottafava D, Ritzen M. Circularity indicator for residentials buildings: Addressing the gap between embodied impacts and design aspects. Resour Conserv Recycl. 2020;164:105120.
[17] Attia S, Al-Obaidy M. Design criteria for circular buildings. In: Crossing Boundaries Parkstad. Parkstadt, The Netherlands: Zuyd Uninversity; 2021.
[18] Attia S. Towards regenerative and positive impact architecture: A comparison of two net zero energy buildings. Sustain Cities Soc. 2016; 26:393–406.
[19] Sheppard R. Potential for Denmark as a Circular Economy: A Case Study From: Delivering the Circular Economy - a Toolkit for Policy Makers [Internet]. Ellen Macarthur Foundation; 2015 [cited 2020 Jan 11] p. 1–134. Available from: https://books.google.be/books?id=HgwBkAEACAAJ
[20] Blocks, B., & Society, L. (2017). Transition Towards 2030 NB ! Transition Towards 2030. June
[21] Karhu J, Linkola L. Circular Economy in the Built Environment in Finland - A case example of collaboration. IOP Conf Ser Earth Environ Sci. 2019 Sep 2;297:012–24.
[22] Kuittinen M. Method for the whole life carbon assessment of buildings. :60.
[23] Sánchez Cordero A, Gómez Melgar S, Andújar Márquez JM. Green building rating systems and the new framework level (s): A critical review of sustainability certification within Europe. Energies. 2020;13(1):66.
[24] RE2020 : Une nouvelle étape vers une future règlementation environnementale des bâtiments neufs plus ambitieuse contre le changement climatique. 2020.
[25] De Valk E, Quik JT. Eenduidig bepalen van circulariteit in de bouwsector. 2017 [cited 2020 Oct 21]; Available from: http://rivm.openrepository.com/rivm/handle/10029/620930
[26] Bepalingsmethode Milieuprestatie Gebouwen en GWW-werken. 2019; Available from: https://milieudatabase.nl/wp-content/uploads/2019/05/SBK-Bepalingsmethode-versie-3.0-1-januari-2019.pdf
[27] Høibye L, Sand H. Circular Economy in the Nordic Construction Sector [Internet]. Nordic Council of Ministers; 2018 [cited 2020 Oct 21]. (TemaNord). Available from: http://urn.kb.se/resolve?urn=urn:nbn:se:norden:org:diva-5166
[28] Wannerström A. Färdplan för fossilfri konkurrenskraft Bygg- och anläggningssektorn [Internet]. 2018. Available from: https://vpp.sbuf.se/Public/Documents/ProjectDocuments/80d42431-39fa-4c59-9e35 c6cbab45037b/FinalReport/SBUF%2013474%20Färdplan_Bygg_Anläggningssektorn.pdf
[29] Lewis M. Building Materials - Impacts and Transparency. 2020;31.
[30] Ejs L. Byg Cirkulært, Miniguide. 2019; Available from: https://www.circularitycity.dk/wp content/uploads/2019/11/Håndværker-Toolkit.pdf
[31] Klimarådet. Kendte veje og nye spor til 70 procents reduktion - retning og tiltag for de næste ti års klimaindsats i Danmark. Klimarådet;
[32] Bruce-Hyrkäs T, Pasanen P, Castro R. Overview of Whole Building Life-Cycle Assessment for Green Building Certification and Ecodesign through Industry Surveys and Interviews. Procedia CIRP. 2018;69:178–83.
[33] Gaëta R, Guldner L, Piton F, Priem L, Thiébaut A. Vers une réglementation environnementale pour les bâtiments neufs. Ann Mines - Responsab Environ. 2018;N° 90(2):55.
[34] Attia S, Eleftheriou P, Xeni F, Morlot R, Ménézo C, Kostopoulos V, et al. Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe. Energy Build.

2017;155:439–458.
[35] MilieuPrestatie Gebouwen - MPG [Internet]. 2020. Available from: https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/wetten-en regels/nieuwbouw/milieuprestatie-gebouwen
[36] CBS. 12,5 duizend woningen door transformatie van gebouwen in 2019. 2020 Oct 29;1.
[37] van Oppen C, Bosch S, Circulair inkopen in 8 stappen, Copper8, Amsterdam, The Netherlands, 2020.
[38] Boverket. Miljöindikatorer. 2019;37.
[39] Riksdagsförvaltningen. "Förordning (2015:517) Om Stöd till Lokala Klimatinvesteringar Svensk Författningssamling 2015:2015:517 T.o.m. SFS 2019:526." Riksdagen [Internet]. 2014. Available from: https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk forfattningssamling/forordning-2015517-om-stod-till-lokala_sfs-2015-517
[40] Høibye L, Sand H. Circular Economy in the Nordic Construction Sector [Internet]. Nordic Council of Ministers; 2018 [cited 2020 Oct 21]. (TemaNord). Available from: http://urn.kb.se/resolve?urn=urn:nbn:se:norden:org:diva-5166
[41] Kuittinen, M., & Häkkinen, T. (2020). Reduced carbon footprints of buildings: new Finnish standards and assessments. Buildings and Cities, 1(1).
[42] Amiri, A., Ottelin, J., Sorvari, J., & Junnila, S. (2020). Cities as carbon sinks—classification of wooden buildings. Environmental Research Letters, 15(9), 094076.

Chapter 02. *A Parametric Approach to Optimizing Building Construction Systems and Carbon Footprint: A Case Study Inspired by Circularity Principles* - *Journal paper*

Abstract: There is a global call for a paradigm shift in the construction industry towards carbon neutrality, but a scant effort has been made in practice, especially concerning circularity. This paper helps bridge the gap by introducing a parametric approach to optimize sustainable construction design. The methodology was tested on a newly constructed office building inspired by circularity principles in Westerlo, Belgium. The methodology consists of parametric construction-typological analysis, automated through One Click LCA software (Life Cycle Assessment) and Microsoft Excel with 21 alternate designs and 630 iterations. The parametric variations involved three key performance indicators: construction system, materials' environmental impact, and materials reuse of content. The environmental effects of both construction systems (i.e., structural system, foundation type, materials, and envelope details) and reused building material content (i.e.,) were evaluated by the parametric analysis for four construction systems scenarios. Environmental impact analysis for timber, steel, concrete, and hybrid construction systems was conducted, following ISO 14040 and CEN/TC 350 standards. The focus of the whole life cycle assessment was mainly on carbon neutrality. Results indicate that using local bio-sourced materials, including timber, can remarkably reduce buildings' environmental impact. The sensitivity analysis results provide hard evidence that the construction material's weight, materials reuse potential, and construction dismantling ability are the most influential factors in carbon-neutral buildings. This paper should improve professionals' understanding of the impact of different structural system choices and inform building designers about the circularity potential and carbon footprint of construction technologies.

Role of Ph.D. candidate: As first author, the Ph.D. candidate conceived the study (conceptualization, Lead) and specified the modelling and LCA scope (methodology, Lead). I implemented the parametric model and assembled datasets (software/resources, Lead), executed scenario runs and curated inputs/outputs (investigation/data curation, Lead), undertook sensitivity/robustness checks (formal analysis, Lead), prepared figures and dashboards (visualization, Lead), and authored the manuscript draft (writing – original draft, Lead). Co-authors provided supervision and writing – review & editing (Equal).

Journal: Sustainability (MDPI)

Journal impact factor: Current Impact Factor: 3.3

5-Year Impact Factor: 3.6

Citations: Google Scholar: 90

Reference: Al-Obaidy, M., Courard, L., & Attia, S. (13 March 2022). A Parametric Approach to Optimizing Building Construction Systems and Carbon Footprint: A Case Study Inspired by Circularity Principles. Sustainability, 14(6), 3370. https://doi.org/10.3390/su14063370 & https://hdl.handle.net/2268/288904

sustainability

MDPI

Article

A Parametric Approach to Optimizing Building Construction Systems and Carbon Footprint: A Case Study Inspired by Circularity Principles

Muheeb Al-Obaidy [1,*], Luc Courard [2] and Shady Attia [1]

1 Sustainable Building Design Laboratory, Department Urban and Environmental Engineering, Faculty of Applied Science, Université de Liège, 4000 Liège, Belgium; shady.attia@uliege.be
2 GeMMe Building Materials, Department Urban and Environmental Engineering, Faculty of Applied Science, Université de Liège, 4000 Liège, Belgium; luc.courard@uliege.be
* Correspondence: muheeb.al-obaidy@uliege.be; Tel.: +32-4-366-95-69

Abstract: There is a global call for a paradigm shift in the construction industry towards carbon neutrality, but a scant effort has been madein practice, especially concerning circularity. This paper helps bridge the gap by introducing a parametric approach to optimize sustainable construction design. The methodology was tested on a newly constructed office building, inspired by circularity principles, in Westerlo, Belgium. The methodology consists of parametric construction-typological analysis, automated through One Click LCA software (Life Cycle Assessment) and Microsoft Excel with 21 alternate designs and 630 iterations. The parametric variations involved three key performance indicators: construction system, materials' environmental impact, and materials; reuse of content. The environmental effects of both construction systems (i.e., structural system, foundation type, materials, and envelope details) and reused building materials content (i.e.,) were evaluated by the parametric analysis for four construction systems scenarios. Environmental impact analysis for timber, steel, concrete, and hybrid construction systems was conducted, following ISO 14040 and CEN/TC 350 standards. The focus of the whole life cycle assessment was mainly on carbon neutrality. Results indicate that using local biosourced materials, including timber, can remarkably reduce buildings' environmental impact. The sensitivity analysis results provide hard evidence that the construction material's weight, materials reuse potential, and construction dismantling ability are the most influential factors in carbon-neutral buildings. This paper should improve professionals' understanding of the impact of different structural systems choices and inform building designers about the circularity potential, and carbon footprint of construction technologies.

Keywords: circular building; environmental impact assessment; life cycle analysis; multicriteria approach; timber construction; carbon emissions

check for updates

Citation: Al-Obaidy, M.; Courard, L.; Attia, S. A Parametric Approach to Optimizing Building Construction Systems and Carbon Footprint: A Case Study Inspired by Circularity Principles. *Sustainability* **2022**, *14*, 3370. https://doi.org/10.3390/su14063370

Academic Editors: Elie Azar, Mounir El Asmar and Caggiano Antonio

Received: 17 February 2022
Accepted: 9 March 2022
Published: 13 March 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

The building sector is a significant contributor to resources exploitation and carbon footprints. According to the Ellen MacArthur Foundation [1], the global consumption of material resources will reach 90 billion tons by 2050 (up 125% since 2010), exceeding all levels that the planet can sustainably provide. Thus, by 2050, 50% of the carbon emissions in the construction sector will come from new buildings [2]. The principles of circularity for the sustainable design of buildings aim to facilitate the durability of construction materials and building elements to reduce the environmental impact [3]. However, implementing resource efficiency concepts and the circular economy to buildings is not widespread [4,5]. The architectural, engineering, and construction (AEC) industry faces several dilemmas concerning structural resistance, elements longevity, ease of disassembly, flexibility, simplicity of products composition, etc. Within the context of the Circular Building: *'t Centrum* project, this article presents the results of a case study for an office building located in Westerlo, Belgium.

The provincial *Center for Sustainable Building & Living Kamp C* of the city of Antwerp developed the first circular building in Belgium. The building is carbon neutral and integrates the circularity principles serving as an accelerator for modular and circular construction. The building's inauguration will occur in March 2022, and the building is planned to be dismantled and re-assembled three times by 2037, every time on a new site next to the original location. The idea of the re-deconstruction is to evaluate the adaptability, durability, ability to reuse the structural elements to reduce waste and facilitate high-quality building elements tracing and management.

Therefore, this paper aims to inform and support actors along with the AEC industry and the construction materials value chain. The article aims to answer three main research questions:

1. How to evaluate resource efficiency and the circular economy concepts applied in this building?
2. What makes a construction system carbon neutral and resource-efficient?
3. To what extent can the design of an office building apply principles of circularity in construction?

1.1. State-of-the-Art Research on Circularity and Environmental Impact

For the last 20 years, an increasing number of scientists have been using the terms 'circularity' or 'regenerative' in the domain of sustainable construction [3]. According to the Ellen MacArthur Foundation, the circular economy principles promote the regeneration of natural systems, keeping products and materials in use as long as possible, removal of pollution and waste [6]. The overarching aim of circular economy is to encourage the transformation towards a sustainable environment and positive impact buildings.

Since 2000, several European initiatives and projects have been conducted to define and promote circularity in the built environment and develop key performance indicators [7]. As part of the Buildings As Material Banks (BAMB) project, 15 partners from seven European countries developed a materials passport for buildings [8] and a framework for reversible building design [9]. However, the question remained on how to use quantifiable key performance indicators that can assist the design decision process [10]. The mandatory entry of Environmental Product Declarations (EPD) in 2018 across Europe helped to provide an objective and consistent method to evaluate building material impact [11] based on Life Cycle Assessment (LCA) [12]. The introduction of EPD played an important role in closing the knowledge gap to evaluate construction materials, products, and building elements [13]. For example, Cambier et al. [14] developed a design decision support tool for circular building design. The tool is based on the Design for Disassembly (DfD) principles (ISO20887) [9] to ease the deconstruction processes and procedures through planning and design [15]. In addition, the latest publications on the European voluntary reporting framework to improve the sustainability of buildings (Level(s)) [16] is a new tool to guide design teams, contractors, and builders. However, it remains challenging to evaluate the circularity of buildings, despite the proliferation of circularity evaluation indicators and technologies and methods that aim to extend buildings' service life to closing material loops in the construction sector [17]. There are recommendations that the EU Member States should develop national strategies or roadmaps to implement circular economy CE [18]. Considering the adoption of CE transformation action plans due to the different socio-economic conditions in the individual countries [19].

In summary, the knowledge gap remains wide on implementing and evaluating the concepts of resource efficiency and the circular economy for buildings. Several steps have been taken to evaluate circularity and carbon neutrality in the building sector.

1.2. Application of Different Construction Systems and Materials

Many building materials are used in construction, such as timber, steel, concrete, and masonry. Each material has different costs, weight, strength, durability, and circularity, suitable for specific applications. The choice of construction materials is based on cost and effectiveness in resisting the loads acting on the structure.

Around 40% of global carbon dioxide emissions, which reached 31 billion tons in 2021, are associated with the construction sector [20]. Embodied energy is another concern that can reach 60% during a building's life cycle [21]. To promote CE principles in the construction sector, The European Commission EC and the EU member states are looking forward to having a CE by 2050 and being halfway to achieving this critical goal by 2030 [17]. The building industry has a central role in responding to climate emergencies, and addressing upfront carbon is an urgent and essential focus [22]. Therefore, calls began to design low-carbon buildings and reduce construction with materials that do not meet the needs of circular design. For example, among others, the French government has announced a plan requiring that newly constructed public buildings need to be built from at least 50% timber or other natural materials by 2022, according to France Press Agency [23]. The new RE2020, the French building energy performance regulation, proposes a threshold of 100 kg of CO_2 per m^2 for embodied carbon emission, favoring biobased materials and timber [24].

The embodied energy of common construction materials such as timber, steel, or reinforced concrete is one of the critical topics currently researched worldwide thanks to the ever-growing concern on Sustainability and CO_2 emissions reduction in the construction domain [25]. There is a gradual shift towards replacing construction systems materials with materials that are more sustainable, circular, and less carbon-emitting, and from here, the idea of this study came to compare different construction system materials (timber, steel, concrete, and hybrid) to prove that.

1.3. Objective

According to the Ellen MacArthur Foundation [26], there are three principles of the CE, all driven by design:

1. Eliminate waste and pollution; it is crucial to consider waste and pollution as flaws in the design, not as inescapable by-products of the things that we make.
2. Circulate products and materials; making and designing things to last forever is not the only solution; the products can be designed to be reusable at their highest value.
3. Regenerate nature; we can boost the natural resources by returning nutrients to the soil, where everything will feed something else.

In this context, the study aims to support the early design decision-making of design teams, including architects and structural engineers, to select a building's construction system inspired by circularity principles. The choice of constructive and structural systems, such as columns, beams, and slabs, is crucial to upgrade the reuse cycles in the future, considering the rest of the building elements, such as the building envelope and others. Demountable construction systems can make it easier to dismantle the constructions and recover, upgrade, modify, or transform building materials. The paper propses a new workflow to integrate environmental performative considerations for choosing materials in a design process, which can be easily expanded to more detailed and specific studies and applied to existing parametric tools and design software. In this context, the study aims to:

- Support the early design decision-making.
- Evaluate the circularity principles in timber construction.
- Adopt a parametric analytical approach to evaluate and compare different structural materials.
- Providing recommendations for circular building design for mid-size (above 1000 m^2) office buildings.

In terms of context, this study focuses on the office buildings, which is considered a first step to realize and evaluate the circularity principles in Belgium in a practical way. This study shares the results of a parametric analytical approach to evaluate and compare different structural materials and systems during early design stages and specifically during the design decision-making process and design iterations regarding the selection and choice of construction systems and building material to bring circularity principles forward in design. This workflow is exemplified by examining the relationship between various building design parameters, environmental impact, and global warming potential. Following a parametric approach, this study investigates whether a circularity-inspired and environmental performance design approach can achieve a low carbon-emitting building. Moreover, it provides an overview of and recommendations for circular building design in Belgium.

The central hypothesis in this work is that the performative aspects of the building can be improved by applying a parametric approach to the building design parameters and choosing materials. The description of this workflow will be addressed in the following sections with the test of this hypothesis, defining its main findings and discussing them.

2. Methodology

2.1. Analytical Approach

Hypothetical models for performative evaluation have been applied with different construction systems (see Section 1.2). These models will increase the analytical exploration variability through the parametric evaluation approach. This study is based on performance predictions of the different construction systems conducted using validated simulation engines. For this study, besides the original design of the *'t Centrum* project mainly constructed in timber, three more models were designed representing the different construction systems of the same project to do the life cycle assessment: concrete construction, steel, and hybrid. For each construction system, a detailed evaluation has been done of the material's life cycle, total energy demand, and daylight performance. As shown in Figure 1, the analytical sequence is started by following the input of the fixed parameters (i.e., energy simulation parameters, materials data). Comparisons of the various construction systems environmental impact are made based on life cycle analysis requirements of ISO 14040, 14044, and CEN 15978 standards [27–29] with a focus on carbon neutrality by using One Click LCA software [30] according to TOTEM tool [31] indicators and MMG method [32]. The energy performance simulation has been started via EnergyPlus [33] and EPB [34] software for the different construction systems. 3D modeling has been made by Building Information Modeling (BIM) software Autodesk Revit® 2021. One-Click LCA plug-in was used for the materials inventory, SketchUp software has been used to visualize the building details. All results have been exported to Excel for post-processing and visualization. Then, all selected input parameters have been automated. Performance outputs are recorded for 21 alternate designs and simulation scenarios with 630 iterations in total. Regarding the calculation period, the four different construction systems simulate a scenario of 20 years, and other scenarios for 40 and 60 years as well to calculate the sensitivity analysis.

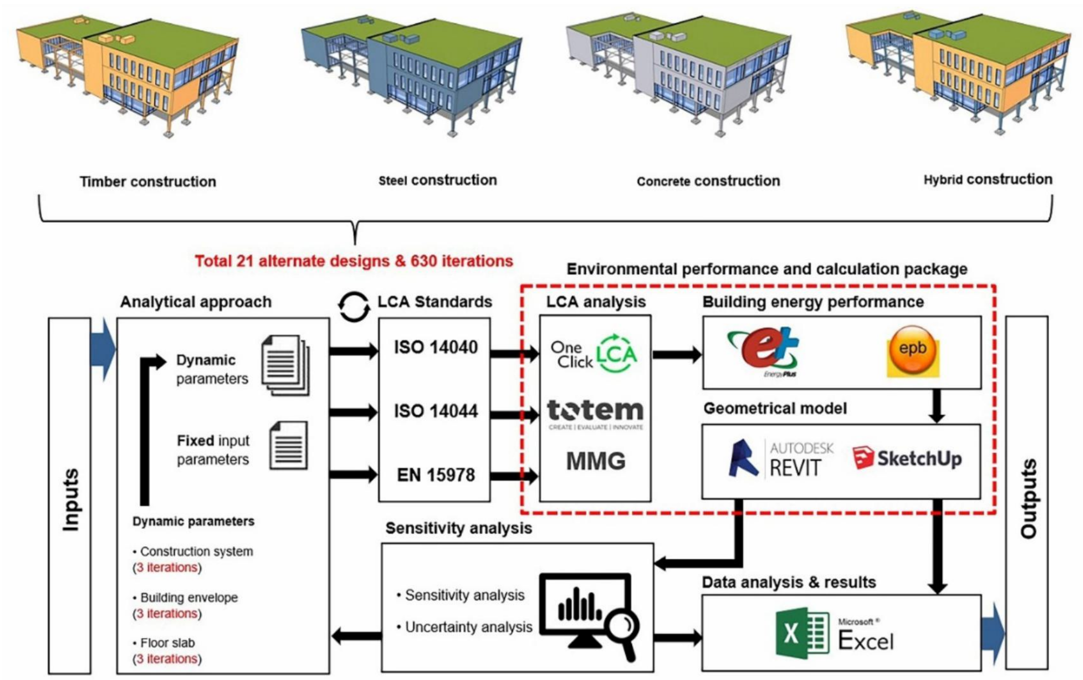


Figure 1. Analytic workflow showing the evaluation process of the different construction systems of *'t Centrum* project.

2.2. Life Cycle Standards and System Boundary

A life cycle assessment of the building construction systems took place to compare the environmental impact and CO_2 emissions according to ISO 14040 and 14044 standards [27,28]. Additionally, the CEN/TC 350 "Sustainability of Construction works" standard was used as a basis for the calculations. The indicated ISO standards provide valuable guidelines for LCA, which many researchers consider, but there is no total clarity on the data quality or the adopted system boundary [35]. LCA calculation has been done using the One-Click LCA software according to EN 15978 [29]. Figure 2 illustrates the five-building life cycle stages.

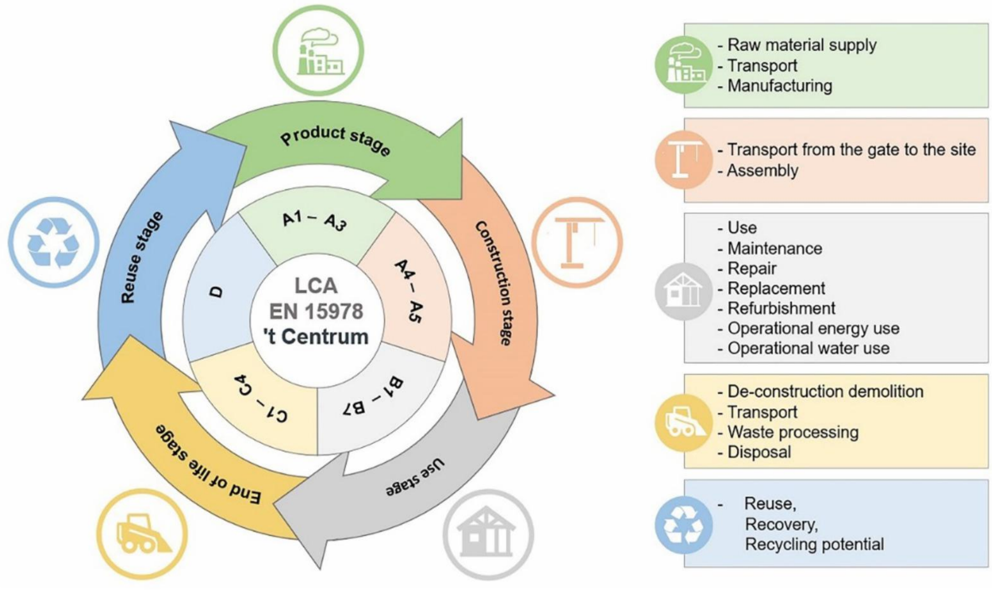


Figure 2. EN 15978 on the Sustainability of construction works.

2.3. Functional Unit Study Tools and Indicators

The LCA functional unit was 1 kg/year, and the occupancy period was estimated for 20 years. The specific nature of the project to be dismantled three times before 2037 made it essential to limit the study to 20 years to assess its durability. Life cycle assessment (LCA) was based on the EPDs of the materials and project documents provided by Kamp C consortium members. The project documents, drawings, and materials quantities allowed the environmental impact assessment to be conducted. The Global Warming Potential (GWP), including biogenic CO_2 captured during the tree's growth, was calculated [3].

Building materials' environmental impact has been evaluated using the One-Click LCA software database [36] and the collected information after contacting the manufacturers. This evaluation was verified using TOTEM tool indicators (see Section 2.6.3).

Regarding the reuse content indicator, according to Rakhshan et al. (2020), the principal identified drivers of reuse content or the building components are economical, organizational, environmental, and social. Cost is the most reported sub-category, energy and global warming, organizational sustainability, and willingness [37]. During the design stage of the new building, it is essential to consider how the building content will be reused as elements or components in multiple cycles instead of the current linear approach [38]. There are new methods for reusing content, such as design for deconstruction (DfD) [39,40], and design for manufacture and assembly (DfMA) [41]. These methods have been introduced to prevent or decrease the waste of materials during the life-cycle of buildings. On the other hand, most of the existing buildings are not designed based on these methods or techniques, which leads to a large amount of waste during the renovation or the demolition phase. Although reuse is preferred to recycling, most of the recovery of construction and demolition wastes (CDW) in the buildings happens in recycling and not reuse [37].

Next, One-Click LCA treats reused content as recycled materials, not as building elements or components such as columns, beams, floors, etc. During the life cycle assessment of the building, One Click LCA leaves the reuse content indicator for the user to be included in the total results of carbon emissions. It is often a negative value. At the same time, EN 15978 neglects the effect of replacements on the surrounding interdependent building parts [42]. Module (D) covers the net benefits and loads arising from the reused content or the recycling or recovery of energy from end-of-waste state materials. Therefore, in this study, module D was calculated with biogenic carbon storage. The project was initially designed to be dismantled and rebuilt every five years.

According to EN 15804+A2 [43], the One-Click LCA calculation method [44] uses the following equation to calculate the net benefits and loads (Equation (1)):

$$e_{module\ D1} = (M_{MR\ out} - M_{MR\ in})\left(E_{MR\ after\ EoW\ out} - E_{VMSub\ out} \cdot \frac{Q_{R\ out}}{Q_{Sub}}\right) \quad (1)$$

where ($M_{MR\ out}$) presents the amount of scrap content exiting the system, ($M_{MR\ in}$) presents the amount of scrap content fed into the system, ($M_{MR\ out} - M_{MR\ in}$) presents the net amount of scrap content produced by the system, ($E_{MR\ after\ EoW\ out}$) presents the amount of emissions, resources, and waste from material made from recycled scrap material, ($E_{VM\ Sub\ out}$) presents the amount of emissions, resources, and waste from material made from primary materials, ($Q_{R\ out}/Q_{Sub}$) presents coefficient of quality difference, where ($Q_{R\ out}$) out corresponds to material made of recycled material and (Q_{Sub}) to material made of primary material. A value of 1 can be used.

Regarding the land-use footprint indicator, buildings cause soil sealing as land remains below constructions. Soil sealing occurs when agricultural or other non-developed land is built on top of it. The removal of topsoil layers to build on top of it leads to the loss of essential soil functions, such as food production or water storage [45]. It is insufficient to limit the land-use impact assessment only to the building's location. A life-cycle of a building includes the extraction of primary raw materials, manufacturing of construction materials, construction process, use stage of building with the maintenance, production of energy over the life-cycle of a building, demolition of the building, and end of life stage [17]. The land-use footprint evaluation was based on the LCA results. One-Click LCA program helps to obtain land-use footprint as a part of its results for all different construction systems in this study.

On the other hand, the number of building occupants has been calculated according to the design brief provided by the architect, which reports that occupants are 115 persons. For every Full-Time Equivalent (FTE), a net area of 12.5 m^2 is made available following the European standard (EN 15221-6) [46].

2.4. Case Study and Input Parameters

The case study was selected based on an extensive case study review in the Netherlands and Belgium [17]. A selection list was developed, including inclusion and exclusion criteria to make sure the case study was designed following circular economy principles. Figure 3 illustrates the chosen building *'t Centrum,* located at latitude N 51.13 and longitude E 4.86 and is 14 m above sea level. Table 1 list the project consortium members inclosing the architects and builders. The building is carbon neutral and integrates the circularity principles serving as an accelerator for modular and circular construction. The building's inauguration will occur in March 2022, and the building is planned to be dismantled and re-assembled three times by 2037, every time on a new site next to the original location.

Table 1. The project consortium companies.

Architect	Design & Engineering	Structural Engineering	Constructor	Constructing with Green & Natural Elements	Geothermal Energy	EPB Reporting	Concrete Technology	Research
West Architecture	TEN-agency	Streng-th	Beneens	Muurtuin	Tenerga	VESTAD	ResourceFull	VITO

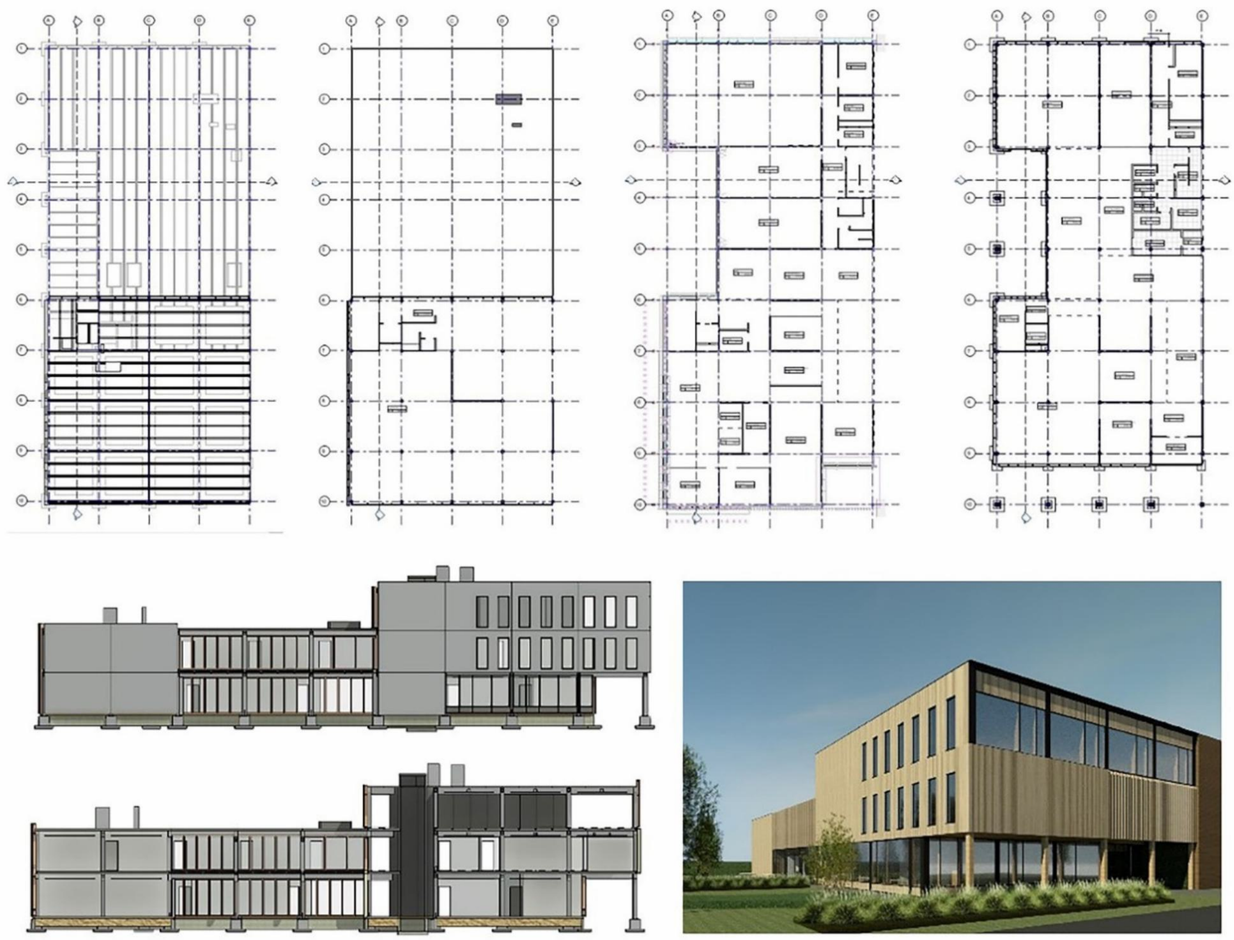


Figure 3. *'t Centrum* project drawings [47].

The building has a modular office layout and transformable workplaces. Therefore, it can be disassembled entirely when outdated. According to the Kamp C scenario, the building will be dismantled entirely during the next 20 years. The building is made from timber. A timber structure of CLT elements, manufactured by Binderholz [48], was used. The connection relies on dry fastening methods for dismountability. Ceiling, floors, and interior partitions are timber elements, using the dry adhesive method for the partitions and floor tiles fastening. The URBCON foundation technology was used to manufacture the concrete foundations of the project, a technology that guarantees the manufacture of foundations from the concrete slag provided by ResourceFull [49]. ResourceFull is a company that offers cement alternatives based on the use of secondary resources for more ecological alternatives to the construction industry. In total, 22,500 kg of secondary raw materials have been used, and 13,000 kg of CO_2 emissions have been saved compared to using other traditional foundations, according to ResourceFull [50].

For the other design options explored in this study, Figure 4 illustrates the use of three construction system materials for all building elements; steel, concrete, and hybrid. For the hybrid option, a steel structure has been used with precast concrete floors and timber envelopes. The same concrete foundations have been used for all other proposed construction systems to calculate LCA.

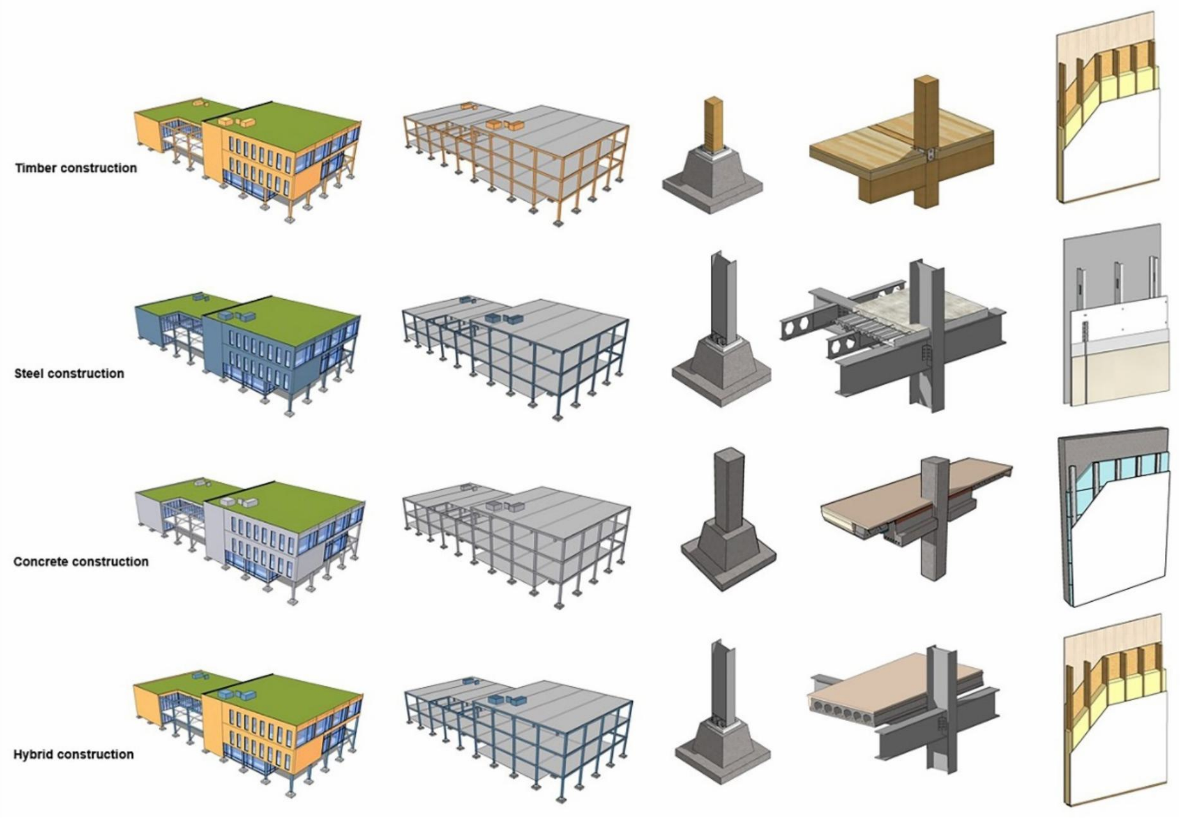


Figure 4. Visualization of the four construction systems and their building technical details.

2.5. Life Cycle Inventory

A life cycle inventory LCI was created based on EN 15978 [29] recommendations. Table 2 and Figure 5 provide a breakdown of materials elements used in the project and their environmental impact share.

Table 2. Breakdown of primary material groups based on their weight four construction scenarios.

Building Material Category	Timber Construction		Steel Construction		Concrete Construction		Hybrid Construction	
	Amount (kg)	Share (%)	Amount (kg)	Share (%)	Amount (kg)	Share (%)	Amount (kg)	Share (%)
Timber	**216,585**	**27**	×	×	×	×	12,324	0.91
Steel	2800	0.35	**312,881**	**20.65**	42,852	2.44	71,479	5.28
Galvanized steel	2210	0.28	2210	0.14	2210	0.12	2210	0.16
Concrete	**135,000**	**17**	**780,464**	**51.51**	**1,303,213**	**74.31**	**863,325**	**63.87**
Gypsum	5352	0.68	5352	0.35	×	×	×	×
Carton grey boards	8500	1.10	8500	0.56	8500	0.48	8500	0.62
Aluminium	2000	0.25	2000	0.06	2000	0.05	2000	0.07
Glass (partitions)	4500	0.57	4500	0.29	4500	0.25	4500	0.33
Glass (windows & doors)	**31,352**	**4.02**	31,352	2.06	27,452	1.56	22,400	1.65
Wall insulation (Cellulose)	5700	0.73	×	×	×	×	×	×
Wall & floor insulation (Rockwool)	3000	0.38	5300	0.35	×	×	3800	0.28
Wall insulation (Polystyrene)	×	×	×	×	2000	0.11	×	×
Roof insulation (Pavatex)	820	0.10	820	0.05	820	0.04	820	0.06
Roof insulation (Steico)	6200	0.79	6200	0.41	6200	0.35	6200	0.45
Services and cables (copper, plastic, etc.)	2000	0.25	2000	0.06	2000	0.05	2000	0.07
Floor insulation (Shells)	**353,983**	**45.40**	**353,983**	**23.64**	**353,983**	**20.18**	**353,983**	**26.19**

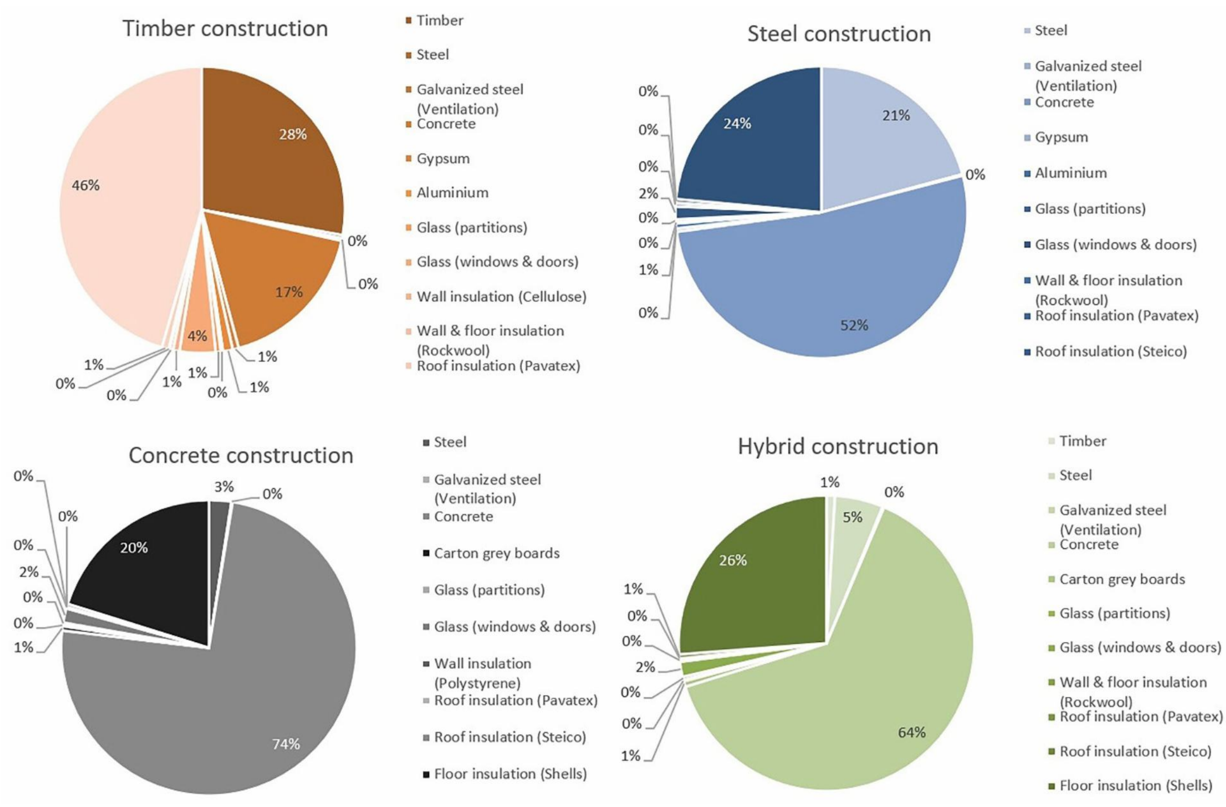


Figure 5. Weight share of the four types of structural materials percentage.

2.6. Environmental Performance and Calculation

In this section, we describe the environmental performance calculation and modeling software. All information about life cycle inventory can be found in Section 2.6.

2.6.1. Geometrical Model

In this study, 3D modeling has been made by Building Information Modeling (BIM) software Autodesk Revit. The Revit model was used and provided by the architect and Kamp C consortium members. One-Click LCA has been used to do life cycle assessments. SketchUp software has been used to show more clear details for the structure and envelope visualization.

2.6.2. Building Energy Performance Modeling

For energy simulation, EnergyPlus [33] has been used. Researchers, architects, and engineers use a whole building energy simulation program to model energy consumption such as heating, cooling, ventilation, lighting, and process loads in buildings. Antwerp weather file was selected as the closest and data-rich airport weather file to Westerlo. Antwerp falls under the Köppen-Geiger classification of temperate oceanic climate with no dry season and warm summer. Overall, Belgium's climate is mild-cold and humid, with significant rainfall during the year. Offices are typically heating- and cooling-dominated with an average of 2300 Heating Degree Days (HDD) and 45 Cooling Degree Days (2016–2020, base temperature 15 °C HDD and 24 °C CDD) [51]. Antwerp meteorological weather data for 2016–2019 were requested from the Belgian Royal Meteorological Institute [52]. The characterization of the building properties and occupant profiles was based on the input used for the Belgian EPB dynamic simulation model [34] that has been used for energy simulation in this project. The energy performance assumptions comply with the Flemish energy performance regulations for 2019, including insulation, installation, ventilation, and overheating requirements. The building is an all-electric zero energy building with three glazed facades. The ground floor is glazed with vacuum glass, and the upper floors are triple glazed. The building relies on a mechanical ventilation system with heat recovery. Six boreholes are coupled to the heat pump to meet the heating and cooling demand. Additionally, a parametric study was performed to estimate the impact of roof greening based on the work of Taleghani et al. [53]. The parametric study investigated the influence of using vacuum glass instead of triple glass and helped size the geothermal water to the air heat pump. VESTAD, the building services firm and member of the project consortium, provided their EPB report for the building envelope and installations, including the photovoltaic system. A complete study on the building energy model can be found in the master thesis of Caleys [54].

2.6.3. Building Life Cycle Analysis

Life cycle analysis was conducted with the help of One-Click LCA software. One-Click LCA allows the calculation of buildings' environmental impacts based on materials quantities [30,36]. The software allows being installed as a plug-in in Revit software. The software allows customizing the calculation according to the specificity of any geographical location, taking into account the available EPD and energy mix.

TOTEM is the second tool used to calculate the environmental impact of materials in this study. TOTEM stands for "Tool to Optimize the Total Environmental Impact of Materials" [31]. The TOTEM tool (version 1.0) was launched in Brussels on the 22nd of February 2018. Flanders started to develop this project under the Public Waste Agency of Flanders OVAM [55]. There are three main ambitions of the tool, according to Roos Servaes, 2018 [56]:

1. to analyze the environmental impact of building materials according to an objective and scientific-based evaluation method.
2. to optimize a design to reduce the environmental impact of the materials;
3. to support the architects, clients, etc., to decide in the design stage.

It is worth noting that the TOTEM tool does not refer to a database specific to reused and reclaimed materials. It uses the databases available for new materials (ECOINVENT and EPD's). TOTEM does not consider the impact of the production stage for the reclaimed materials or components [57].

2.6.4. Operational Carbon Emissions

The operational carbon emission calculation was based on the Flemish minimum building requirements for the primary energy use of 2020 [58]. The *E-peil* is a score that indicates how energy-efficient a building is. The lower the *E-peil*, the more energy-efficient the building is. Therefore the project is a zero energy building [59] (Equation (2)):

$$\frac{Annual\ primary\ energy\ use}{The\ reference\ value\ of\ the\ annual\ primary\ energy\ use} \times 100 \leq E - peil \quad (2)$$

The use stage or operational energy is responsible for a considerable share of buildings' life cycle environmental impact. Most environmental impact assessments, operational energy use, and other impacts are kept unchanged during the lifespan of the building, which is 60 years according to the accredited national LCA method for buildings in Belgium TOTEM [31] and EN 15978 [29]. The energy mix in Belgium will change over the building life cycle, impacting operational energy use. Several parameters impact the operational energy use and the carbon emissions of buildings, such as policy rules, insulation level, energy equipment technology, occupant behavior, climate conditions, and energy mix [60,61].

This study relied on calculating the operating energy in the use stage during the life cycle of building on the diversity of energy mix scenarios in Belgium, as shown in Table 3. The current energy mix scenario 2020 and the future scenario of 2040 were adopted in the calculations [62,63]. Belgium is transitioning to phase out nuclear energy sources and will rely on renewables by 2060. However, during the transition period, natural gas will be used. Therefore, we focused our study on a calculation interval of 20 years during the next 60 years. As shown in Figure 6, another future energy mix scenario for the years 2060 and 2080 was proposed based on the future indicators of energy production in Belgium. There are no data yet available on the energy mix in Belgium from 2050 onwards [64].

Nuclear radioactive waste has been considered in Belgium's 2020 energy mix scenario. Radioactive waste is classified into three categories: A, B, or C as follows:

1. A: low- and intermediate-level short-lived waste (working clothes, gloves, safety shoes, masks, laboratory waste, etc.).
2. B: low- and intermediate-level long-lived waste (residual products from the processing of fuel, filters from the primary cooling circuit, etc.).
3. C: high-level waste (irradiated fuel).

According to ENGIE Electrabel [65], the total amount of nuclear waste per person per year (category A, B, and C combined) corresponds to 0.5 kg. Therefore, it was imperative to provide the project with 100% green electricity during its lifespan. The project relies on an off-site 100% green electric energy provider named the *Vlaams Energiebedrijf VEB* [66]. VEB is an energy company approved by the Flemish government to supply green electricity and natural gas to all public services and supervise energy efficiency projects [67].

Table 3. kg CO_2 emissions according to Belgium's current and future energy mix scenarios for the four different construction system materials.

Construction System	Calculation Period	CO_2 Emissions		
		Embodied	Operation	Total
Timber	20 years	−385,810	323,448	−62,362
	40 years	−507,077	646,895	244,528
	60 years	−628,344	970,343	487,609
Steel	20 years	542,269	323,448	865,717
	40 years	436,804	646,895	1,083,699
	60 years	331,794	970,343	1,302,137
Concrete	20 years	331,483	323,448	654,930
	40 years	226,473	646,895	873,368
	60 years	121,007	970,343	1,091,350

Table 3. *Cont.*

Construction System	Calculation Period	CO_2 Emissions		
		Embodied	Operation	Total
Hybrid	20 years	394,989	323,448	718,437
	40 years	289,524	646,895	936,419
	60 years	184,059	970,343	1,154,402

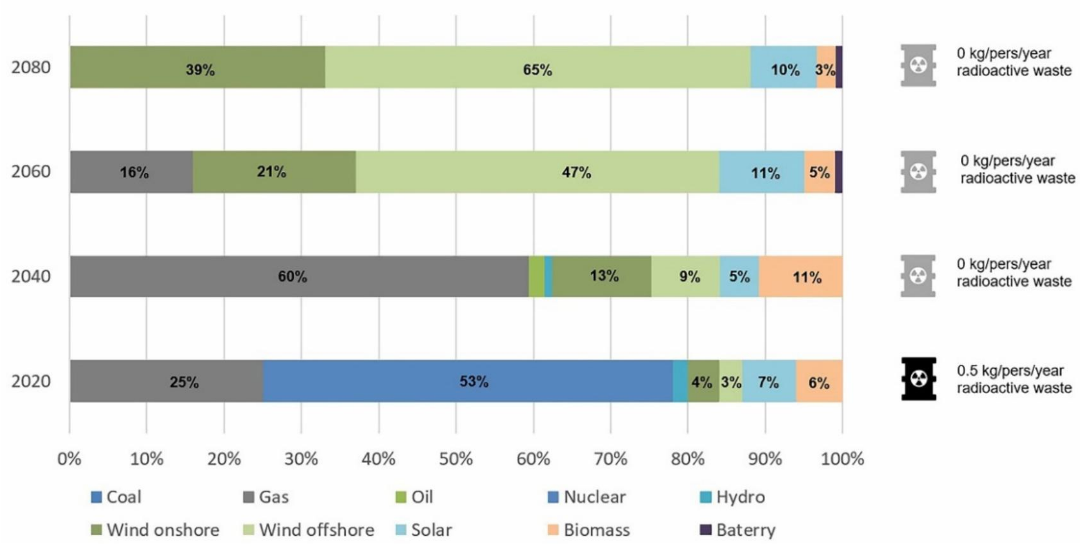


Figure 6. Current and future energy mix scenarios in Belgium [62,63].

2.7. Data Quality and Validation

2.7.1. Data Sources

Necessary data regarding the building materials and the construction system, including drawings, technical documents, and other details, were collected. Meetings and regular site visits have been done from the first stage of the project construction to the final stage to follow up the construction operation in detail. The materials specifications and the environmental impact data source have been based on the EPDs and available information on the One-Click LCA database. We compiled an open-access dataset that comprises all EPDs used in this study [68].

2.7.2. Data Quality Assessment

One-Click LCA contains two tools to record data quality in life cycle assessment. The first tool is the Plausibility Checker, which checks the plausibility of all the building material inputs to count the life cycle assessment for the project. The second tool is Completeness Checker, which checks if all required elements of the project are in place regarding the applicable standard or certification in question [69]. According to One-Click LCA and as shown in Table 4, the data Quality Policy (DQP) of One-Click LCA is explicitly designed for ensuring data fit for construction sector applications, using attributional LCA models and standardized life-cycle impact results in line with EN 15804+A2 [43].

Table 4. One-Click LCA data quality principles were implemented in this study [69].

Principle	Meaning in Practice
Availability	Revise and integrate all publicly and freely available LCA data that meet One Click LCA's Data Quality Policy (DQP).

Table 4. *Cont.*

Principle	Meaning in Practice
Plausibility (ref. EN 15978) [29]	Any market-based LCA data have to satisfy the Data Quality Policy (DQP) of One Click LCA to be included and used in the software. It covers ten steps and over 40 different checks.
Consistency (ref. EN 15978) [29]	LCA data consistency is ensured. If data include biogenic carbon storage, it is homogenized to ensure consistency of calculations (–) in One Click LCA's non-regulated LCA tools, biogenic carbon is always reported as a separate set of results to ensure transparency and clarity.
Representativeness (UN Guidelines)	All data are comprehensively classified on geographical and time representativeness. The data are documented based on available information for technological representativeness as a textual description.
Transparency	The data are enriched with metadata and information, allowing for a better understanding of the data point and its quality.

The environmental data provided by any assessment tool should be valid regarding the time and the location. If regional data are unavailable, the factors to adapt to regional conditions can be used [70]. In addition, Figure 7 illustrates the additional measures taken by the authors to reach the highest possible degree of data verification. Figure 7 was developed based on the ISO 14040 standard and was used to self-assess the data quality and intensive our research effort were necessary. The criteria adopted in the project data quality assessment included the following:

- Credibility (verified data based on measurements, assumptions, or estimation).
- The holistic briefing (representative data from the sites relevant for the market considered, over an adequate period to even out normal fluctuations).
- Temporality (the difference of the period of the dataset).
- Geographic distance (the difference of the geographic distance that allows verification and observation to ensure the validity of the dataset).

Scores for evaluation have been set as follows; Any information based on personal observation and a recent EPD receives the highest rating . Any information based on an only recent EPD receives an average rating of ++. Any other information receives an acceptable rating +. All composite materials and elements that contain different materials have been taken with caution. In addition to the above, we have carried out a self-check to assess the data quality through the following:

1. Conducting focus group discussions and workshops.
2. Intensive contact with suppliers and visits to manufacturers to determine the stages of production and transportation methods based on self-observations.
3. Contacting members of the TOTEM database and the Belgian Building Research Institute (BBRI) members to learn more about the innovative materials used in the project and search for EPDs.
4. Conducting site observations and regular site visits of the construction site every week.

Materials	Indicators			
	Credibility	Holistic briefing	Temporal period	Geographic distance
Timber	+++	+++	+++	++
Steel	++	++	+++	+++
Galvanized steel (Ventilation)	+++	+++	++	+++
Concrete	+++	+++	+++	+++
Gypsum	+++	++	++	++
Carton grey boards	++	++	++	+++
Aluminium	+++	+++	++	++
Glass (partitions)	++	++	++	+++
Glass (windows & doors)	++	++	++	++
Wall insulation (Cellulose)	+++	++	++	+++
Wall & floor insulation (Rockwool)	++	++	++	++
Wall insulation (Polystyrene)	+	++	++	++
Roof insulation (Pavatex)	++	++	+	+++
Roof insulation (Steico)	++	+	+	++
Other plastic items	++	++	++	+
Floor insulation (Shells)	+++	++	+	+++

Key:
+++ High quality; +++ Medium quality; +++ Acceptable quality

Figure 7. Data quality assessment indicators of timber construction (Kamp C scenario).

2.7.3. Sensitivity analysis

Sensitivity analyses are used to check the impact of critical assumptions on models results [71]. Regarding sensitivity analyses, this study focused on the sensitivity of results of the most carbon-emitting material used in the building according to the construction material pyramid [72], such as; aluminum, galvanized steel, and copper, in addition to the materials that had the most significant weight share, such as timber and concrete, as a larger quantity of materials can lead to higher environmental impacts [73]. A sensitivity analysis was also conducted for the building lifespan after increasing it by 20 and 40 years, as designers often ignore the building's lifespan while it can have a significant environmental impact [74]. These parameters are considered to most affect the results regarding their environmental impact and the carbon emissions they cause (see Section 3.5).

2.7.4. Uncertainty Analysis

According to Huijbregts et al. (2003), uncertainty comes from mathematical models (model uncertainty), data uncertainty (parameter uncertainty), the output used to compare (output variable), and normative choices (scenario uncertainty) [75]. The results of a building's LCA can be affected by several uncertainty sources, mainly due to the system boundaries, the quality of the available data, and other factors [76]. In this study, uncertainty analysis addressed the materials with a large weight share in the building, such as; timber, concrete, glass, and shells insulation (see Section 3.5).

3. Results

Table 5 and Figure 8 present the carbon emissions of the four construction system scenarios. As illustrated in Figure 9, the environmental impact of construction materials also played a significant role in the life cycle assessment of the four different construction systems, (see Videos S1 and S2).

Table 5. kg CO_2 emissions (operational) for the four different construction system scenarios.

Life Cycle Stages EN 15978	Timber Construction	Steel Construction	Concrete Construction	Hybrid Construction
	20 Years Kamp C Scenario	20 Years Proposed Scenario	20 Years Proposed Scenario	20 Years Proposed Scenario
Biogenic carbon storage *	−385,086	−11,506	−11,506	−30,686
Product stage A1–A3	156,197	623,380	425,884	507,889
Construction Stage A4–A5	108,503	111,608	110,319	110,290
Use Stage B1–B7	323,448	323,448	323,448	323,448
End-of-life Stage C1–C4	34,056	8314	8223	8112
Re-use D *	−299,479	−189,527	−201,438	−200,617
Total life cycle	−62,362	865,717	654,930	718,436

* Note: One Click LCA leaves the values of Biogenic carbon storage and reuse content indicators for the user to be included in the overall results of carbon emissions.

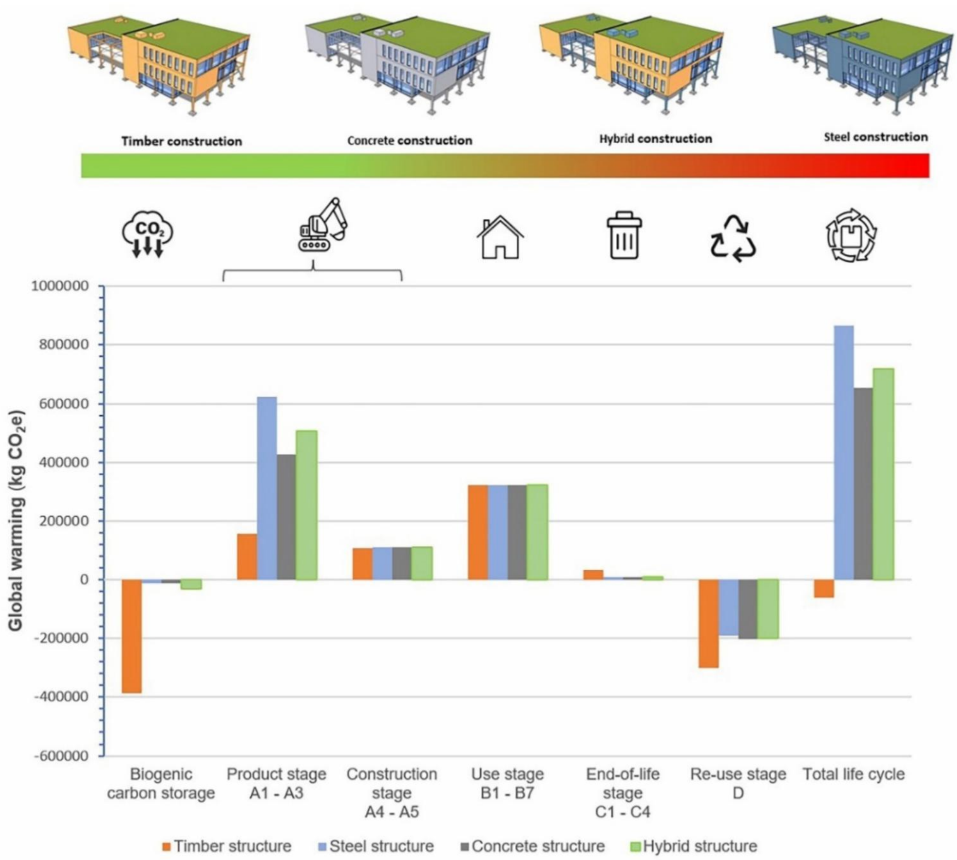


Figure 8. Comparison of the global warming potential during life cycle stages for the four different construction system materials.

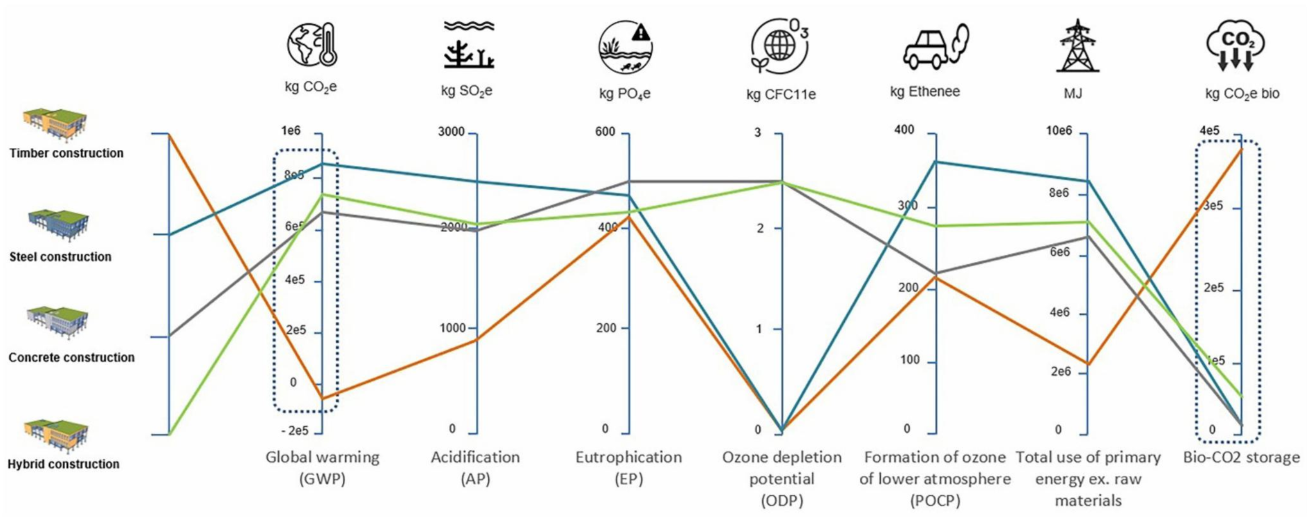


Figure 9. Parallel coordinated graph for the environmental impact of the four different construction system materials.

3.1. Environmental Impact and Carbon Footprint

Most of the building carbon emissions occur during the product stage (A1–A3). As shown in Table 5, carbon emissions in timber construction are four times less than steel construction and three times less than concrete and hybrid construction during this stage.

No significant difference was found concerning the carbon emissions during the construction stage (A4–A5) and use stage (B1–B7) for the four different scenarios. In the end-of-life stage (C1–C4), the carbon emissions of the timber construction were three times more than the other construction systems. As shown in Figure 10, the total carbon emissions indicate the effectiveness of implanting a timber construction. Biogenic carbon storage substantially affected these results favoring timber construction in this comparison.

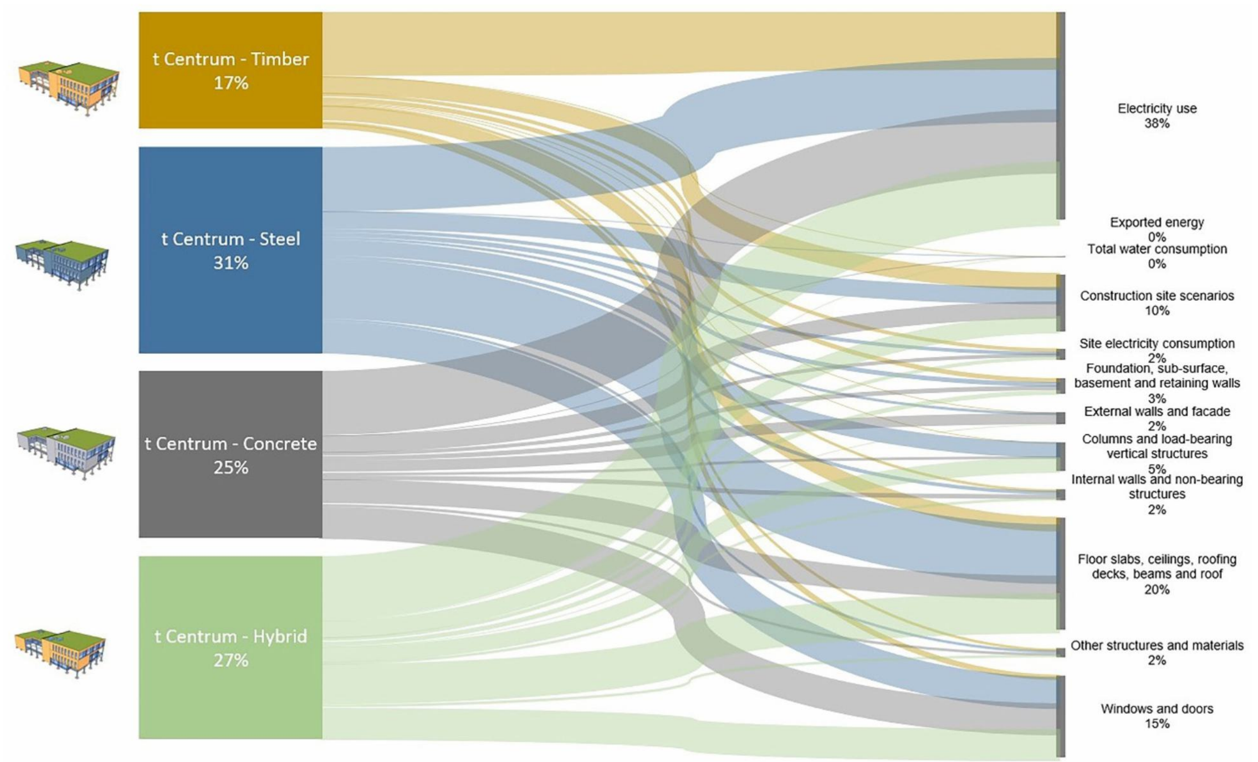


Figure 10. Comparison of the four construction systems regarding the carbon emissions according to energy usage and construction elements.

3.2. Reuse Content

One-Click LCA treats reused content as recycled materials, not as reused elements or components mentioned in Section 2.3.

According to One Click LCA, the reuse content score represents the total materials circularity in materials for the project and the end-of-life handling. It is calculated as the average of Materials Recovered (representing use of circular materials in the project) and Materials Returned (representing how effectively materials are returned, instead of disposed of or downgraded in value). The calculation is purely mass-based without material weighing.

Thus, the reused timber construction content scenario achieved a score of up to 73%, followed by 49% for the hybrid scenario, 41% for steel, and 39% for the concrete scenario. It was accompanied by a negative value of carbon emissions in timber construction reaching −299,479 kg CO_2e, while the carbon emissions resulting from the reused content in the steel, concrete, and hybrid construction reach −189,527, −201,438, −200,617 kg CO_2e, respectively.

On the other hand, regarding the realistic future scenario of *'t Centrum* project after dismantling and rebuilding it, several projects in which building elements or components were reused, such as Circular Retrofit Lab [77], Joseph Bracops Hospital [78], and the Institute of Botany in Liege university [79] were visited to evaluate the reused content. AGC glass company was visited to understand better the manufacturing process and reuse of building elements [80]. Additionally, ROTOR company that trades in reused building components was visited [81]. The evaluation of the reuse of building elements was discussed to reach a simulation closer to reality to explore and evaluate the reused content potential in the future scenario.

According to the European standard EN 15978 [29] for Life Cycle Assessment of construction products and buildings, the number of replacements for a part of the building can be obtained by applying the following equation (Equation (3)):

$$N_R\ (j) = \frac{ReqSL}{ESL(j)} - 1 \quad (3)$$

where ($N_R\ (j)$) presents the number of replacements of the part, ($ReqSL$) presents the Required Service Life of the building, and ($ESL(j)$) presents the Estimated Service Life of the part, rounded up and minus 1, to exclude the initial installation of the part at the construction of the building [29]. Therefore, the number of replacements for the main building elements during the proposed building lifespan of 20 years is 0.

To explore the reused content future scenarios and the ability for dismantling and rebuilding the building elements, we had to explore two stages:

1. Before construction will be 80% of total reuse content.
2. After the end of life will be 20% of total reuse content.

The calculation method is based on the weight of the building elements' material. The total reuse content percentage will be aggregated of these two sections. *'t Centrum* project will be dismantled and rebuilt in the future, the project aims to reuse more than 95% of its components as a material bank, taking into account a 5% material loss for LCA studies in the Belgian construction sector set [42,82]. The calculation period of this study is 20 years as a new building. Therefore, illustrated in Figure 11, the reused content before the construction is not with a large percentage, but it will be that after the end of life and the project is rebuilt in the other place. Therefore we can not call it a reused building, but we can call it a reusable building after dismantling it in the future more than once, and this is the main aim of this project, according to Kamp C [83].

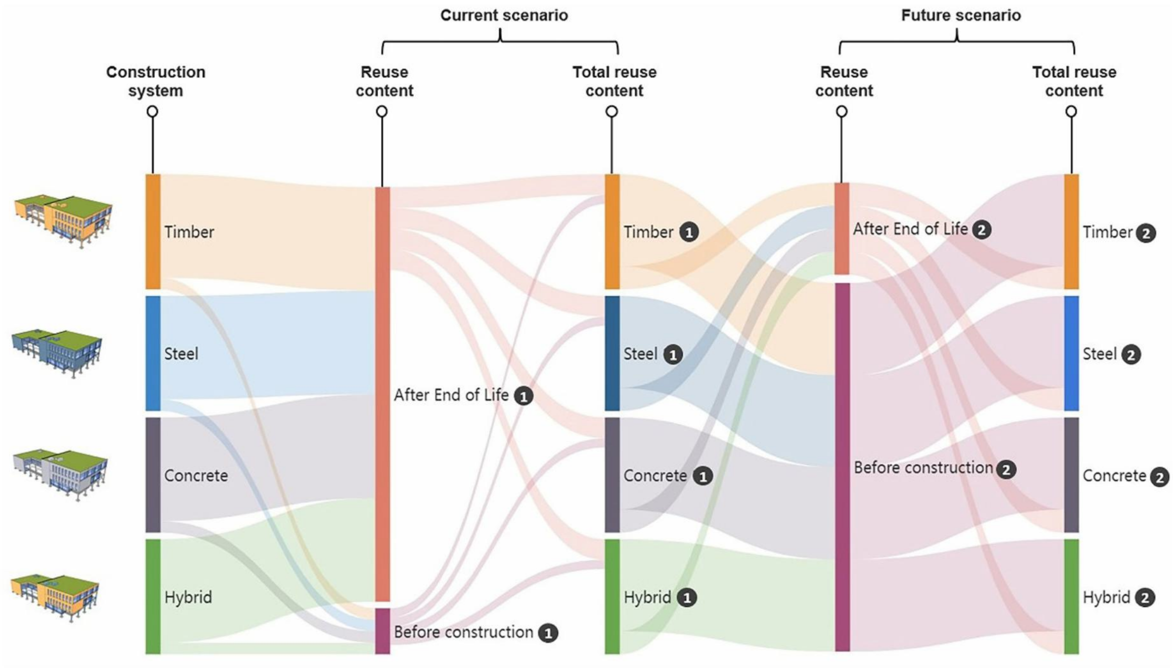


Figure 11. 't Centrum reuse content in the current and future scenario.

The results show a precise match in the reuse content indicator for the different building systems as they are designed primarily for future disassembly. Therefore, we can see that the reuse content indicator reaches approximately 25% in the current scenario as a new building, while the content reuse rate reaches up to 95% after dismantling and rebuilding.

3.3. Land Use Footprint

The land-use footprint was calculated based on the available data on the EDPs of the materials in the One-Click LCA database. In addition, from the other information of the project in general, as shown in Figure 12, the results prove the superiority of timber construction also by achieving (−1.3 kg CO_2e/m^2/year), followed by concrete (13.5 kg CO_2e/m^2/year), then hybrid (15 kg CO_2e/m^2/year), and then steel (18 kg CO_2e/m^2/ year), (see Video S3).

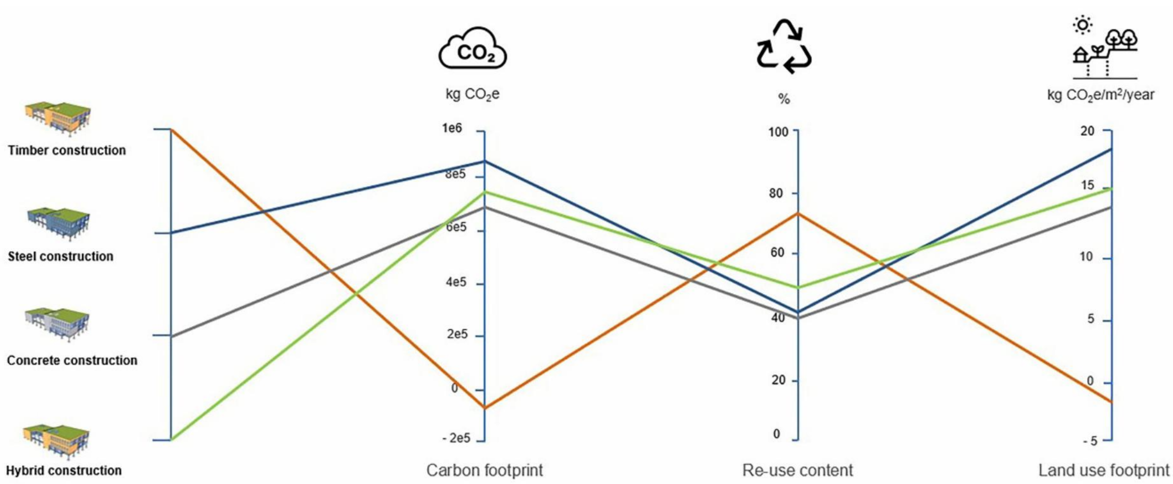


Figure 12. Comparison of the four construction systems according to the study indicators and One-Click LCA results.

3.4. Sensitivity Analysis

Sensitivity analysis can be defined as the study of how the uncertainty in the calculation and model results (outputs) can be explained and quantified by the uncertainty of the model inputs (parameters and/or boundary conditions) that are used in the study [84]. The choice of a sensitivity analysis method is based on the model complexity, computational time, required extractable information, and the usability and accessibility of the algorithm [85].

The global sensitivity approach has been considered by the use of analysis of variance (ANOVA). The good practice in sensitivity analysis and simulation that computes the intuitive Sobol first-order sensitivity index (SI) [86]. This sensitivity measure is based on the input variability and provides a value between 0 and 1. For example, an input with a SI equal to 0.75 is responsible for 75% of the output variability, and so on for the rest of the output.

Regarding this study, as illustrated in Table 6, the results are recalculated for a 10% increase/decrease in the most carbon-emitting material used in the building, such as; aluminum, galvanized steel, and copper. In addition to timber and concrete, they are the more sensitive categories of the current scenario (timber construction) and the most significant weight share of the materials after the shells insulation, which was excluded because it is a natural material and does not require manufacturing. In addition, all data and assumptions for the process parameters of building lifespan or calculation period were assessed. Specifically, the calculation period of the building was assessed in the sensitivity analysis by increasing the assumed lifespan or calculation period of 20 years by 20 and 40 years more. The sensitivity analysis results indicate that Global Warming Potential (GWP) is the most sensitive to the assumed building lifespan, with a focus on the use stage and energy consumption, where the electricity has been calculated according to the Federal Planning Bureau 2017 [63], and the Belgian energy landscape by 2050.

Table 6. Sensitivity analysis of more sensitive categories of the current scenario—timber construction.

Impact Category	Unit	Alum ± 10%	Galv. Steel ± 10%	Copper ± 10%	Timber ± 10%	Concrete ± 10%	Building Lifespan	
							+ 20 Years	+ 40 Years
Global Warming (GWP)	kg CO_2e	±0.8%	±0.9%	±0.3%	±60%	±01%	+392%	+781%
Acidification (AP)	kg SO_2e	±0.8%	±0.4%	±0.9%	±2.5%	±0.2%	+12%	+38%
Eutrophication (EP)	kg PO_4e	±0.01%	±0.01%	±0.17%	±2.7%	-	+4.3%	+15%
Ozone depletion potential (ODP)	kg CFC11e	-	-	-	±25%	-	-	+25%
Formation of ozone of lower atmosphere (POCP)	kg Ethenee	±0.02%	-	±0.02%	±7%	-	+2.8%	+21%
Total use of primary energy ex. raw materials	MJ	±1.6%	±1.4%	±1.4%	±3.8%	-	+0.4%	+65%
Bio-CO_2 storage	kg CO_2e bio	-	-	-	±8.6%	-	-	-
Land use footprint	kg CO_2e/m^2/year	±0.08%	±0.1%	±0.03%	±54%	-	+300%	+360%

Key: - No change; 0–25% increase or decrease; 26–50% increase or decrease; 51–100% increase or decrease; <100% increase or decrease.

3.5. Uncertainty Analysis

Uncertainty analysis aims to estimate the uncertainty in model results prediction without identifying which model input is responsible for this in the study. It also aims to optimize the extractable information from model output variability [84].

In this study, the uncertainty analysis focuses on the heaviest materials used in the original design or the Kamp C scenario: Timber, concrete, glass, and insulation shells. According to the Revit model, timber constitutes 27% of the building weight share, expressed in (kg or m^3). Through the EPD in the One-Click LCA database, the weight of the total timber used was calculated, with a density of 450 kg/m^3, global warming potential (A1–A3) before local compensation of 0.43 kg CO_2e/kg, and Biogenic CO_2 storage of 1.54 kg CO_2e/kg. While the project's timber specifications talk about different densities of timber such as 460 kg/m^3 and 470 kg/m^3 produced by the factory, including the types that are used in this project [87], which will not significantly affect the results of the analysis.

Regarding the concrete, the URBCON foundation technology was used to manufacture the foundations and the rest of the concrete parts of the project, a technology that guarantees the manufacture of foundations from the concrete slag provided by ResourceFull [50].

For the life cycle assessment of concrete, EPD available on the One Click LCA database was used. According to ResourceFull, 13,000 kg of CO_2 emissions has been saved compared to traditional foundations [50].

AGC glass [80] has been used in this project. In the calculation method, the weight of the glass and its environmental impact was calculated according to the One-Click database, which has a fixed thickness and may allow, in certain types, changing the thickness of the glass to obtain an analysis close to reality. With AGC glass experts in Belgium, the different weights of glass per square meter were verified, and it appeared that there are differences of 10% to 15% between the actual weight of the square meter and the weight resulting from LCA calculations.

Shells insulation is a natural material provided by Ecoschelp [88]. Despite the significant weight share of shell insulation used in the building, there is not enough information about its environmental impact and carbon emissions. The available information about shells does not indicate more than the ability of the material to be highly insulating and resist mechanical pressure. Therefore, it was considered natural and unmanufactured material collected and transported to the construction site. However, the materials were not found in the One-Click LCA database. One-Click LCA was contacted to include this type of shell insulation in its database for future use.

4. Discussion

4.1. Summary of Main Findings and Recommendations

This study implemented a multicriteria approach to evaluate a unique case study's carbon neutrality and circularity. This study focused on the carbon footprint and the reused content in addition to the land-use footprint. The most relevant parametric analysis outcomes are described below:

- Timber construction is better than other construction systems; carbon emissions of timber construction are three times less than concrete, and hybrid construction and four times less than steel construction (see Table 5).
- The biogenic carbon storage capacity of timber had the most significant effect in achieving this result based on a cradle to cradle calculation approach.
- The timber construction's carbon emissions are lower than the requirements of the new French Building Regulation RE2020, which introduces a new threshold of 4 kg CO_2e/m^2 for new buildings [24].
- According to the circularity definition, this building is not a "reused building", but we can call it a "reusable building" because the reused content before the construction is reaching 5%, but it will be 95% after the end of life and rebuilt in the other location.
- Regarding the land-use footprint, the timber construction achieved a negative value reaching (-1.3 kg $CO_2e/m^2/$year) for 20 years, unlike the other construction systems as shown in Figure 12.
- The consumption of electrical energy during the operation stage was one of the most influencing factors in increasing carbon emissions and global warming. As shown in Table 5, carbon emissions during the operational stage (B1–B7) reached 323,447.58 kg CO_2 in the original Kamp C scenario (Timber construction). The sensitivity analysis and uncertainty analysis indicate that operational energy use significantly contributes to the environmental life cycle impact, in line with studies found in the literature [89,90].

This research develops a workflow and parametric approach (see Section 2.1) to apply to several projects. Below are some recommendations for future circular building designs:

- Designers should increase the materials reused content to achieve the highest circularity value. In Belgium, for example, it is challenging to use reclaimed and reused materials because of the lack of compliance and certification of those second-life ma-

terials. The construction industry in Belgium is heavily standardized and does not encourage building designers to use reclaimed building elements or materials.
- LCA must be based on dynamic enviornmental impact characterization factors and combined with circularity principles [91]. For *'t Centrum* project a digital twin will be created to allow for a digital twins-based LCA.
- To avoid falling into the greenwashing trap, we advise not to use any material that does not have an EPD. Many industrial manufacturers claim the sustainability of new and green materials, including low-impact concrete or products that have no EPDs.
- Scientists should develop simple evaluation methods and audits for reusing building elements, which can characterize building components or structural elements based on fatigue, durability, and duration of its second or third extended life.

4.2. Strengths and Limitations of This Research

This study has developed a parametric methodology for environmental performance analysis of four different construction systems. An analytic workflow was created and applied for 21 alternate designs and 630 iterations. The strength of the parametric approach presented allowed the evaluation of four different design alternatives based on circular building design principles. The multicriteria evaluation approach provides an evaluation process used during the early design stages. By choosing and evaluating the construction materials, the study succeeded in evaluating to what extent a building is circular. The methodology brought operational carbon and embodied carbon into a whole life-cycle carbon assessment workflow by combining building energy modeling with LCA and considering changes in the energy mix affecting operational carbon. As indicated in Section 2.1 and shown in Figure 2, this methodology used tools already continuously used by researchers, engineers, and architectural companies. Using One Click LCA and Revit software with average expertise is enough to apply this methodology.

Also, a system of unique criteria was developed to reach the highest possible degree of data verification (see Figure 7). Self-checks have been done to assess the data quality through focus group discussions, workshops, intensive contact with suppliers, visits to manufacturers, personal observations, and weekly site visits to the construction site. Sensitivity and uncertainty analysis was conducted for the most carbon-emitting materials and the building's heaviest materials, as shown in Table 6. The sensitivity and uncertainty analysis allowed identify the hot spots and carbon profiles of different building materials and construction elements. Moreover, EPDs used in this study were compiled and made available in an open-access dataset [68]. Thus, the study findings align with similar studies investigating the influence of structural and construction system design on the green has house emissions [92].

On the other hand, life cycle assessment programs like One-Click LCA do not include EPDs of the new innovative materials in its databases, such as green concrete and shells insulation used in this project. Therefore, their environmental impact was calculated with caution and under high uncertainty. Additionally, the One-Click LCA program deals with reusing content based on recycling materials rather than reusing building elements, according to Module D of EN 15978. Therefore, future work should test this novel workflow to calculate the reused content as building elements or components and not recycled materials.

It is worth noting that the transportation impact associated with dismantling and re-assembling the building in this project is almost negligible because it will be done on the same project site during the following years. It is planned to dismantle and re-assemble the building three times by 2037, on a new site around 20 m away from the original location. However, in reality, the associated transportation charges will be higher because the building elements will be expected to be transported far, for example, from one city to another; therefore, they should be considered.

4.3. Future Work and Possible Applications

This study provides a novel incremental contribution to the body of knowledge on circular economy principles for buildings' design towards circular construction and carbon-neutral buildings. The workflow developed in this study could be applied to other projects in several regions and climate conditions. We believe that the future carbon tax schemes proposed by the EU can increase the market uptake of circularity principles and create a real demand for design workflows and early design decision support tools. The presented case study proves the feasibility of implementing zero-carbon buildings. The use of bio-sourced materials such as timber and hemp can make it easy to neutralize the embodied carbon emissions [93,94]. However, for the reduction in whole life carbon of buildings, operational carbon will remain the most considerable challenge to the 2050 climate target [95].On the other hand, the circularity gap is still wide. Circularity principles require further development to create simple key performance indicators for the construction sector. Despite the development of the European Frameworks for building sustainability evaluation—including Level(s)—there is a need for a rating system for circular buildings [96]. There is a need for independent certification and audits to distinguish low carbon materials from carbon-intensive materials and recycled materials from reused and reclaimed materials. Awareness should be raised regarding the difference between reclaimed materials, recycled materials, and reused content or elements. There is a real difficulty in using the reclaimed materials because they may contradict the required specifications or are not included in the database of environmental product declaration [57]. For example, the Public Waste Agency of Flanders OVAM funded a new project carried out by the Flemish Institute for Technological Research VITO. The project is a demolition guide that recognizes building materials for recycling or reuse [97]. According to Gobbo et al. (2021) [57], most environmental impact assessment tools hinge on databases of environmental declarations, which do not include any data for reclaimed materials. Therefore, many new low-impact materials/products are not found in environmental impact declarations databases. There is still a need for methods and tools to accurately calculate the reused content as elements or components when working on the life cycle assessment of the building, which can be easily combined with design modeling software. Thus, it is not easy to find a good balance between user-friendliness and the consistency of the approach, which needs to be transparent and verifiable [57].

Finally, carbon footprint and EPDs remain the most valuable tools for classifying building materials and evaluating circular projects in the future. Other LCA tools could be used and coupled with this workflow to evaluate the circularity for each scenario, thus expanding the broad environmental indicators and the circularity criteria and addressing and optimizing this workflow. This study is considered as the foundation for future work. Designers and researchers can quickly expand it to more detailed and specific studies using parametric tools. Digital twins can play a significant role in performing digital twins-based LCA. Another possible extension of this study would be developing a new tool or a plug-in to calculate the reused content as building elements, not as recycled materials, which would add a more realistic aspect to the analysis process. Also, the new standards of CEN/TC 350 [98] and ISO/TC 323 [99], which are under development, are expected to proliferate the CE principles in the construction sector and build on the EC initiatives.

5. Conclusions

As part of the EU's goals towards a circular economy, this paper presented a workflow to evaluate the impact of building materials on environmental performance. Capitalizing on the new possibilities offered by the environmental parametric tools like One Click LCA and the building information modeling BIM software like Revit, a wide range of input design parameters were systematically evaluated for four different design scenarios, timber, steel, concrete, and hybrid, with doing the energy performance simulations for the original scenario (timber construction). The results reveal a correlation between the building materials choices and the carbon emissions. The results reveal a clear superiority of wood in construction to reduce carbon emissions and achieve circularity.

The use of steel, concrete, or hybrid constructions is associated with a remarkable negative environmental impact compared to timber. According to Kamp C, the reuse content indicator showed high potential to be an effective indicator to achieving circularity in terms of reusing the content as components or elements that will be achieved after dismantling and reconstructing the building in the future. The land-use footprint indicator also confirmed the superiority of the timber construction scenario. Finally, there is a need to develop other multicriteria approaches (quantitative and qualitative) and early design workflows with general and specific indicators to evaluate the circularity.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14063370/s1, Video S1: Life Cycle Assessment; Video S2: Environmental Impact; Video S3: Performance Indicators.

Author Contributions: Conceptualization, M.A.-O. and S.A.; methodology, M.A.-O. and S.A.; software, M.A.-O.; validation, M.A.-O. and S.A.; formal analysis, M.A.-O.; investigation, M.A.-O.; resources, M.A.-O.; data curation, M.A.-O. and S.A.; writing—original draft preparation, M.A.-O. and S.A.; writing—review and editing, M.A.-O., L.C. and S.A.; visualization, M.A.-O.; supervision, S.A.; project administration, M.A.-O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The following supporting data can be downloaded at: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/Z1CS97, Environmental product declaration dataset of *'t Centrum* circular building in Westerlo, Belgium.

Acknowledgments: This publication is part of PhD research project 2020–2024 entitled: A circularity evaluation framework for office buildings design in Belgium. The authors would like to gratefully acknowledge Kamp C and the companies consortium of *'t Centrum* project for sharing information about the case study. We would also like to recognize the Sustainable Building Design (SBD) Laboratory at the University of Liege to use the circularity audits in this research and valuable support during the case study's observations and data analysis.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ellen MacArthur Foundation. Completing the Picture: How the Circular Economy Tackles Climate Change. Available online: https://ellenmacarthurfoundation.org/completing-the-picture (accessed on 9 December 2021).
2. Sánchez-Garrido, A.J.; Navarro, I.J.; Yepes, V. Multi-criteria decision-making applied to the sustainability of building structures based on Modern Methods of Construction. *J. Clean. Prod.* **2022**, *330*, 129724. [CrossRef]
3. Attia, S. *Regenerative and Positive Impact Architecture*; Springer International Publishing: Cham, Switzerland, 2018. [CrossRef]
4. Heisel, F.; Rau-Oberhuber, S. Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster. *J. Clean. Prod.* **2019**, *243*, 118482. [CrossRef]
5. Cottafava, D.; Ritzen, M. Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects. *Resour. Conserv. Recycl.* **2021**, *164*, 105120. [CrossRef]
6. Çimen, Ö. Construction and built environment in circular economy: A comprehensive literature review. *J. Clean. Prod.* **2021**, *305*, 127180. [CrossRef]
7. Al-Obaidy, M.; Santos, M.C.; Baskar, M.; Attia, S. Assessment of the circularity and carbon neutrality of an office building: The case of't Centrum in Westerlo, Belgium. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *855*, 012025. [CrossRef]
8. Honic, M.; Kovacic, I.; Rechberger, H. Concept for a BIM-based Material Passport for buildings. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *225*, 012073. [CrossRef]
9. Durmiševic, E. Reversible building design. In *Designing for the Circular Economy*, 1st ed.; Charter, M., Ed.; Routledge: Abingdon, UK; New York, NY, USA, 2018; pp. 344–359. [CrossRef]
10. Nuñez-Cacho, P.; Górecki, J.; Molina-Moreno, V.; Corpas-Iglesias, F.A. What Gets Measured, Gets Done: Development of a Circular Economy Measurement Scale for Building Industry. *Sustainability* **2018**, *10*, 2340. [CrossRef]

11. Tallini, A.; Cedola, L. A review of the properties of recycled and waste materials for energy refurbishment of existing buildings towards the requirements of NZEB. *Energy Procedia* **2018**, *148*, 868–875. [CrossRef]
12. Passer, A.; Lasvaux, S.; Allacker, K.; De Lathauwer, D.; Spirinckx, C.; Wittstock, B.; Kellenberger, D.; Gschösser, F.; Wall, J.; Wallbaum, H. Environmental product declarations entering the building sector: Critical reflections based on 5 to 10 years experience in different European countries. *Int. J. Life Cycle Assess.* **2015**, *20*, 1199–1212. [CrossRef]
13. Baldo, G.L.; Cesarei, G.; Minestrini, S.; Sordi, L. 6—The EU Ecolabel scheme and its application to construction and building materials. In *Eco-Efficient Construction and Building Materials*; Pacheco-Torgal, F., Cabeza, L.F., Labrincha, J., de Magalhães, A., Eds.; Woodhead Publishing: Cambridge, UK, 2014; pp. 98–124. [CrossRef]
14. Cambier, C.; Galle, W.; De Temmerman, N. Research and Development Directions for Design Support Tools for Circular Building. *Buildings* **2020**, *10*, 142. [CrossRef]
15. Rios, F.C.; Chong, W.K.; Grau, D. Design for Disassembly and Deconstruction—Challenges and Opportunities. *Procedia Eng.* **2015**, *118*, 1296–1304. [CrossRef]
16. Cordero, A.S.; Melgar, S.G.; Márquez, J.M.A. Green Building Rating Systems and the New Framework Level(s): A Critical Review of Sustainability Certification within Europe. *Energies* **2020**, *13*, 66. [CrossRef]
17. Attia, S.; Al-Obaidy, M. *Design Criteria for Circular Buildings*; Zuyd Uninversity: Parkstadt, The Netherlands, 2021; p. 11.
18. Smol, M.; Duda, J.; Czaplicka-Kotas, A.; Szołdrowska, D. Transformation towards Circular Economy (CE) in Municipal Waste Management System: Model Solutions for Poland. *Sustainability* **2020**, *12*, 4561. [CrossRef]
19. Smol, M. Inventory and Comparison of Performance Indicators in Circular Economy Roadmaps of the European Countries. *Circ. Econ. Sustain.* **2021**. [CrossRef]
20. Grover, R. Towards Zero Carbon Buildings: Reducing the Embodied Carbon Footprint of a Construction. 2020. Available online: https://repository.tudelft.nl/islandora/object/uuid%3A98e2c46c-7321-4eab-9f88-c3d10912003a (accessed on 19 July 2021).
21. Huberman, N.; Pearlmutter, D. A life-cycle energy analysis of building materials in the Negev desert. *Energy Build.* **2008**, *40*, 837–848. [CrossRef]
22. WGBC. Bringing Embodied Carbon Upfront. *World Green Building Council*. Available online: https://www.worldgbc.org/news-media/bringing-embodied-carbon-upfront (accessed on 26 July 2021).
23. Dezeen. French Public Buildings to Be Built with 50 Per Cent Wood. Available online: https://www-dezeen-com.cdn.ampproject.org/c/s/www.dezeen.com/2020/02/12/france-public-buildings-sustainability-law-50-per-cent-wood/amp/ (accessed on 27 July 2021).
24. Ministère de la Transition Écologique. RE2020: Une Nouvelle Étape vers une Future Règlementation Environnementale des Bâtiments Neufs Plus Ambitieuse Contre le Changement Climatique. *Ministère de la Transition Écologique*. Available online: https://www.ecologie.gouv.fr/re2020-nouvelle-etape-vers-future-reglementation-environnementale-des-batiments-neufs-plus (accessed on 26 July 2021).
25. Rossi, B.; Marique, A.-F.; Reiter, S. Life-cycle assessment of residential buildings in three different European locations, case study. *Build. Environ.* **2012**, *51*, 402–407. [CrossRef]
26. Ellen MacArthur Foundation. What Is a Circular Economy? Available online: https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview (accessed on 9 January 2022).
27. ISO. ISO 14040:2006: Environmental Management—Life Cycle Assessment—Principles and Framework. Available online: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/74/37456.html (accessed on 19 July 2021).
28. ISO. ISO 14044:2006: Environmental Management—Life Cycle Assessment—Requirements and Guidelines. Available online: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/84/38498.html (accessed on 19 July 2021).
29. EN 15978:2011. Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method. *iTeh Standards Store*. Available online: https://standards.iteh.ai/catalog/standards/cen/62c22cef-5666-4719-91f9-c21cb6aa0ab3/en-15978-2011 (accessed on 19 July 2021).
30. One Click LCA. Calculate Your Environmental Impacts in Minutes. *One Click LCA® Software*. Available online: https://www.oneclicklca.com/ (accessed on 19 July 2021).
31. OVAM. Totem: Tool to Optimise the Total Environmental Impact of Materials. Available online: https://www.ovam.be/materiaalprestatie-gebouwen-0 (accessed on 24 July 2021).
32. OVAM. Annex. Monetisation of the MMG Method. Update 2017. Available online: https://www.vlaanderen.be/publicaties/annex-monetisation-of-the-mmg-method-update-2017 (accessed on 21 July 2021).
33. EnergyPlus. Available online: https://energyplus.net/ (accessed on 21 July 2021).
34. EPB-Eisen. Available online: https://www.energiesparen.be/epb-pedia/epb-eisen (accessed on 21 July 2021).
35. Reap, J.; Roman, F.; Duncan, S.; Bras, B. A survey of unresolved problems in life cycle assessment. *Int. J. Life Cycle Assess.* **2008**, *13*, 374–388. [CrossRef]
36. One Click LCA. LCA Database of Building Products: Local and Global Data for Your LCA. *One Click LCA® software*. Available online: https://www.oneclicklca.com/support/faq-and-guidance/documentation/database/ (accessed on 19 July 2021).
37. Rakhshan, K.; Morel, J.-C.; Alaka, H.; Charef, R. Components reuse in the building sector—A systematic review. *Waste Manag. Res. J. A Sustain. Circ. Econ.* **2020**, *38*, 347–370. [CrossRef]
38. Ritzen, M.; Van Oorschot, J.; Cammans, M.; Segers, M.; Wieland, T.; Scheer, P.; Creugers, B.; Abujidi, N. Circular (de)construction in the Superlocal project. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *225*, 012048. [CrossRef]

39. Akinade, O.O.; Oyedele, L.O.; Ajayi, S.O.; Bilal, M.; Alaka, H.A.; Owolabi, H.A.; Bello, S.A.; Jaiyeoba, B.E.; Kadiri, K.O. Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills. *Waste Manag.* **2017**, *60*, 3–13. [CrossRef]
40. Tingley, D.D.; Davison, B. Design for deconstruction and material reuse. *Proc. Inst. Civ. Eng. Energy* **2011**, *164*, 195–204. [CrossRef]
41. Kalyun, M.; Wodajo, T. Application of a Design Method for Manufacture and Assembly, Flexible Assembly Methods and Their Evaluation for the Construction of Bridges. *Undefined*. 2012. Available online: https://www.semanticscholar.org/paper/Application-of-a-Design-Method-for-Manufacture-and-Kalyun-Wodajo/17f0e56185797c39d9789c07544a4fdab9212bed (accessed on 28 October 2021).
42. Vandervaeren, C.; Galle, W.; Stephan, A.; De Temmerman, N. More than the sum of its parts: Considering interdependencies in the life cycle material flow and environmental assessment of demountable buildings. *Resour. Conserv. Recycl.* **2022**, *177*, 106001. [CrossRef]
43. Standards, E. EN 15804+A2. Available online: https://www.en-standard.eu/csn-en-15804-a2-sustainability-of-construction-works-environmental-product-declarations-core-rules-for-the-product-category-of-construction-products/ (accessed on 18 August 2021).
44. One Click LCA. How Do I Model Module D for Recycled Material? *One Click LCA Help Centre*. Available online: https://oneclicklca.zendesk.com/hc/en-us/articles/360022222720-How-Do-I-Model-Module-D-For-Recycled-Material- (accessed on 15 December 2021).
45. EEA. The European Environment—State and Outlook 2020: Knowledge for Transition to a Sustainable Europe—European Environment Agency. Available online: https://www.eea.europa.eu/soer (accessed on 29 July 2021).
46. European Committee for Standardization. Standard NBN EN 15221-6:2011. Available online: https://www.nbn.be/shop/en/standard/nbn-en-15221-6-2011_20688/# (accessed on 23 July 2021).
47. Beneens. We Build Camp Circular. *Beneens*. Available online: https://www.beneens.be/circulair (accessed on 19 July 2021).
48. Binderholz GmbH. WOOD The Intelligent and Versatile Raw Material. *binderholz.com*. Available online: https://www.binderholz.com/?klenk= (accessed on 15 November 2021).
49. ResourceFull. Low Carbon Concrete ResourceFull Houthalen-Helchteren. Available online: https://www.resourcefull.eu (accessed on 9 January 2022).
50. ResourceFull. Foundationst Centrum Built without Cement. *ResourceFull.eu*. Available online: https://www.resourcefull.eu/tcentrum-kampc-cementless-foundations (accessed on 4 August 2021).
51. *Eurostat, Cooling and Heating Degree Days by NUTS 3 Regions—Annual Data*; European Commission: Brussels, Belgium, 2021. Available online: https://ec.europa.eu/eurostat/databrowser/view/nrg_chddr2_a/default/table?lang=en (accessed on 8 January 2022).
52. RMI. Royal Meteorological Institute of Belgium. 2021. Available online: https://www.meteo.be/en/belgium (accessed on 8 January 2022).
53. Taleghani, M.; Marshall, A.; Fitton, R.; Swan, W. Renaturing a microclimate: The impact of greening a neighbourhood on indoor thermal comfort during a heatwave in Manchester, UK. *Sol. Energy* **2019**, *182*, 245–255. [CrossRef]
54. Caleys, L. Comparing the Energy Performance and Sustainability of Vacuum Insulated Glass vs. Triple Glass in an Office Building: A Case Study in Belgium. Master's Thesis, Liege University, Liege, Belgium, 2022.
55. Meex, E. Early Design Support for Material Related Environmental Impact Assessment of Dwellings. 2018. Available online: https://documentserver.uhasselt.be//handle/1942/27512 (accessed on 31 July 2021).
56. Roos Servaes, TOTEM & Circulariteit. Roos Servaes Masterclass Kamp C, 4 Oktober PDF Gratis Download. Available online: https://docplayer.nl/131574855-Totem-circulariteit-roos-servaes-masterclass-kamp-c-4-oktober-2018.html (accessed on 24 October 2021).
57. Gobbo, E.; Ghyoot, M.; Paduart, A.; Nasseredine, M. Reuse in Environmental Impact Assessment Tools. 2021. Available online: https://www.nweurope.eu/media/15802/reuse_in_environmental_impact_assessment_tools_2021.pdf (accessed on 10 December 2021).
58. E-Peil: Eis Voor Niet-Residentiële Gebouwen, Vlaanderen is Energie. 2021. Available online: https://www.energiesparen.be/epb-pedia/e-peil/eis-niet-residentieel-2021 (accessed on 19 July 2021).
59. Attia, S. *Net Zero Energy Buildings (NZEB): Concepts, Frameworks and Roadmap for Project Analysis and Implementation*; Elsevier: Amsterdam, The Netherlands, 2018. [CrossRef]
60. Blom, I.; Itard, L.; Meijer, A. Environmental impact of building-related and user-related energy consumption in dwellings. *Build. Environ.* **2011**, *46*, 1657–1669. [CrossRef]
61. Collinge, W.O.; Landis, A.E.; Jones, A.K.; Schaefer, L.A.; Bilec, M.M. Dynamic life cycle assessment: Framework and application to an institutional building. *Int. J. Life Cycle Assess.* **2012**, *18*, 538–552. [CrossRef]
62. EnergyVille. Belgian Long Term Electricity System Scenarios. Available online: https://www.energyville.be/belgian-long-term-electricity-system-scenarios (accessed on 29 September 2021).
63. Federaal Planbureau—Publicatie—Het Belgische Energielandschap Tegen 2050—Een Projectie Bij Ongewijzigd Beleid. Available online: https://www.plan.be/publications/publication-1728-nl-het_belgische_energielandschap_tegen_2050_een_projectie_bij_ongewijzigd_beleid (accessed on 4 September 2021).
64. Ramon, D.; Allacker, K. Integrating long term temporal changes in the Belgian electricity mix in environmental attributional life cycle assessment of buildings. *J. Clean. Prod.* **2021**, *297*, 126624. [CrossRef]

65. ENGIE Electrabel. Radioactive Waste. *ENGIE Electrabel*. Available online: https://nuclear.engie-electrabel.be/en/nuclear-energy/nuclear-power-plants-and-climate/radioactive-waste (accessed on 26 October 2021).
66. VEB. Vlaams Energiebedrijf, Efficiënt in Energie. Available online: https://www.veb.be/ (accessed on 17 October 2021).
67. Vlaanderen. Vlaams Energiebedrijf. Available online: https://www.vlaanderen.be/organisaties/administratieve-diensten-van-de-vlaamse-overheid/beleidsdomein-omgeving/vlaams-energiebedrijf (accessed on 28 October 2021).
68. Al-Obaidy, M.; Attia, S. Environmental Product Declaration Dataset of 't Centrum Circular Building in Westerlo, Belgium. Harvard Dataverse, 23 January 2022. Available online: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/Z1CS97 (accessed on 23 January 2022).
69. One Click LCA. How We Work with Data at One Click LCA. *One Click LCA® Software*. Available online: https://www.oneclicklca.com/how-we-work-with-data-at-one-click-lca/ (accessed on 21 July 2021).
70. Meex, E.; Hollberg, A.; Knapen, E.; Hildebrand, L.; Verbeeck, G. Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. *Build. Environ.* **2018**, *133*, 228–236. [CrossRef]
71. Li, Y.; Allacker, K.; Feng, H.; Heidari, M.D.; Pelletier, N. Net zero energy barns for industrial egg production: An effective sustainable intensification strategy? *J. Clean. Prod.* **2021**, *316*, 128014. [CrossRef]
72. Byggeriets Materialepyramide. Available online: https://www.materialepyramiden.dk/ (accessed on 7 December 2021).
73. Larivière-Lajoie, R.; Blanchet, P.; Amor, B. Evaluating the importance of the embodied impacts of wall assemblies in the context of a low environmental impact energy mix. *Build. Environ.* **2022**, *207*, 108534. [CrossRef]
74. Grosso, M.; Thiebat, F. Life Cycle Environmental Assessment of Temporary Building Constructions. *Energy Procedia* **2015**, *78*, 3180–3185. [CrossRef]
75. Huijbregts, M.A.J.; Gilijamse, W.; Ragas, A.M.J.; Reijnders, L. Evaluating Uncertainty in Environmental Life-Cycle Assessment. A Case Study Comparing Two Insulation Options for a Dutch One-Family Dwelling. *Environ. Sci. Technol.* **2003**, *37*, 2600–2608. [CrossRef] [PubMed]
76. Cellura, M.; Longo, S.; Mistretta, M. Sensitivity analysis to quantify uncertainty in Life Cycle Assessment: The case study of an Italian tile. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4697–4705. [CrossRef]
77. Vlaanderen Circulair. Circular Retrofit Lab. *Vlaanderen Circulair*. Available online: https://vlaanderen-circulair.be/en/cases/detail/circular-retrofit-lab (accessed on 5 November 2021).
78. Archipelago. Joseph Bracops Hospital, Anderlecht: An Urban Hospital Based on Circular Economy Principles. *Archipelago*. Available online: https://archipelago.be/en/projects/how-can-we-design-an-urban-hospital-according-to-circular-economy-principles/ (accessed on 5 November 2021).
79. OPALIS. L'Institut de Botanique de l'ULg. *Opalis*. Available online: https://opalis.eu/fr/projets/linstitut-de-botanique-de-lulg (accessed on 5 November 2021).
80. AGC Glass, AGC Glass Belgium. AGC Belgium—Glas—Beglazing—Pyrobel—WBDBO. Available online: https://www.agcglassbelgium.be/ (accessed on 5 November 2021).
81. ROTOR, Rotor—Brussels Rotor. Available online: http://rotordb.org/en (accessed on 5 November 2021).
82. Allacker, K.; Debacker, W.; Delem, L.; De Nocker, L.; De Troyer, F.; Janssen, A.; Peeters, K.; Servaes, R.; Spirinckx, C.; Van Dessel, J. Environmental Profile of Building Elements [Update 2020], Danny Wille, OVAM.; Stationsstraat 110, 2800 Mechelen, 2020. Available online: https://lirias.kuleuven.be/1954287 (accessed on 9 November 2021).
83. Kamp, C. Circular Building: 't Centrum. Available online: https://www.kampc.be/tcentrum/circulair-bouwen-t-centrum (accessed on 19 July 2021).
84. Goffart, J.; Woloszyn, M. EASI RBD-FAST: An efficient method of global sensitivity analysis for present and future challenges in building performance simulation. *J. Build. Eng.* **2021**, *43*, 103129. [CrossRef]
85. Saltelli, A.; Aleksankina, K.; Becker, W.; Fennell, P.; Ferretti, F.; Holst, N.; Li, S.; Wu, Q. Why so many published sensitivity analyses are false: A systematic review of sensitivity analysis practices. *Environ. Model. Softw.* **2019**, *114*, 29–39. [CrossRef]
86. Saltelli, A.; Sobol', I.M. Sensitivity analysis for nonlinear mathematical models: Numerical experience. *Mat. Modelirovanie* **1995**, *7*, 16–28.
87. Baubook. Binderholz Brettsperrholz BBS (Fichte). Available online: https://www.baubook.at/vlbg/?URL_R=https%3A%2F%2Fwww.baubook.at%2Fm%2FPHP%2FInfo.php%3FSI%3D2142705769%26SW%3D2&SW=2 (accessed on 15 November 2021).
88. Ecoschelp. Bouw en Bescherm Met Schelpen. Available online: https://www.ecoschelp.be/nl/ (accessed on 14 November 2021).
89. Decorte, Y.; Steeman, M.; Bossche, N.V.D. Effect of a one-dimensional approach in LCA on the environmental life cycle impact of buildings: Multi-family case study in Flanders. *Build. Environ.* **2021**, *206*, 108381. [CrossRef]
90. Giordano, R.; Serra, V.; Demaria, E.; Duzel, A. Embodied Energy Versus Operational Energy in a Nearly Zero Energy Building Case Study. *Energy Procedia* **2017**, *111*, 367–376. [CrossRef]
91. Levasseur, A.; Lesage, P.; Margni, M.; Deschênes, L.; Samson, R. Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. *Environ. Sci. Technol.* **2010**, *44*, 3169–3174. [CrossRef]
92. Helal, J.; Stephan, A.; Crawford, R.H. The influence of structural design methods on the embodied greenhouse gas emissions of structural systems for tall buildings. *Structures* **2020**, *24*, 650–665. [CrossRef]
93. Manfren, M.; Tagliabue, L.C.; Cecconi, F.R.; Ricci, M. Long-Term Techno-Economic Performance Monitoring to Promote Built Environment Decarbonisation and Digital Transformation—A Case Study. *Sustainability* **2022**, *14*, 644. [CrossRef]

94. Churkina, G.; Organschi, A.; Reyer, C.P.O.; Ruff, A.; Vinke, K.; Liu, Z.; Reck, B.K.; Graedel, T.E.; Schellnhuber, H.J. Buildings as a global carbon sink. *Nat. Sustain.* **2020**, *3*, 269–276. [CrossRef]
95. Robati, M.; Oldfield, P.; Nezhad, A.A.; Carmichael, D.G.; Kuru, A. Carbon value engineering: A framework for integrating embodied carbon and cost reduction strategies in building design. *Build. Environ.* **2021**, *192*, 107620. [CrossRef]
96. Akadiri, P.O.; Chinyio, E.A.; Olomolaiye, P.O. Design of A Sustainable Building: A Conceptual Framework for Implementing Sustainability in the Building Sector. *Buildings* **2012**, *2*, 126–152. [CrossRef]
97. VITO. Demolition Guide Recognizes Building Materials for Recycling or Reuse. Available online: https://vito.be/en/news/demolition-guide-recognizes-building-materials-recycling-or-reuse (accessed on 9 December 2021).
98. CEN/TC 350, CEN/TC 350/SC 1—Circular Economy in the Construction Sector. *iTeh Standards Store*. Available online: https://standards.iteh.ai/catalog/tc/cen/51316ef3-3dea-4483-8aab-cd1a8033cd41/cen-tc-350-sc-1 (accessed on 12 December 2021).
99. ISO, ISO/TC 323—Circular Economy (under Development). *ISO*. Available online: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/committee/72/03/7203984.html (accessed on 12 December 2021).

Chapter 03. *Disassembly calculation criteria and methods for circular construction – Journal paper*

Abstract: Circular economy opportunities occur at every building life cycle stage. The consistent evaluation of the disassembly potential of buildings at different scales supports the decision-making for the sustainability of construction works. The main limitation in this field is the fragmentation and dispersion of criteria and methods for circular construction. The paper provides an overview of disassembly evaluation methods using a hybrid systematic review. The review is structured into two sections. The first section investigates generic studies assessing the disassembly potential of buildings, while the second section focuses on studies that address quantitative criteria and methods of disassembly evaluation of buildings. The study discusses the state-of-the-art metrics and criteria that can be used in future European standards for circular construction. Also, the review helps researchers and building professionals to identify the most appropriate methods to evaluate buildings based on the principle of design for disassembly.

Role of Ph.D. candidate: As co-author, the Ph.D. candidate co-shaped the research questions and coding schema (conceptualization/methodology, Equal), undertook literature screening and evidence extraction (investigation/data curation, Equal), synthesised criteria into an evaluative scheme (formal analysis, Equal), and produced synthesis tables/figures (visualization, Lead). I drafted substantial portions of the text (writing – original draft, Equal) and participated in writing – review & editing (Equal); senior authors provided supervision.

Journal: Automation in Construction (Elsevier)

Journal impact factor: Current Impact Factor: 11.5

5-Year Impact Factor: 12.7

Citations: Google Scholar: 30

Reference: Attia, S., Al-Obaidy, M., Mori, M., Campain, C., Giannasi, E., Van Vliet, M., & Gasparri, E. (2024). Disassembly calculation criteria and methods for circular construction. Automation in Construction, 165, 105521. https://doi.org/10.1016/j.autcon.2024.105521 & https://hdl.handle.net/2268/319405

Automation in Construction 165 (2024) 105521

Contents lists available at ScienceDirect

Automation in Construction

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

Review

Disassembly calculation criteria and methods for circular construction

Shady Attia [a,*], Muheeb Al-Obaidy [a,b], Maxime Mori [c], Clémentine Campain [d], Enola Giannasi [c], Mike van Vliet [e], Eugenia Gasparri [f]

[a] Sustainable Building Design Lab, Dept. UEE, Faculty of Applied Sciences, Université de Liège, Belgium
[b] Sustainable Building Material, Construction Department, Colruyt Group, 1500 Halle, Belgium
[c] EPF Graduate School of Engineering, 2 Rue Fernand Sastre, 10430, Rosières-Prés-Troyes, France
[d] ENTPE, University of Lyon, 3 rue Maurice Audin, 69120 Vaulx-en-Velin, France
[e] Alba Concepts and BCI Gebouw, 's-Hertogenbosch, the Netherlands
[f] School of Architecture, Design and Planning, The University of Sydney, 148, City Road, Darlington 2006, NSW, Australia

ARTICLE INFO

Keywords:
Transformation
Building
Design for disassembly
DfD
Connection
Demolition

ABSTRACT

Circular economy opportunities occur at every building life cycle stage. The consistent evaluation of the disassembly potential of buildings at different scales supports the decision-making for the sustainability of construction works. The main limitation in this field is the fragmentation and dispersion of criteria and methods for circular construction. The paper provides an overview of disassembly evaluation methods using a hybrid systematic review. The review is structured into two sections. The first section investigates generic studies assessing the disassembly potential of buildings, while the second section focuses on studies that address quantitative criteria and methods of disassembly evaluation of buildings. The study discusses the state-of-the-art metrics and criteria that can be used in future European standards for circular construction. Also, the review helps researchers and building professionals to identify the most appropriate methods to evaluate buildings based on the principle of design for disassembly.

1. Introduction

1.1. General background

The construction sector is based on a linear process that exploits raw materials and the disposal of waste at the end of life. >50% of Greenhouse Gas (GHG) emissions are a result of the exploitation of raw materials [48]. In Europe, >30% of the construction sector's waste and demolition waste is downcycled [70]. To eliminate material consumption waste and encourage resource utilisation circularity principles are needed [19]. Circular economy and the application of circular economy-inspired principles [11] are becoming a critical field for the achievement of sustainable development targets, fostering the uptake of circularity principles in the built environment [60]. The importance of adopting holistic assessment methods and criteria to quantify circular design and performance has been highlighted greatly in the existing literature [33].

One of the key criteria of circular construction is the design for disassembly. Research into the potential for disassembly has been increasing to reduce the environmental impact of the construction sector. For example, in 2015, Akinade et al. developed a BIM-based score system to assess the deconstructability of buildings [5]. In 2019, Aknabi et al. presented a disassembly and deconstruction analysis

Abbreviations: BCI, Building Circularity Indicator; BIM, Building Information Modelling; CA, Connection Accessibility; CCEF, Circular Construction Evaluation Framework; CD, Connection Disassembly factor; CE, Circular economy; CEN, European Committee of Normalization; CT, Connection Type; DAS, Deconstructability Assessment Score; D-DAS, Disassembled and deconstruction analytics system; DfA, Design for Adaptability; DfD, Design for Disassembly; DfromD, Design from Disassembly; DGBC, Dutch Green Building Council; DPb, Disassembly Potential of building; DPc, Disassembly Potential of connection; DPcp, Disassembly Potential of composition; DPI, Disassembly Potential of layer brand; DPp, Disassembly Potential of product; ECI, Environmental Cost Indicator; EOL, End-Of-Life; EU, European Union; EU, European Union Construction Products Regulation; GHG, Greenhouse Gas; GPE, Geometry of Product Edge; HELEN, Holistic design of taller timber buildings; ID, Independency of Component; ISO, International Organization for Standardization; ISSO, Dutch Knowledge Centre; KPI, Key Performance Indicators; LCA, Life Cycle Assessment; PDE, Potential Ductile Elements; PDF, Product Disassembly Factor; PfD, Potential for Disassembly; RRP, Recyclability inherent in the relative product; SC, Sub-Component; SCI, System Circularity Indicator; SE, Static Entropy; SSC, Start-Of-Life Sub-sub-component.

* Corresponding author.
E-mail address: shady.attia@uliege.be (S. Attia).

https://doi.org/10.1016/j.autcon.2024.105521
Received 12 February 2024; Received in revised form 30 May 2024; Accepted 1 June 2024
Available online 8 June 2024
0926-5805/

system [3]. In 2023, Xiao et al. developed a deconstruction evaluation method for building structures [69]. More recently, Allam et al. presented 2024 a model that supports circularity in construction with performance-based disassembly and deconstruction [6]. Those studies are just examples of the growing importance of design for disassembly principles and calculation methods. However, despite all those examples, no review to date offers an overview of disassembly calculation methods and criteria for circular construction.

1.2. Building disassembly

Building disassembly is an important research topic that has attracted the attention of several researchers during the last 15 years. According to ISO 20887, disassembly is non-destructive taking part in construction work or constructing assets into constituent materials or components [41]. ISO 20887 provides examples of how specific building components or assessments can be assessed qualitatively. Since the publication of Durmisevic's dissertation in 2006 on transformable building structures [27] and the introduction of the Circularity Indicators by the Ellen Mac Arthur Foundation [31], several scholars and building professionals investigated this topic. Indeed, there is an increasing body of knowledge on calculation methods and criteria to assess building disassembly potential. Several Green Building Councils have also been researching the Design for Disassembly (DfD). Het Centrum is an example of a recent circular building that is planned to be dismantled five years after its construction to assess its ability to disassemble [7]. Fig. 1 shows t' Centrum's beam-column connection, designed for future disassembly. Research that couples the disassembly potential to the circularity of buildings is also growing in popularity [35,49].

1.3. Motivations for the data-driven potential of disassembly indicators

This article reviews calculation methods and criteria for assessing the disassembly potential of buildings at the end of their service life through a literature search since 2004. The main aim is the identification of accurate calculation method(s) and quantitative criteria to assess the DfD of new constructions and the potential for disassembly (PfD) of existing buildings that can be used during early design stages or pre-demolition audits. The review uses a hybrid approach that combines scientometric and systematic review methods to analyze prior research on disassembly potential evaluation criteria and methods. The objective is to identify gaps and potential links between the assessment methods and criteria employed at component, product or building levels. This study is focused on timber, steel, concrete, and hybrid buildings. The review caters to researchers and building professionals, including architects and demolition contractors. Also, the work is part of EU COST Action 21,103 - Implementation of Circular Economy in the Built Environment (CircularB) and COST Action 20,139 - Holistic Design of Taller Timber Buildings (HELEN).

1.4. Research questions

The novelty of this review is twofold; it offers a unique perspective on building disassembly criteria and methods and the key knowledge gap of assessing the disassembly potential. Secondly, it advances science in the area of building disassembly evaluation based on a set of cohesive recommendations to evaluate the disassembly of buildings quantitatively. These recommendations are not limited to specific building types and encompass valuable insights for potential enhancements in quantitative disassembly evaluation methods in the future. This study is part of the EU COST Action CircualrB. It has great potential to influence construction standards and regulations -including the European standards for circular construction CEN/TC 350/SC1: Sustainability of construction works, thereby improving design practices and reducing the environmental impact of the construction industry. Hence, this review is important as it addresses the following questions:

- What are the criteria to assess the ability to dismantle buildings at the end of their service life?
- What are the methods to assess the ability to dismantle buildings at the end of their service life for existing buildings or new construction?

Fig. 1. Example of a bolted beam-column and slab-column connection that allows disassembling and reassembling.

2. Methodology

The study employs a hybrid review methodology to analyze a selected list of papers, reports and standards from the Scopus and Google Scholar databases. The hybrid literature review focuses on generic and specific studies that investigated ways to evaluate DfD and building disassembly potential using indicators and metrics. The methodology consists of three main sections. The first section involves a screening stage with inclusion and exclusion criteria. The second section includes a parallel scientometric and systematic review, as illustrated in Fig. 2. The second section is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) that seeks an evidence-based minimum set of items aimed at helping scientific authors report a wide array of systematic reviews. The third section of the methodology focuses on presenting the results of the review, identifying the gaps in literature and developing a discussion on the significant findings and contribution of the study and future research.

2.1. Document screening

The first stage comprises the document screening for the database creation. We primarily searched for articles, journals, and international standards in the fields of engineering, environmental sciences, construction and building materials. The searches were conducted in English, Danish, Dutch, French, German, and Swedish languages, spanning the period from 2003 to 2023. The diversity of the selected document languages is a result of an internal call to the members of COST Actions 21,103 (CircularB) and 20,139 (HELEN). Some articles were also manually added to the list of selected papers by the authors. Special attention was given to publications, especially standards and guides, on circularity and DfD published by Green Building Councils worldwide.

For the literature search in Scopus, the keywords and search strings in Table 1 were used to filter studies. When defining the keywords, the symbol "*" was chosen as a suffix for some keywords to account for all existing variants of these words [43]. For example, by using "disassembl*", words such as "disassemble, "disassembly", "disassembling" and "disassembled" are all considered in the query. Four sets of queries were defined to qualify the overall scope of the research, the definitions of disassembly, disassembly potential, and its quantification. The search was conducted using the "AND" operator between the different query sets for the title, abstract, and keywords of publications. Additional exclusion criteria were used based on the keywords listed in Appendix A.

Table 1
Set of queries for literature search.

KEYWORDS	MEANING
Building* OR construct* OR architect*	Overall, Scope of the Research
Disassembl* OR dismantl* OR deconstruct* OR DfD	Disassembly definition keyword
Disassembl* potential OR dismantl* potential OR reus* potential OR deconstruct* potential	Disassembly potential Keyword
Criteria* OR indicat* OR quantif* OR characteriz* OR asses* OR evaluat* OR estimat*	Disassembly quantification keyword

The number of publications obtained at the end of the search amounted to 130 items. After adding the articles manually selected by us, we compiled a list of 182 publications. An initial selection was made by removing irrelevant and out-of-scope articles. Once the first stage of the study was conducted, stage two was implemented. The methodology of the scientometric review and a systematic review are presented in Sections 2.1 and 2.2.

2.2. Scientometric review

The scientometric examination involves the statistical analysis of large bibliographic series using different metrics. This enabled us to understand the development of science and scientific practices [45]. Several software packages were used to model the document data, such as Excel, VOSviewer and Datawrapper. Firstly, we compiled the list of selected papers (from the Scopus and Google Scholar search and those added by the authors) in the Zotero library in order to be able to use the data. The Zotero library was imported into the VOSviewer software, which created graphic maps of the most frequently used words in the titles and abstracts of the publications, as well as the occurrence of

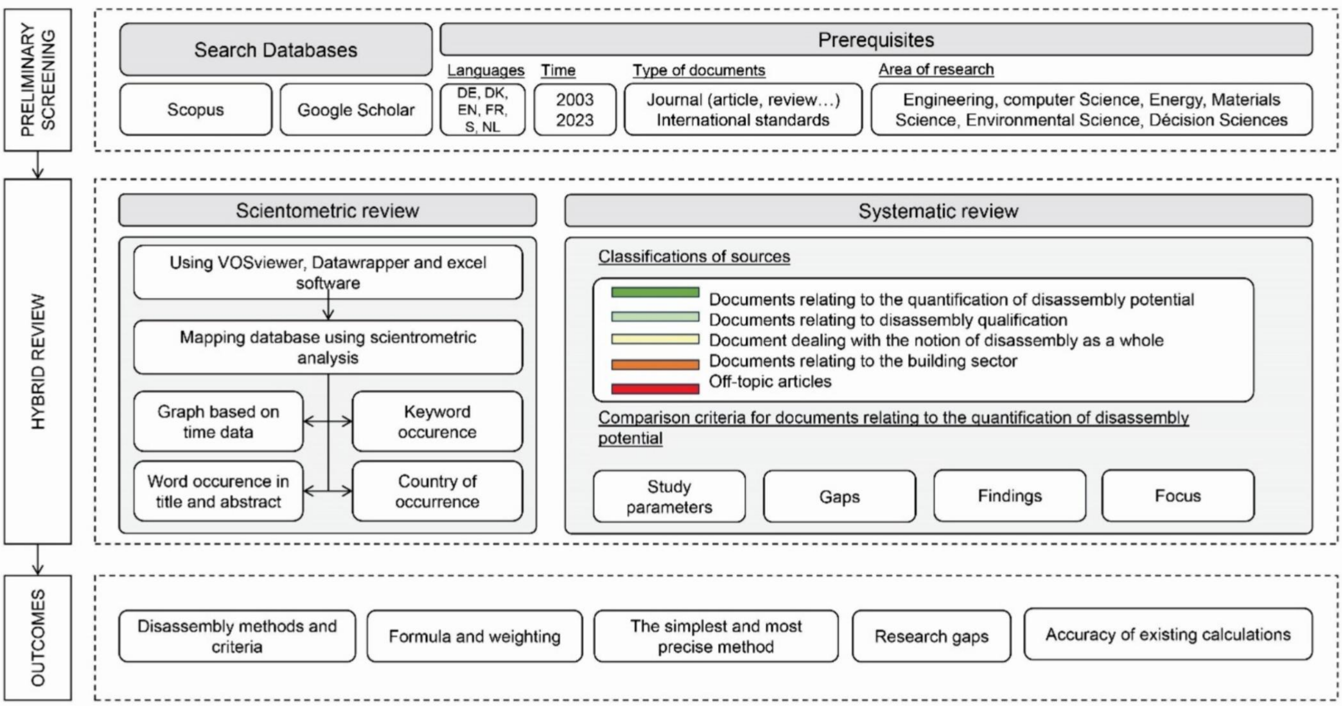


Fig. 2. Methodology of the literature review.

keywords. Using the dates of all selected articles, we produced a graph showing the number of publications per year since 2004 in Excel. To analyze the origin of each study, we drew maps (Europe and the World) of the number of articles per country using Datawrapper. The results of the scientometric are presented in Section 3.1.

Additionally, a search was carried out for case-study buildings that were designed and constructed by taking into account future disassembly opportunities. This was an important step to make this study more practicle and directly relevant to the construction industry. Eight buildings were identified, presented in Section 3.1. This list of projects is non-exhaustive, non-competitive and non-representative. Several criteria were predefined to select low and midrise buildings that can be potentially or fully dismantled. The chosen buildings needed to be designed based on the principles of circular building design and DfD with low environmental impact. The scientometric initial results indicated that Europe has the most advanced research and application of building disassembly research. Therefore, the search was limited to buildings located in Europe.

2.3. Systematic review

A systematic review involves the statistical examination of a broad range of scientific publications on the subject [43]. To accomplish this, we conducted a second round of document selection, retaining only those publications that quantitatively addressed disassembly potential based on the inclusion and exclusion criteria. The review was conducted based on the PRISMA approach to screen and select the study publications. The resulting papers at each phase of the search are illustrated in Fig. 3. This list includes the results of the keyword search (130 publications) and the publications added by the authors (53 publications), totaling 182 publications.

After skimming titles and abstracts, all publications that were out of scope were excluded. A total of 118 publications were selected initially.

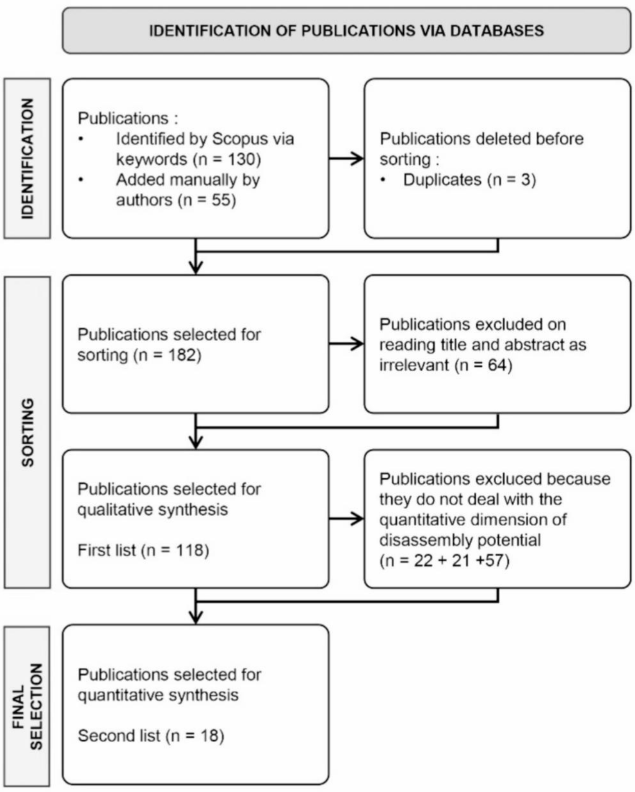


Fig. 3. PRISMA Flowchart for the selection of publications used in the literature review.

Among the publications, many publications were more focused on the positive environmental impact of buildings through life cycle assessments or building energy modelling. In other words, many studies did not address the DfD from a quantitative approach, addressing disassembly calculations with indicators and methods. Therefore, we had to filter the 118 publications to identify the publications that addressed the subject of disassembly potential quantitatively. Based on a thorough reading of abstracts and titles, publications were classified under four categories, namely dark green, light green, yellow and orange. The color dark green was assigned for publications dealing with the subject of disassembly potential quantitatively. Light green for publications qualitatively dealing with the topic. The color yellow for publications dealing with assembly potential, and the color orange for papers dealing with the building and construction sector. A complete list of all the publications can be found in Appendix B. The classification of the publications and their coloring allowed us to move from the identification and sorting stage to the final selection of the systematic review publications.

In total, 18 publications were chosen for the systematic review. The limited number of chosen publications is a result of the application of the inclusion and exclusion criteria. The focus of the study was to identify the quantitative studies that addressed the disassembly evaluation. Therefore, a thorough content analysis took place to read and analyze the 18 publications. The analysis of those publications allowed to development of a high-quality, state-of-the-art overview based on more specific details. Each document was analyzed to answer the research questions and to list and rank the most important criteria for disassembly evaluation and disassembly evaluation methods.

2.4. Results analysis and validation

Data analysis was conducted through reading and classification of themes and codes related directly to disassembly, reversibility of connections and components and buildings' demountability. The 18 publications were read and analyzed based on a content analysis. The content analysis focused on developing a coding scheme to categorize the main criteria and methods. Coding is a way of indexing or categorizing the text in order to establish thematic groups of ideas. The analysis method relied on reading and synthesis workshops following seven chronological steps: transcription, familiarization with the manuscripts, coding, developing tables of classification, application of disassembly calculation methods and criteria, charting data on flip charts, and interpreting the data. A detailed description of text processing can be found in the video by Attia [10].

Next, to validate the results and improve the analysis and conclusion of the review, the author conducted several internal workshops for content analysis. Each part of the study was designed and reviewed by the authors to ensure its accuracy. Three workshops were organized to evaluate the research strategy, including the PRISMA analysis, and improve the analysis. The first workshop took place on 10/08/2023 and aimed to define the research questions, the study guidelines, and the methodology to be adopted. The second, on 25/09/2023, was used to organize the results in terms of methods and to choose the figures to be used throughout the article. The third, on 30/11/2023, was a reflection on the results concerning the criteria and the discussion section. The fourth workshop took place on 12/01/2024 at the Sustainable Building Design Lab at Liege University to refine and elaborate the discussion section of the paper and reflect on the context of the study.

3. Results

In this section, we present the scientometric review analysis and the in-depth analysis based on the systematic review. Out of 182 publications, 57 generic publications were found related to DfD, 22 publications on the qualitative part of disassembly potential, and 21 on the notion of disassembly, as shown in Fig. 4. Only 18 publications were found to be

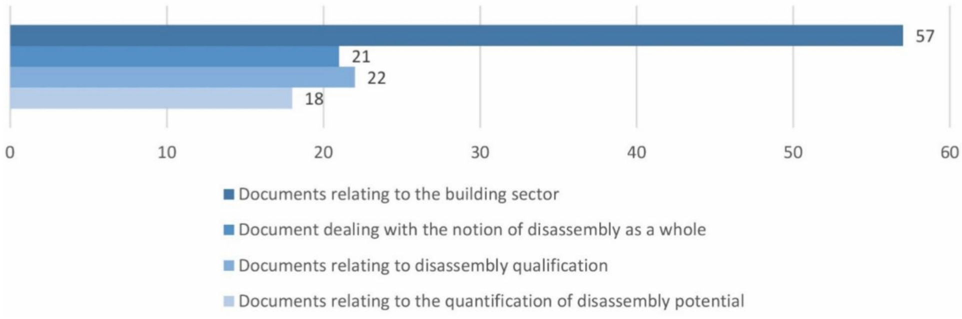


Fig. 4. Classification and quantification of publication on the potential for disassembly of buildings based on their approach.

highly relevant to answer our research questions.

3.1. Results of the scientometric review

Using VOSviewers software, publications data (authors' names, citations, countries) were presented in graphical maps based on keywords and recurring words in the title and abstract (see Fig. 5). The most recurrent words are remarkably similar between charts, for example, life cycle assessment. On the data-based mapping of the word occurrence included in the titles and abstracts, the most frequently recurring words are connection, recycling, value, circularity, construction sector, and cost. And, for the data-based mapping on the keyword occurrence, the words that stand out from the rest are environmental impact, circular economy, eco-design, architectural design, reuse, and sustainable development. The mapping revealed a proliferation of ways to measure circularity [26] and quantify or evaluate [54] buildings disassembly. The high frequency of use of the term 'connection' in paper titles reflects fragmented research that is on the rise in the area of building parts and components. Also, the high use of the term 'circular economy' in the keywords reflects a knowledge gap [4] of the interdependencies in materials reuse, material flows and building demountability [64].

Moreover, most of the studies that were associated with the term circularity or circular economy remain theoretical and discuss those concepts during the early design and modelling stages [44,57] of new construction. The graphs reflect the lack of application of circular approaches in the construction sector ecosystem [30] and the emergence of this field. None of the graphs indicated the presence of highly cited or applied indicators-related publications used for disassembly calculations. Also, the mapping did not reveal any connection or synergies to other indicators for circularity evaluation approaches. Even relevant EU frameworks and policy documents like level (s), Waste Framework Directive or Circular Economy Action Plan did not gain sufficient citations or impact in the maps of Fig. 5.

Using a software program called Data Wrapper, a world map showing the number of publications by country has been created. Fig. 6 reveals that Europe is the continent that has published the most articles on disassembly potential. Even if America or Asia have published a few articles or reports, Europe accounts for over 75% of the world's publications. To take our analysis further, on a European and global scale, England is the most advanced country on the subject, with 15 publications. Italy, Germany, and Belgium are close behind, with between 12 and 14 publications. (See Fig. 7.)

Disassembly potential is a recent topic, with the first publications appearing in 2004, but it's from 2014 to 2015 that the number of publications has increased considerably. Indeed, between 2004 and 2014, only 2 publications were published per year. Since 2015, the number of publications has risen steadily so that today, 26 publications will be published in 2022 and 2023. Since 2015, there has been a real interest in the idea of reusing and not just recycling.

To better visualize the progress in the practice of research into DfD and disassembly potential, a list of all the construction projects on this subject has been created (Table 2). To date, ten projects have been identified. These examples demonstrate the data analyzed above. The first building to take disassembly into account was built in 2007, and as time goes on, the number of projects increases.

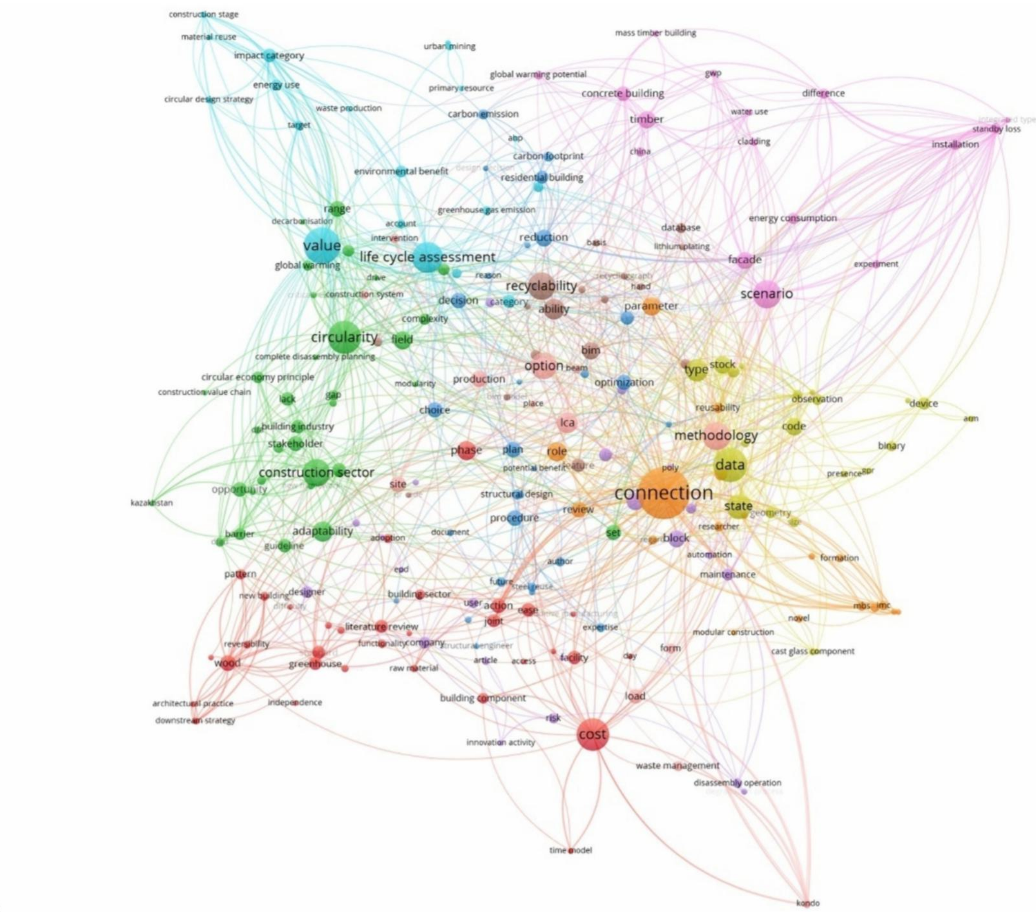
3.2. Results of the systematic review

For a more in-depth analysis of the publications on the shortlist, a literature review was carried out using a matrix (see Appendix C and Appendix D). In this matrix, we extracted from each document the study parameters, focus, gaps, and key findings that enabled us to understand the disassembly criteria used by the authors and the methods developed. According to the timeline shown in Fig. 8 of major publications on the assessment of disassembly potential, Durmisevic initiated the subject of disassembly potential in her dissertation [27]: Design for Disassembly to introduce sustainable Engineering to Building Design & Construction.

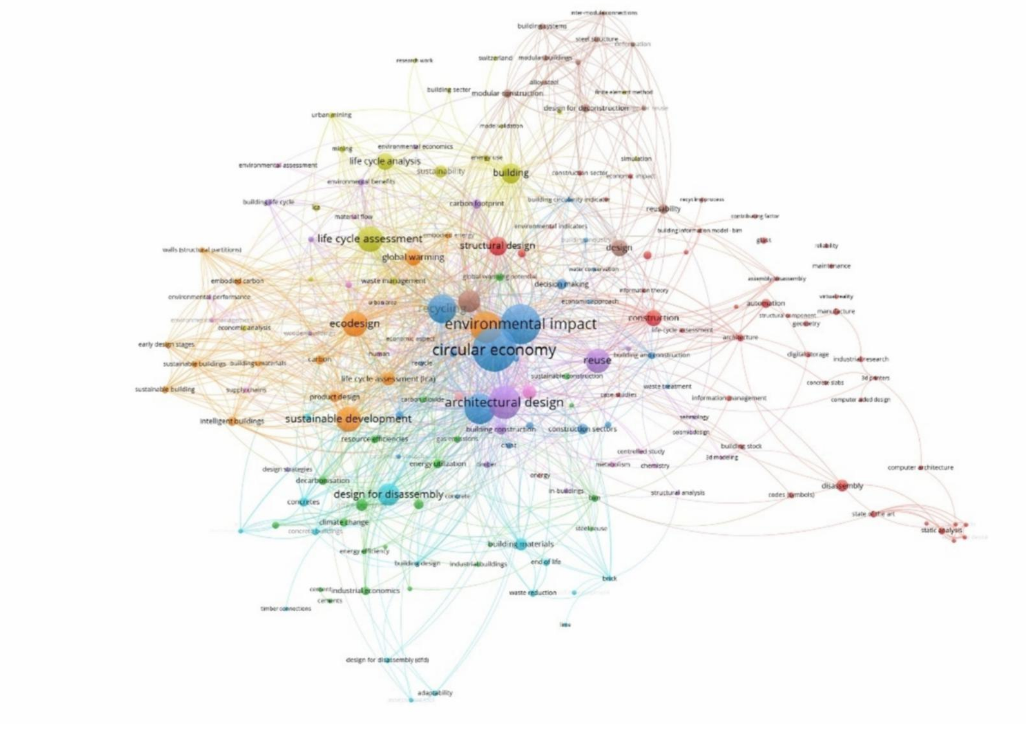
3.2.1. What are the methods to assess the ability to dismantle buildings at the end of their service life for existing buildings or new construction?

Based on Fig. 8, we found that the most relevant work on the disassembly potential evaluation was initiated by Durmisevic in 2006 [27], Verberne in 2016 [66] and Van Vliet in 2018 (M. [61]). Circular economy approaches in the built environment are becoming more and more relevant to their impact on carbon and construction waste reduction. The master's thesis of Verbene, published in 2016, proposes a circularity assessment method for buildings: the Building Circularity Indicator (BCI). The indicator considers five scales: materials (MCI), products (PCI), systems (SCI) and buildings (BCI), which tend to represent the different levels of circularity of a building. The four indicators are evaluated in the order presented here, as each indicator is necessary for the calculation of the next. However, assessing the circularity of a building and the potential for reusing products is pointless if they cannot be disassembled without being damaged. Verberne, therefore, introduces the notion of disassembly potential at the scale of each product. The aim is to study connections and their ability to be disassembled. Taking disassembly into account in the calculation of PCI makes it a practical indicator of a product's circularity, as opposed to MCI, which is a purely theoretical indicator of a material's circularity. In 2018, van Vliet (M. [61]) further developed the work of Verberne until the Dutch Green Building Council DGBC adopted it and became a disassembly potential measurement method [23,24].

Since Durmevic Verberne's work, there has been a wide variety of other studies [19] that used his method or newly developed calculation methods for assessing the disassembly potential of a building [22]. Many are based on the methods previously developed, but none of them is really comprehensive of all criteria that impact disassembly potential. Accounting for all the criteria that make a building suitable for disassembly and calculating its potential for disassembly remains highly challenging. To answer the research question, the authors listed the most relevant methods that aimed to assess the ability to dismantle buildings using quantitative approaches. Sections 3.2.1.1 to 3.2.1.5 describe and



a)



b)

Fig. 5. Visualization for analysis of bibliometric data of all publications on the disassembly potential based on: a) word occurrence included in the title and abstract of each document, b) keywords occurrence.

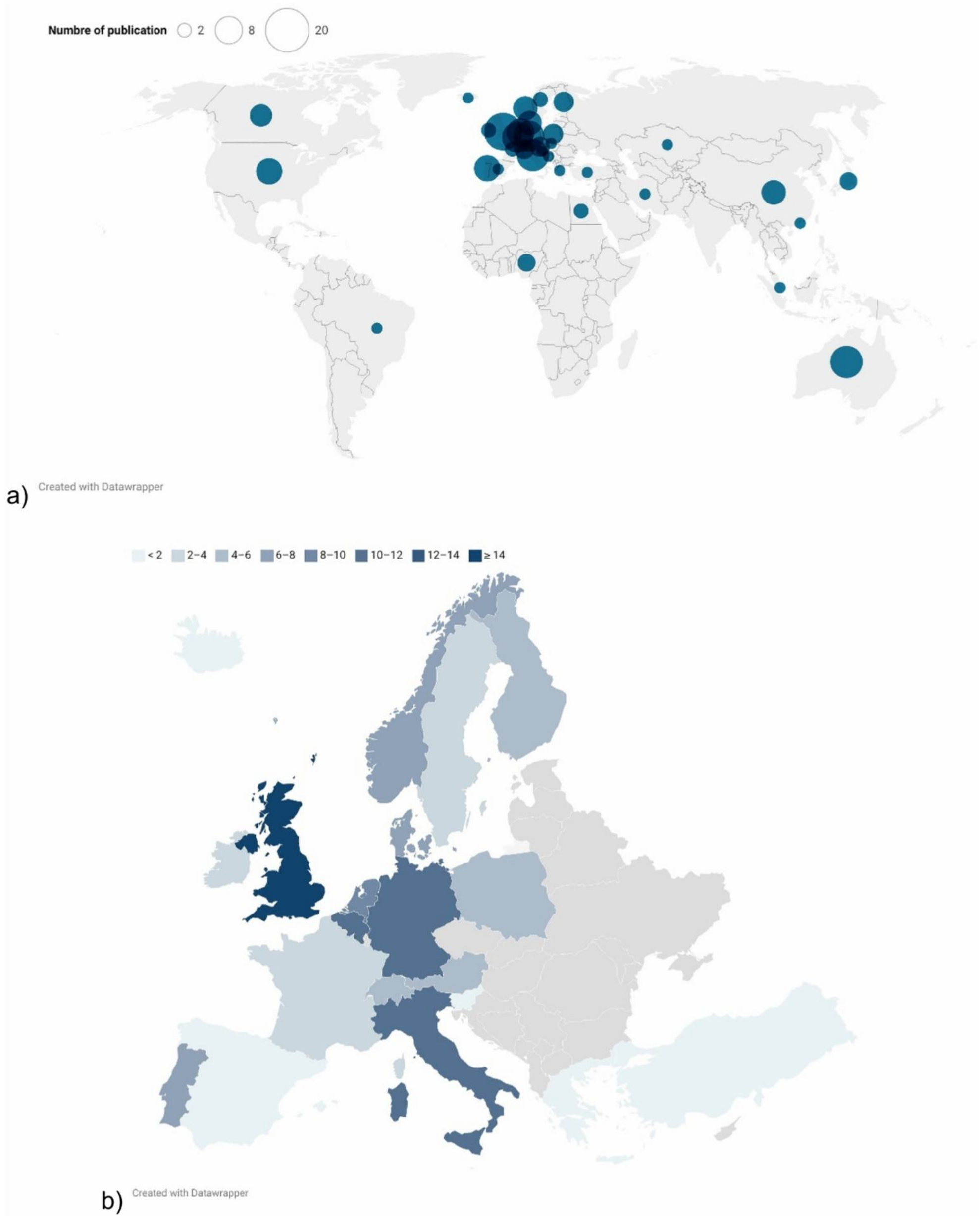


Fig. 6. Number of publications about the disassembly potential country of occurrence a) on a global scale and b) on a European scale.

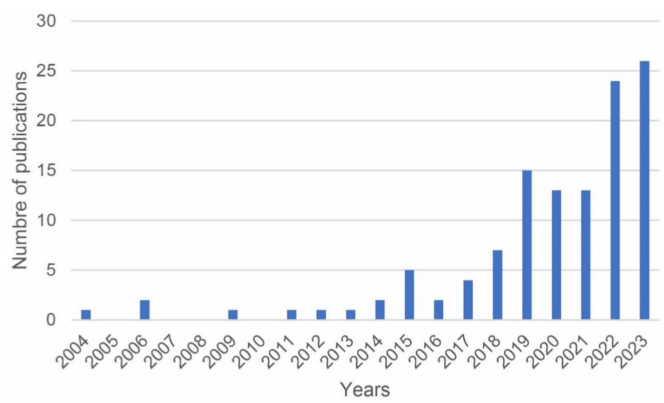


Fig. 7. Evolution of the number of publications on the disassembly potential of buildings per year.

analyze those publications.

3.2.1.1. Van Vliet method. One of the most accurate and complete methods is developed by van Vliet [63]. Inspired by the calculation method proposed by Dumirsevic dissertation on building connections disassembly potential in 2006 and Verberne in 2016, revised and improved thanks to different versions [63] is version 2.0. Mr. van Vliet's work is divided into three publications [61–63].

In his publication, (M. [61]) focuses on the disassembly potential indicator, which alone represents 50% of the BCI indicator developed by [66]. The study aims to validate the assumptions made during the development of the BCI and to refine the method for calculating the disassembly potential. Through two surveys of professionals in the sector, 12 criteria are selected and weighted. At the end of the two surveys, no criteria stand out, the idea of weighting the criteria is aborted, and only seven of the 12 criteria are finally retained: those classified as «technical requirement.» The seven criteria listed below are divided into two families: connection disassembly factor (CD) and product disassembly factor (PD).

Table 2
Examples of disassembly projects.

Project Name	Project photo	Architect	Place	Year
Het Centrum		Beneens	Westerloo, Belgium	2021
This office building is made up of standardized modular walls, floors, columns, and beams made of wood. The elements are assembled with prefabricated connectors, and the connections are dry, with screws and seals. Also, the foundation and the screed are made of cement-free concrete. And the glazed façade is easy to dismantle because it is made of aluminum profiles screwed onto a wooden substructure [67].				
Green Offices		Lutz	Givisiez, Switzerland	2007
Green Offices is made of prefabricated wooden elements. For instance, the façade and the floor units are prefabricated. And the connections between the different elements are reversible [9].				
Circl: Circular Pavilion		Architekten Cie	Amsterdam, Netherlands	2017
The load wooden structure is made locally completely dismountable. The connections are reversible because the materials are clicked or bolted together without the use of glue (the floor covering is not glued to the floor) [17].				
Braunstein Taphouse		ADEPT	Koege, Denmark	2020
This house is built with mechanical joints, and all the primary wall surfaces are free of paint and grout. The construction is made from unmixed sustainable materials [2].				
Circle House		Vandkunsten Architects	Lisbjerg, Denmark	2020
This construction is made with prefabricated concrete elements. The structural system is limited to a few different standardized elements to facilitate disassembly [65].				
Solar Direct Gain House N11		N11 Architekten GmbH	Zweisimmen, Switzerland	2014
This timber construction is made from untreated materials, composites have been avoided, and joints have been made using wooden screws or dowels (N11 [47]).				
Kalkbreite		Müller Sigrist Architekten	Zurich, Switzerland	2014
This construction is made with a concrete structure and prefabricated wooden façade [46].				
Triodos Bank		RAU	Driebergen-Rijsenburg, Netherlands	2019
The main structure is built entirely of wood. And there are unprocessed timber elements that are assembled using screws (meaning they can be unscrewed and reused [51]. The building products, components and materials are documented through a materials passport to be used in the future as ‘loose property’. The building has 165,312 screws traced for future disassembly.				
Green House		cepezed Projects	Utrecht, Netherlands	2017
The Green House (Utrecht), was developed with demolished materials designed to be relocated in 15 (now 10) years [16]. The two-floor pavilion has a demountable steel skeleton of galvanized profiles. The grid sizing is based on the glass facade panels’ size of the former Knoop barracks; these have been reused for the second skin and the greenhouse of the pavilion.				

(*continued on next page*)

Table 2 (*continued*)

Project Name	Project photo	Architect	Place	Year
De Tijdelijke Rechtbank		cepezed Projects	from Amsterdam to Enschede, Netherlands	2021

De Tijdelijke Rechtbank was constructed in Amsterdam and relocated to Enschede. The project was dismantled by Lagemaat BV and reassembled by cepezed projects [15]. The cepezed architects carefully dismantled and reassembled the building components in the new location, *Kennispark Twente* in Enschede [18], where it will serve as a business center. The disassembly potential of that project was determined based on the [24] method before it was actually disassembled, and a case study report on learned lessons has been published [58].

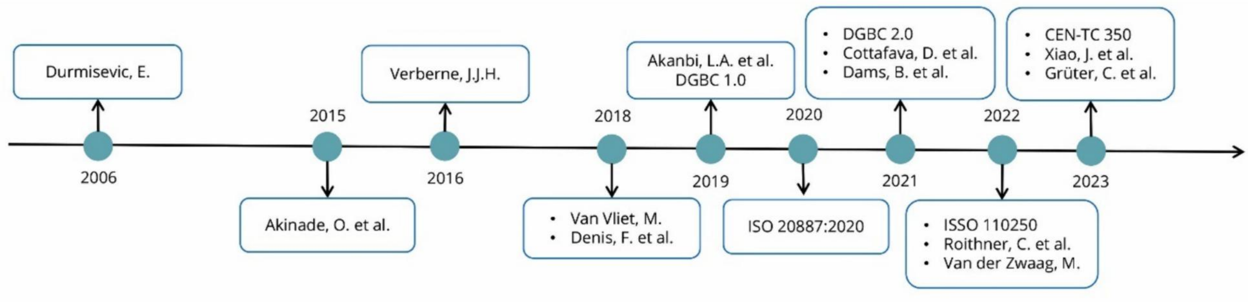


Fig. 8. Chronology of major work on assessing the disassembly potential of buildings.

1. Accessibility (CD)
2. Type of connection (CD)
3. Form of assembly (PD)
4. Independence (PD)
5. Method of manufacture (PD)
6. Assembly Sequence (CD)
7. Relational Schema Type (PD)

The formula for calculating the disassembly potential is improved compared to the work developed in [66]. The disassembly potential of each product is calculated by summing all criteria for the most unfavorable assembly. Mike van Vliet suggested the introduction of a criterion relating to the environmental impact of products. DGBC adopted this improvement and integrated it into a new method as part of a program to establish indicators of circularity [23]. The method confirms Verberne's hypothesis that it is impossible to establish a weighting between the different disassembly criteria. The main weakness of this method is obtaining the disassembly score. Indeed, summing the criteria can introduce a bias since a low score for one criterion can be compensated by a high score for another criterion.

In the 2021 publication [24], the method makes it possible to assess the disassembly potential of the entire building, starting by calculating the disassembly potential of each component and then each layer. The methodology is mainly based on the work of van Vliet, published in 2018 that includes seven criteria related to the technical potential of disassembly [61]. The methodology was adopted in the first version of the DGBC 1.0 in 2019, combining the Environmental impact as weighting for the building. The Disassembly potential product is the average of the four criteria [23] these are: 1) the type of connection, 2) the accessibility of the connection, 3) the independence of the components and 4) the geometry at the ends of the component from the composition in which it is located. Each criterion has a table with a score ranging from 0 to 1 associated with the situation encountered. In 2021, the second version of the DGBC 2.0 calculation method was released [24]. The main change was the introduction of the harmonic mean [37] of the four criteria where the disassembly potential product can be calculated. The identification of the difference between layers of components and connection is specifically stated in the latest version.

For each component, a connection disassembly potential (DPc) is determined by the geometric mean of the scores assigned to the connection type (CT) and accessibility (CA). The disassembly potential of a product is the harmonic mean of the four criteria to make it impossible to compensate for low-scoring factors. A composition disassembly potential (DPcp) is also determined by the geometric mean of the scores attributed to independence (ID) and component geometry (GPE). The component disassembly potential (DPp) is then obtained by the geometric mean of the previously calculated criteria. The scores of all components of a layer are then summed to obtain the layer disassembly potential (DPI). Finally, the disassembly potentials of each layer are summed to obtain the disassembly potential of the building as a whole (DPb).

It should be noted that the calculation method provides for weighting the disassembly potential of the components by their environmental cost indicator (ECI) in the calculation of the disassembly potential of the layer and the building. The ECI is an indicator, very widespread in the Netherlands, expressed in euros (€), which illustrates the environmental impact of a product throughout its life cycle [38]. This method calculates the disassembly potential of existing (older) buildings [58]. It has been used to calculate the disassembly potential of two newly constructed buildings: the Het Centrum and the Green offices [14]. However, the use of a digital 3D model for building connections can make the application of this methodology more easy to achieve.

3.2.1.2. ISO 20887. The ISO 20887:2020 [41] is a standard that provides a framework for the principles and issues of Design for Disassembly (DfD) and Design for Adaptability (DfA). This document covers economic, environmental, social, technical and functional aspects. This standard distinguishes the principles relating to adaptability with use and space and those relating to disassembly with material resources, as shown in Table 3. These criteria may apply to any building and civil engineering work. Whether renovation or new construction. However, certain principles are to be preferred according to the different case studies, and these principles must be applied to the main components. In this standard, no quantitative criteria or method of calculation of

Table 3
Principles developed in the standard [41].

Design principles for adaptability	Design principles for disassembly
Versatility (accommodate various functions with little change) Convertibility (anticipate the possibility of changing users' needs) Extensibility (allows the addition of new spaces, capacity, ...)	Easy access to components Independence Avoid unnecessary treatments and finishes. Support for economic models of reuse Simplicity Standardization Disassembly safety

building disassembly is developed. However, an informative guide to determine the different criteria to apply is presented in Annex C of standard ISO 20887.

3.2.1.3. ISSO 110250. The ISO [41] Reference Details standard provides examples of dismantlable building products and component connections through detailed section drawings [42]. The drawings are colored and represent the different building materials. The construction details are based on the EU CPR definition for products with CE marking. The report shows different types of connections and compositions for building products and evaluates the ease of disassembly to reuse the dismantle building components or products. The disassembly evaluation is based on characterizing the type of connection and the accessibility to the connection during the demolition process. The disassembly potential calculation approach is based on the DGBC method developed by Alba Concepts [24].

In ISSO 110250, it was not easy to show the independence (ID) and element geometry (GPE) in a technical detail drawing. Therefore, these two criteria were not included. The ISSO standard, written in Dutch, discusses the disassembly potential of existing construction details but not how those details can be improved regarding disassembly. ISSO 110250 includes circular detail drawings alternatives that include circular principles in the drawings and their scores. Also, the standard uses a color coding system (green, yellow and red) to distinguish the disassembly potential. Therefore, The document is a good start but not sufficiently useful for those who want to design and build for disassembly.

3.2.1.4. Witteveen+Bos and circular building methods. The Witteveen+Bos [68] Evaluation method is based on the [24] research for building disassembly and provides designers with relevant insights to design more modular/demountable structures [24]. The method report, written in Dutch, is based on a hierarchical classification system for building components and materials associated with life expectancy. Alba Concepts conducted a study to see what the major differences were between civil infrastructure and buildings. Witteveen + Bos elaborated on this research to determine a methodology focussed on civil infrastructure and not on buildings. The new 2023 method does discuss the disassembly potential of existing construction details but not how those details can be improved in terms of disassembly.

The method is purely theoretical and focuses on the technical aspects of disassembly, such as connection types or materials binding. The method includes several examples of technical details and section drawings in existing buildings. However, the example do not present the practice of architectural detachable details, which is the most important topic for designers and builders [50]. Witteveen + Bos is currently still conducting the follow-up on this research to determine the practical implications of the method on case studies.

Another document developed by the Dutch Circular Building is the Disassembly Details Guide [50]. This guideline goes a step further and offers concrete tools to design releasable details as well as possible in the building sector. The study of the Dutch Circular Building builds on the ISSO report and DGBC method and provides constructive feedback and guidance on improving the disassembly potential of building connections. In this case, the study further improves the details rather than just evaluating them.

3.2.1.5. Grutër, Roithner and Akanbi methods. Three articles develop methods for assessing disassembly potential different from the one published by the DGBC method [24] entitled Circular Buildings.

In the study [52], a case study is carried out on a building modeled in wood and concrete. The calculation method used is a method for assessing the recyclability of a smartphone using static entropy (developed by [39] and reviewed by [52]) but applied to a building designed to be disassembled by Honic and al. using BIM software.

Called RPR ("recyclability inherent in the relative product"), the method involves calculating the recyclability rate of a building based on its composition and structure. This method focuses primarily on the number of materials and the different mixes of materials used to design the building. The more materials are mixed, the less they can be recycled. To achieve this, they use a "material passport" for the different structural levels of a building: Product, Component, Composition and Material. In this study [52], the entire building is taken into account, as each component and material is broken down. It takes into account its components, sub-components and sub-sub-components. In this method, a sub-component is a component, and a sub-sub-component is a material. And also the different types of existing connections (screwed, bolted, glued…). This method relies primarily on the static entropy (SE) of materials, which is a good indicator of their recyclability to calculate a building's RPR. Indeed, if a material is not mixed, it will have a low SE and will be more easily recycled. On the other hand, if a material is mixed or bonded with another, its SE will be high and difficult to recycle.

This method shows that if no specific deconstruction is carried out (= demolition), concrete buildings, for example, are less recyclable. However, if a structure is built with a high number of materials at SC and even SSC levels, such as wooden buildings, the recyclability rate will be higher. The RPR decreases as the materials in a building are mixed. The method only considers wood and concrete structures. As this study was carried out only on a building designed to be disassembled, it is not known whether this method can also be applied to existing buildings.

The study by [3] focuses on the development of a D-DAS (Disassembled and Deconstruction Analytics System), which is a different version of the DAS score developed in the article by [5]. This score provides an assessment of end-of-life building performance right from the design stage. The main objective is to ensure an efficient choice of materials to ensure the circularity of a building at its end of life. The system architecture is based on existing building information. It comprises four layers that are logically connected to function as a single system. Firstly, we have the data storage layer, which collects data about deconstruction, material properties and building design. Secondly, the semantic layer offers two possibilities: the formatting of data exchange and the provisioning of data to the application layer. Thirdly, the analytical and functional layer of the architecture enables the development of D-DAS functionalities: 1. construct analysis of rendering throughout the life of the building, 2. Analysis of deconstruction of building components, 3. Pre-deconstruction analysis, 4. Design advice for deconstruction, and 5. visualize dismantling. Finally, the application layer through BIM software and visualization and simulation platforms.

Although this method allows designers to try out several combinations by proposing alternatives to optimize the building's end-of-life and provides quantified data on a building, this method only quantifies the number of materials that can be reused, not their disassembly potential.

The method proposed by [35] focuses primarily on the reuse of wooden components in the design process. This study focuses on two perspectives. The first aims to study the recyclability at the beginning of the life cycle (SOL) of buildings through a design for disassembly (DfD) strategy by calculating the potential for disassembly and reuse through a system of scoring components one by one. The second evaluates the end-of-life (EOL) potential of buildings to ensure the continuity of wooden components, using a disassembly-based design optimization tool (DfromD).

The study of these two methods revealed that it is preferable to study the potential for reuse right from the design process. It allows better optimization of building components. The DformD-optimization tool was created not only to assess the potential for disassembly and reuse but also to facilitate the use of reused components in new construction.

Finally, in these three methods, several case studies are proposed to understand better how to apply the calculation methods. In Grüter et al. [35] study, the case study is based on an existing residence in Switzerland. In Roithner et al. [52,53] and Akanbi et al. [3], the case studies are carried out on modeled buildings created to test their methods. As with the Grüter method, we cannot be certain that the methods can be applied to pre-existing buildings. However, for existing buildings, no digital mockup exists. It may be that the Grüter et al. [35] method cannot be applied either.

3.2.1.6. Conclusion. Our systematic literature review indicates Dutch approaches dominate the proliferation of disassembly calculation methods. Table 4 explains the difference between the five methods based on eight attributes that were distilled from the literature review. The eight attributes together allow us to evaluate each method and investigate its approach to define the disassembly potential. The technical nature of disassembly requires a detailed breakdown of the building as an object and as an assembly of components and materials. The reliance on LCA was not a priority when calculating the disassembly potential because LCA is mainly focused on the materials flows regardless of the ease or success of materials recovery during building demolishing. Therefore, in the first step, we compared the five methods based on their sensitivity and ability to scan building connections and products during pre-demolition audits or early design stages. The eight attributes used in Table 4 allow us to make specific distinctions on the quantitative nature of each method and its ability to score or scale the disassembly potential and handle the complexity of building nodes or details through a weighing system or agglomerated rating approach.

As a result of our review, one must distinguish theoretical and practical disassembly potential approaches to assess the disassembly potential of a building. Most of the listed calculation methods above are theoretical. The theoretical methods are purely based on technical aspects of disassembly, such as the connection types or materials binding as indicated in the abovementioned methods. Also, the object, whether a building or infrastructure, of dismantling, plays a major role in influencing the disassembly method. For example, Witteveen + Bos tried to implement some practical factors regarding weather influence and the surrounding infrastructure. Our review shows that taking into account external factors like weather underground parameters is more suitable for civil engineering project disassembly evaluation and less for buildings. Civil engineering objects are always part of a 'network.' Buildings are 'connected' with each other during their lifetime. However, it is usually feasible to surround a building with fences and 'start deconstructing' without influencing the surroundings.

Thus, the practical or empirical approach is missing. The practical approach should contain the process and financial factors associated with disassembly at the end of a building's lifespan. The practical approach is influenced by other factors, such as material degradation due to weather influences, the effect of construction work on the surrounding infrastructure and the method of disassembly. The practical approach should involve demolishing contractors and post-demolition approaches to develop consistent disassembly evaluation methods that combine theoretical and practical approaches towards accurate and reliable calculation methods.

3.2.2. What are the criteria to assess the ability to dismantle buildings at the end of their service life?

In defining the potential for disassembly, Elma Durmisevic, in her 2006 doctoral thesis, introduced the principle of disassembly criteria [27]. She identifies 17 sub-criteria necessary to assess the disassembly potential of a building. These criteria are classified into three main categories: functional, technical, or physical. Functional decomposition criteria are used to determine the degree of functionality of a component. Then, technical decomposition criteria are used to determine the order in which products are assembled. The physical decomposition criteria are used to assess the importance of components and whether any replacement is possible. Although there is general agreement that the sub-criteria developed by [27] work form a sound basis for disassembly, they do not take into account all the crucial aspects of disassembly. Indeed, most of these sub-criteria are characterized as technical. However, the environmental and economic aspects of disassembly are not taken into account.

Numerous criteria and principles for disassembly have been introduced as a result. In 2007, Guy & Ciarimboli formulated ten main principles for DfD, taking into account material properties and deconstruction methods, connection types and accessibilities, electrical and plumbing systems and component handling, deconstruction safety, simplicity and interchangeability [36]. These major principles are taken up by most of the scientific community and reformulated in the form of criteria for inclusion in calculation methods. In 2016 and 2018, Verberne revived the methods of Durmicevic and refined them (see Section 3.2.1.1). In 2020, the ISO 20887:2020 report introduced a new criterion based on reuse through the support of economic models. In 2021, the criterion "existence of a detailed plan for disassembly" was developed in the publication by [22] [22]. This is also part of the material passport requirements, where many material passport instances imply the requirement of a disassembly plan. More recently, in [52,53], an approach that takes greater account of building design parameters. Roithner developed an approach that counts the number of materials, the number of components, the mass of each material, the total mass of the product, the mass shares of components, etc. [53]. Very recently, a

Table 4
Comparison of the five calculation methods based on eight attributes extracted from the literature.

Method/ Attribution	Sets terms & definitions for building disassembly	Defines detailed disassembly criteria (technical criteria)	Defines economic criteria (cost-related)	Defines environmental criteria (LCA-based)	Evaluate the disassembly potential based on material components	Evaluate the disassembly potential based on connection composition	Set a quantifiable score for disassembly criteria or subcriteria	Allows to calculate an aggregated indicator for overall disassembly
Van Vliet Method	✓	✓ 7	✓ 1	✓ 1	✘	✓	✓	✓
ISO 20887	✓	✓ 5	✘	✘	✘	✓	✘	✘
ISSO 110250	✓	✓ 3	✘	✘	✘	✓	✓	✘
Witteveen+Bos & CB Methods	✓	✓ 5	✘	✘	✘	✓	✘	✘
Grutër, Roitner & Akanbi Methods	✘	✓ 4	✘	✘	✓	✘	✓	✘

study on design for and from disassembly was published by [35] [35]. They developed a calculation method and a design aid based on numerous criteria divided into 4 categories: reusability (inspired by Hradil et al. [40] [40], structural connections inspired by Enzio Pozzi [32] as well as damage caused during disassembly and accessibility/independence, the importance of which was guaranteed in Thormark's work [59].

Thus, numerous ways have been developed to assess the disassembly potential of buildings, depending on the different study cases or approaches desired. In most cases, however, the same method is used to evaluate the criteria. Their evaluation or grading follows Durmisevic's subjective scale-based evaluation. In other words, each criterion can be assigned a real value between 0 and 1 (or 0 and 5) depending on the situation encountered, 0 being the most unfavorable situation and 1 (or 5) the most favorable. The personal justification of the grading and the subjective interpretation of each detail and connection requires developing more robust ways of evaluation. Our review indicates more than twenty or so publications in existence with calculation methods. The results of our review of indicators across those studies are summarized in Table 5.

As many building disassembly evaluation methods rely on previously developed criteria and make different interpretations for their implementation, the title and wording of each criterion and their definitions may vary between methods or can be found very similar. Table 5 is for information only. The names of the criteria may differ between the appellation in the method and the table. For example, independence may be called crossing [20]. Based on Table 4, six criteria were identified as the most important based on their recurrence across the identified methods. In addition, a hierarchy of criteria from the most important (and recurring) to the least important has been established. The following paragraphs illustrate the criteria individually and list them based on their level of importance, with criterion 1 being the most important and criterion six the least important.

- Criterion 1: Type of Connection

Introduced by Durmisevic [28], this criterion is the most widely used and, therefore, the most important. In fact, almost all the methods for calculating the potential for disassembly use it. This criterion is qualitative. In other words, the evaluation is based on the quality of the connection and not the number. This criterion is generally accompanied by an evaluation scale that assigns a score to a connection according to its type. For example, the score will be higher if the connection is dry (bolt, screw, etc.). If the connection is chemical (glued, welded, etc.), the score will be lower.

- Criterion 2: Component accessibility

The accessibility of the connection is also a very important qualitative criterion. The potential for disassembly will differ if the connection is directly accessible or if there are manipulations to be carried out before the products linked to the connection can be disassembled.

- Criterion 3: Independence of the component

Independence means that the different components of the same layer or different layers are intertwined with each other, either completely, partially or, in the best case, not at all. This criterion is, therefore, a qualitative criterion used in many calculation methods.

- Criterion 4: Geometrical Composition or geometry of product edge

This criterion, which can be confused with the independence of the components, will enable a qualitative assessment to be made of how the components are placed in the composition. It determines whether the composition is open or closed and, therefore, whether the component

Table 5
Comparison of the different calculation methods and the criteria used.

Publications	Criteria: Assemblysequence	Componentaccessibility	Degreeoffreedom	Disassemblysafety	Dismantlingdamage	Easeofassembly	Easeofdisassembly	Elementcomplexity	End − of − lifewaste	Functionalseparation	Geometryofproductedge	Independency	Manufacturingmethod	Normalization/standardization	Reusability	Reversibility	Simplicity	Structuralstrength	Supportingbusinessmodels	Transportability	Treatmentandfinishing	Typeofconnection	Typeofelement	Typeofrelationalmodel
[3]													×			×					×	×	×	
[5]													×			×					×	×	×	
[19,20]		×									×	×										×		
[22]		×		×								×		×		×					×			
Denis et al. 2018		×					×								×	×		×		×	×			
[27]	×	×									×	×		×							×	×	×	×
[35]		×	×		×	×	×	×	×			×	×		×			×			×			
[41]		×		×								×		×			×		×		×			
[42]		×									×	×										×		
[52,53]								×				×												
[64]		×									×	×										×		
[24]		×									×	×										×		
[61]	×	×									×	×	×									×		×
[66]	×	×								×	×	×		×								×		
[69]												×	×									×		

can be disassembled without obstruction.

- Criterion 5: Treatment and Finishing

The treatment and finishing criterion is mainly used for the reuse of materials. However, depending on the different coatings or materials used for finishing, the disassembly potential of a building can be considerably reduced. For example, if asbestos has been used, there will be a safety issue as it is a toxic material and will complicate dismantling. It is, therefore, a qualitative criterion.

- Criterion 6: Dismantling Damage

Dismantling damage is a criterion used less frequently in the methods. It was developed by Grüter et al. [35] and is only used in this method. However, this criterion is relatively important as it will reduce the potential for disassembly and limit the reuse of materials. This criterion is qualitative but can also be quantified according to its use.

4. Discussion

Literature highlights how there is a need for best practice guidance, tools, methods and indicators [33] to disincentivize building demolition towards more sustainable design practices that promote building disassembly and reuse of its parts and components. Building material waste and demolition are design mistakes that can be avoided through the DfD. In this hybrid review, we identified the key criteria and methods that have been developed in the last twenty years to assess building disassembly potential. This field is not new, dating to the work of Brand [13] on what happens after with building they are built and the work of many schools in the 1990ies [21]. However, the EU Circular Economy Action Plan published in 2015 [29] and the introduction of level (s) framework for building sustainable assessment [25] attracted the attention of researchers to this domain. The study is an enabler to future frameworks and tools that aim to provide design for disassembly decision support in the built environment. This is the first comprehensive review of building disassembly evaluation methods and criteria, providing practical recommendations to foster circular economy principles uptake in the construction industry. In the following sections, we discuss the study's key findings and articulate a series of recommendations towards a standardized and comprehensive approach that allows assessing the potential for disassembly of buildings and future reuse of building materials. We further reflect on the strengths and weaknesses of this study and provide future perspectives for policymakers, building stakeholders and scientists.

4.1. Study findings and recommendations

Our review indicates the proliferation of evaluation criteria and methods of building disassembly potential. The scientometric review results confirmed the leadership of the EU member states in the field of DfD, disassembly and reversible building connection systems. The mapping in Fig. 5 revealed a proliferation of ways to measure circularity [26] and quantify or evaluate [54] building disassembly. The high frequency of use of the term 'connection' in paper titles reflects fragmented research that is on the rise in the area of building parts and components. Also, the high use of the term 'circular economy' in the keywords reflects a knowledge gap [4] of the interdependencies in materials reuse and building demountability [64].

Out of 182 publications published between 2004 and 2024, only 18 publications developed quantitative criteria or methods to evaluate the disassembly potential of new or existing buildings. The 18 publications analyzed and presented in Appendix C provide a variety of approaches and methods to evaluate building connections, components, and products on a component level of building level. Also, the study identified eight existing buildings (Table 2) that are constructed based on the DfD principles and can be used as case studies or reference buildings.

More importantly, the systematic literature review presented the most important methods and criteria to assess the building disassembly potential and measure circularity. We found the DGBC method as one of the most relevant and consistent methods [24]. The method is flexible and can evaluate the dismantling potential depending on the type of connection, number of connections for components, products, and structures. Despite the monetization and integration of the environmental impact of materials, the method can be used universally if those aspects are excluded. The Building Circularity Indicator (BCI) indicator remains the most logical criterion to evaluate building connections. Based on the study findings, we strongly recommend the use of the six criteria listed in Table 5 and Section 2.2. Also, the study allowed us to see that accessibility of the connection and dismantling damage criteria are tightly connected in one-factor criteria in most calculation methods. On the other hand, it is better to separate them and rely on the six disassembly criteria listed in Table 5.

On the other hand, the recommended criteria and methods require further development. Most of the reviewed methods remain theoretical and do not emerge from field experience. None of the investigated studies addresses the disassembly sequence for the building components and connections and the structural and accessibility dependencies of construction components, products and materials [1]. The feedback of demolition contractors and workers in real demolition conditions or through demolition audits is missing. Furthermore, most of the methods are generic. There are no specific methods for assessing the future reuse potential of timber or steel building infrastructures [56], for example. In addition, the geographical concentration of the investigated studies in Europe highlights a regional bias in the available research. The lack of a universal, standardized method for calculating building disassembly potential and future materials reuse potential remains a major challenge. The interpretations of the criteria and application of the DGBC method [24], particularly regarding composition and connections, can vary remarkably [14].

4.2. Strengths and limitations of the study

The mixed research methodology that was used, combining both scientometric and systematic methods, was successful in providing a general and specific overview at the same time. The study was able to track most English-speaking publications in a representative and objective way based on Scopus and Google Scholar. However, non-English speaking documents depended on the author's network through the EU COST Actions and CEN committees and the author's search in foreign languages. The non-English speaking content was more random, but we made sure to provide a short English description of those documents in Appendix D. While the literature identified over 50 qualitative and generic studies, there are only around 20 quantitative studies. It demonstrates the lack of maturity in this field. Therefore, we cannot claim to present a fully representative overview. However, to our best knowledge, this work is the first and most date review in this area. The chronological review made it possible to understand the evolution of the methodologies over the study period (2004–2024). We organized more than four workshops to validate with all the authors the method and the results found. We thus ensured the robustness of the approach and its utility during early design stages and pre-demolition audits. One of the main strengths of the study is that many methods have been reviewed, analyzed, and compared. This made it possible to establish links between the different methods and their criteria and to be able to interpret them.

On the other hand, it is important to acknowledge the limitations of the study. Firstly, we deliberately decoupled the evaluation of disassembly potential from its environmental impact and LCA studies. It is important to note that a building exhibiting high disassembly potential is not necessarily a sustainable building. Also, our content evaluation methodology was based entirely on reading and human content analysis.

We did not rely on machines to interpret the text. Finally, the reviewed evaluation methods were not tested on real case studies. Despite the presence of many disassembly methods and projects [55], like the *Tijdelijke Rechtbank* [58], listed in Table 2, we could not find preconstruction examples that applied the disassembly methods. We focused on answering the research question first to identify the most relevant methods for conducting case study-based calculations or benchmarking. Therefore, we believe that our review provides valuable information on the disassembly of buildings. However, it remains theoretical because case studies can shed light on several critical aspects within the field of building demolition and end-of-life.

4.3. Implication on practice and future work

The implications of the research results for practice call for strategic interventions to quantify the sustainability evaluation approaches of the construction industry. Firstly, it is necessary to accelerate the development of a standardized calculation method for assessing the potential for disassembly. There is an urgent need for standardized methods based on case studies and exemplary buildings and databases for building connections. Investing in such a knowledge ecosystem will allow us to learn how to perform the building disassembly evaluations more consistently. Standardized demolition audits are also recommended to ensure a systematic approach to the assessment process. The creation of digital models in BIM format coupled with material passports for disassembled buildings is crucial to evaluate their disassembly potential accurately and swiftly.

Such an approach of standardization and development of evaluation methods should be used not only at the national level but also at the EU and even the international level. This would ensure consistency and effectiveness across borders. The evaluation methods can be coupled with building permit issuing steps and building performance certification. This disassembly evaluation could be linked to building materials passport for all buildings, as well as an obligation to produce digital twins to facilitate dismantling at the end of a building's life. For sure, there are limitations of digital twins and material passports due to the post-occupancy modifications. Builders can glue, cement, or pour a flooring system or create wall finishing that impedes the disassembly potential. Therefore, standardization must go hand in hand with testing the disassembly sequence and materials recovery potential of the most common construction components connections in experimental destruction labs and on-site settings. There is a need to display the structural and accessibility dependencies at connection and product levels to calculate the disassembly potential and, finally, the building materials recovery potential. Experimental investigation can ensure that disassembly and reuse are considered right from the design phase.

We need to remind the reader that the main reason for a low rate of building components reuse and disassembly is 1) the high cost/time needed to disassemble a building [34] and 2) existing standards are not aiding the circular reuse of building components [8]. Current regulations do not allow the reuse of building components and products. Safety, durability, and stability are paramount in the construction, but we need to spread decentralized third-party material testing facilities to cross this barrier. From a research point of view, several major projects need to be carried out. In parallel, the development of the demolition sector, including contractors and workers, should prioritize the acquisition of technical skills for effective on-site dismantling abilities. There is also a need to provide learning material and good scoping/guidelines for the interpretation of disassembly evaluation methods.

Therefore, we believe future research should focus on more detailed case study evaluation to ensure that the disassembly evaluation methods are accurate and can be applied consistently. In addition, there is a need to develop and customize disassembly assessment methods for specific construction technologies, such as wood, steel, concrete, and hybrid constructions. We believe modularity will play a major role in the construction industry under the influence of DfD. This targeted approach will ensure the applicability and accuracy of disassembly potential assessments for various construction materials and methodologies. Through modularity and specialization of the disassembly evaluation methods based on the construction technology, we will be able to steer and manage the positive change towards modular and low-impact buildings in the construction industry.

5. Conclusions

The paper reviewed and discussed evaluation criteria and methods for building disassembly potential. The study approach combined a scientometric approach reviewing >180 publications and systematic reviews of 18 highly relevant publications. The importance of disassembly and revisable connections was highlighted, and examples of DfD-based projects were listed. The paper recommends the calculation methods developed by the Dutch Green Building Council as one of the highly relevant approaches. It presents six key criteria to assess the disassembly potential of buildings, namely: 1) Connection type, 2) Connection accessibility, 3) Independence of the component, 4) Geometrical Composition or geometry of product edge, 5) Treatment and Finishing, and 6) Dismantling Damage. Several challenges were identified, and future research recommendations included the evaluation of case studies and standardization of the disassembly evaluation method based on the study recommendations.

CRediT authorship contribution statement

Shady Attia: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Muheeb Al-Obaidy:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maxime Mori:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Clémentine Campain:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Enola Giannasi:** Visualization, Validation, Software, Investigation, Data curation. **Mike van Vliet:** Writing – review & editing, Validation, Investigation. **Eugenia Gasparri:** Writing – review & editing, Writing – original draft, Validation, Investigation.

Declaration of competing interest

None.

Data availability

A dataset is availavle and cited in the text with a DOI.

Acknowledgments

This study is part of the research project DeConstruct: A circularity evaluation framework for Office Buildings Design supported by Liege University. We want to acknowledge the Sustainable Building Design Lab for the use of data processing software in this research and the valuable support during the focus group discussions and the content analysis of data.

This research was supported by the EU Cost Action 21103 - Implementation of Circular Economy in the Built Environment (CircularB), EU COST Action 20139 - Holistic Design of Taller Timber Buildings (HELEN) and CEN/TC 350/SC1: Sustainability of Construction works. We thank our colleagues from the COST Action Workgroups and CEN/TC 350/SC1 and SC2, who provided insight and expertise that greatly assisted in screening the review papers. However, they may not agree with all of the opinions presented in this study.

Appendix A. Keywords excluded from the Scopus search

- Amino Acids	- Human cell
- Animal	- Hydrogen-Ion Concentration
- Animals	- In vitro study
- Apoptosis	- Medical application
- Biomedical Applications	- Medical nanotechnology
- Cell Deaths	- Molecules
- Cell Line, Tumor	- Mousse
- Cell Nucleus	- Nanoparticle
- Chemistry	- Nanoparticles
- Controlled Drug Delivery	- Nanostructures
- Cyclodextrins	- Neoplasm
- Cytology	- Neoplasms
- Diseases	- Particle Size
- DNA	- PH
- Doxorubicin	- Polyethylene glycols
- Drug delivery	- Polyethylene oxides
- Drug delivery system	- Proteins
- Drug release	- Scanning electron microscopy
- Enzymes	- Silica nanoparticles
- Flocculation	- Sodium
- Fluorescence	- Sulfur compounds
- Genes	- Supramolecular Chemistry
- Hela Cell Line	- Targeted Drug Delivery
- Hela Cells	- Unclassified Drug
- High Resolution Transmission Electron Microscopy	- Zeta Potential

Appendix B. Complete list of review publications

No.	Publication ajouté par les auteurs
Aborde le potentiel de désassemblage de manière quantitatif	
	Akinade, O. O., Oyedele, L. O., Bilal, M., Ajayi, S. O., Owolabi, H. A., Alaka, H. A., & Bello, S. A. (2015). Waste minimisation through deconstruction : A BIM based Deconstructability Assessment Score (BIM-DAS). Resources, Conservation and Recycling, 105, 167-176. https://doi.org/10.1016/j.resconrec.2015.10.018
	Akanbi, L. A., Oyedele, L. O., Omoteso, K., Bilal, M., Akinade, O. O., Ajayi, A. O., Davila Delgado, J. M., & Owolabi, H. A. (2019). Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. Journal of Cleaner Production, 223, 386-396. https://doi.org/10.1016/j.jclepro.2019.03.172
	Campain (2023), Evaluation du potentiel de désassemblage des batiments en bois en vue d'une réutilisation.
	CEN-TC 350-SC 1_N139_Gap consultation draft report
	Cottafava, D., & Ritzen, M. (2021). Circularity indicator for residential buildings : Addressing the gap between embodied impacts and design aspects. Resources, Conservation and Recycling, 164, 105120. https://doi.org/10.1016/j.resconrec.2020.105120
	Dams, B., Maskell, D., Shea, A., Allen, S., Driesser, M., Kretschmann, T., Walker, P., & Emmitt, S. (2021). A circular construction evaluation framework to promote designing for disassembly and adaptability. Journal of Cleaner Production, 316, 128122. https://doi.org/10.1016/j.jclepro.2021.128122
	Denis, F., Vandervaeren, C., & Temmerman, N. D. (2018). Using network analysis and BIM to quantify the impact of Design for Disassembly. Buildings, 8(8). Scopus. https://doi.org/10.3390/buildings8080113
	Durmisevic, E. (2006). Design for disassembly as a way to introduce sustainable engineering to building design & construction.
	Grüter, C. et al. (not published) Design for and from Disassembly with Timber Elements: Strategies based on two Case Studies from Switzerland
	ISSO 110250 Circulariteit in referentiedetails. (s. d.). ISSO. Consulté 7 juillet 2023, à l'adresse https://open.isso.nl/publicatie/isso-rapport-110250-circulariteit-in-referentiedetails/2021
	Platform CB'23 (2023) Losmaakbaar detailleren, in Dutch, Platform CB'23, Version 1.0, Delft, The Netherlands.
	Roithner, C., O. Cencic, M. Honic, et H. Rechberger. « Recyclability Assessment at the Building Design Stage Based on Statistical Entropy: A Case Study on Timber and Concrete Building ». Resources, Conservation and Recycling 184 (2022). https://doi.org/10.1016/j.resconrec.2022.106407.
	Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements and guidance ISO 20887:2020. Consulté le 7 juillet 2023.
	van der Zwaag, M. (2022). Data-Driven Decision-Making for Circular Building Design : Development of an automated decision-support framework for an improved circular design workflow. https://repository.tudelft.nl/islandora/object/uuid%3Ad4752ebd-7d70-4136-b0d7-685fc070ac56
	Van Vliet, M., Van Grinsven, J., Teunizen, J. (2021). Circular Buildings Meetmethodiek Losmaakbaarheid version 2.0. Alba Concepts.
	van Vliet. (2018). *Disassembling the steps towards Building Circularity*.
	Verberne, J.J.H. (2016). Building circularity indicators an approach for measuring circularity of a building
	Xiao, J., Zeng, L., Ding, T., Xu, H., & Tang, H. (2023). Deconstruction evaluation method of building structures based on digital technology. Journal of Building Engineering, 66, 105,901. https://doi.org/10.1016/j.jobe.2023.105901
Aborde DfD de manière qualitatif	
	Abuzied, H., Senbel, H., Awad, M., & Abbas, A. (2020). A review of advances in design for disassembly with active disassembly applications. Engineering Science and Technology, an International Journal, 23(3), 618-624. https://doi.org/10.1016/j.jestch.2019.07.003
	Akinade, O. O., Oyedele, L. O., Ajayi, S. O., Bilal, M., Alaka, H. A., Owolabi, H. A., Bello, S. A., Jaiyeoba, B. E., & Kadiri, K. O. (2017). Design for Deconstruction (DfD) : Critical success factors for diverting end-of-life waste from landfills. Waste Management, 60, 3-13. https://doi.org/10.1016/j.wasman.2016.08.017
	Askar, R., L. Bragança, et H. Gervásio. « Design for Adaptability (DfA)—Frameworks and Assessment Models for Enhanced Circularity in Buildings ». Applied System Innovation 5, no 1 (2022). https://doi.org/10.3390/asi5010024.
	Check-list Conception Réversible, Guide bâtiment durable
	Crowther, P. (2018). Re-Valuing construction materials and components through design for disassembly. In Unmaking Waste in Production and Consumption : Towards The Circular Economy (p. 309-321). Scopus. https://doi.org/10.1108/978-1-78714-619-820181024
	Crowther, P. « Exploring the Principles of Design for Disassembly through Design-Led Research ». In IOP Conf. Ser. Earth Environ. Sci., édité par Behm M., Aranda-Mena G., Wakefield R., et Mellencamp E., Vol. 1101. Institute of Physics, 2022. https://doi.org/10.1088/1755-1315/1101/6/062031.

(*continued on next page*)

(*continued*)

No.	Publication ajouté par les auteurs
	Dinh, D.-H., P. Do, et B. Iung. « Degradation Modeling and Reliability Assessment for a Multi-Component System with Structural Dependence ». Computers and Industrial Engineering 144 (2020). https://doi.org/10.1016/j.cie.2020.106443.
	Fatourou-Sipsi, A., et I. Symeonidou. « Designing [for] the Future: Managing Architectural Parts through the Principles of Circular Economy ». In IOP Conf. Ser. Earth Environ. Sci., Vol. 899. IOP Publishing Ltd, 2021. https://doi.org/10.1088/1755-1315/899/1/012014.
	Fujita, M., T. Fujita, M. Iwata, Y. Iwata, T. Kanemitsu, U. Kimura, K. Koiwa, et al. « Japanese Efforts to Promote Steel Reuse in Building Construction ». Journal of Structural Engineering (United States) 149, no 1 (2023). https://doi.org/10.1061/(ASCE)ST.1943-541×.0003473.
	Honic, Meliha, Iva Kovacic, et Helmut Rechberger. « Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study ». Journal of Cleaner Production 217 (20 avril 2019): 787-97. https://doi.org/10.1016/j.jclepro.2019.01.212.
	Khadim, N., R. Agliata, A. Marino, M.J. Thaheem, et 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.
	Kręt-Grześkowiak, A., & Baborska-Narożny, M. (2023). Guidelines for disassembly and adaptation in architectural design compared to circular economy goals—A literature review. Sustainable Production and Consumption, 39, 1-12. https://doi.org/10.1016/j.spc.2023.04.020
	Laasonen, S., et S. Pajunen. « Assessment of Load-Bearing Timber Elements for the Design for Disassembly ». Buildings 13, no 7 (2023). https://doi.org/10.3390/buildings13071878.
	Mahmoudi Motahar, M., S.H. Hosseini Nourzad, et F. Rahimi. « Integrating Complete Disassembly Planning with Deconstructability Assessment to Facilitate Designing Deconstructable Buildings ». Architectural Engineering and Design Management, 2023. https://doi.org/10.1080/17452007.2023.2187753.
	Munaro, M.R., et S.F. Tavares. « Design for Adaptability and Disassembly: Guidelines for Building Deconstruction ». Construction Innovation, 2023. https://doi.org/10.1108/CI-10-2022-0266.
	Ostapska, K., Gradeci, K., & Ruther, P. (2021). Design for Disassembly (DfD) in construction industry : A literature mapping and analysis of the existing designs. Journal of Physics: Conference Series, 2042(1), 012176. https://doi.org/10.1088/1742-6596/2042/1/012176
	Piccardo, C., et M. Hughes. « Design Strategies to Increase the Reuse of Wood Materials in Buildings: Lessons from Architectural Practice ». Journal of Cleaner Production 368 (2022). https://doi.org/10.1016/j.jclepro.2022.133083.
	Rios, F. C., Chong, W. K., & Grau, D. (2015). Design for Disassembly and Deconstruction—Challenges and Opportunities. Procedia Engineering, 118, 1296-1304. https://doi.org/10.1016/j.proeng.2015.08.485
	Sandin, Y., Cramer, M., & Sandberg, K. (2023). HOW TIMBER BUILDINGS CAN BE DESIGNED FOR DECONSTRUCTION AND REUSE IN ACCORDANCE WITH ISO 20887. WCTE 2023 - World Conference on Timber Engineering 19.-22. June, 2023, Oslo, Norway. https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-65513
	Schaubroeck, S., R. Dewil, et K. Allacker. « Circularity of Building Stocks: Modelling Building Joints and Their Disassembly in a 3D City Model ». In Procedia CIRP, édité par Dewulf W. et Duflou J., 105:712-20. Elsevier B.V., 2022. https://doi.org/10.1016/j.procir.2022.02.119.
	Schwede, D. « Application of RecyclingGraphs for the Optimisation of the Recyclability in Building Information Modelling ». In IOP Conf. Ser. Earth Environ. Sci., édité par Passer A., Lutzkendorf T., Habert G., Kromp-Kolb H., et Monsberger M., Vol. 323. Institute of Physics Publishing, 2019. https://doi.org/10.1088/1755-1315/323/1/012044.
	Zabek, M., L. Hildebrand, M. Wirth, et S. Brell-Cokcan. « Used Building Materials as Secondary Resources - Identification of Valuable Building Material and Automized Deconstruction ». Journal of Facade Design and Engineering 5, no 2 (2017): 25-33. https://doi.org/10.7480/jfde.2017.2.1684.
Désassemblage: un critère parmi d'autres de l'économie circulaire, lien avec ACV ou émissions	
	Ajayabi, A., H.-M. Chen, K. Zhou, P. Hopkinson, Y. Wang, et D. Lam. « REBUILD: Regenerative Buildings and Construction Systems for a Circular Economy ». In IOP Conf. Ser. Earth Environ. Sci., Vol. 225. Institute of Physics Publishing, 2019. https://doi.org/10.1088/1755-1315/225/1/012015.
	Akbarnezhad, A., K.C.G. Ong, et L.R. Chandra. « Economic and Environmental Assessment of Deconstruction Strategies Using Building Information Modeling ». Automation in Construction 37 (2014): 131-44. https://doi.org/10.1016/j.autcon.2013.10.017.
	Andrade, J.B., et L. Bragana. « Assessing Buildings' Adaptability at Early Design Stages ». In IOP Conf. Ser. Earth Environ. Sci., Vol. 225. Institute of Physics Publishing, 2019. https://doi.org/10.1088/1755-1315/225/1/012012.
	Caroli, T., A. Campioli, et M. Lavagna. « Reversible, Sustainable and Circular Constructive Systems: Buildability Conditions ». In Lect. Notes Networks Syst., édité par Calabrò F., Della Spina L., et Piñeira Mantiñán M.J., 482 LNNS:1860-69. Springer Science and Business Media Deutschland GmbH, 2022. https://doi.org/10.1007/978-3-031-06825-6_179.
	Densley Tingley, D. (2013). Design for Deconstruction : An appraisal [Phd, University of Sheffield]. https://etheses.whiterose.ac.uk/3771/
	Eberhardt, L.C.M., H. Birgisdóttir, et M. Birkved. « Life Cycle Assessment of a Danish Office Building Designed for Disassembly ». Building Research and Information 47, no 6 (2019): 666-80. https://doi.org/10.1080/09613218.2018.1517458.
	Escaleira, C., Amoêda, R., & Cruz, P. J. (2019). Connections and joints in buildings : Revisiting the main concepts on building materials life cycle's circularity. IOP Conference Series: Earth and Environmental Science, 225(1), 012062. https://doi.org/10.1088/1755-1315/225/1/012062
	Figl, H., C. Thurner, F. Dolezal, P. Schneider-Marin, et I. Nemeth. « A New Evaluation Method for the End-of-Life Phase of Buildings ». In IOP Conf. Ser. Earth Environ. Sci., Vol. 225. Institute of Physics Publishing, 2019. https://doi.org/10.1088/1755-1315/225/1/012024.
	Hoang, N. H., Ishigaki, T., Watari, T., Yamada, M., Kawamoto, K. (2022). Current state of building demolition and potential for selective dismantling in Vietnam. Waste Management, 149, 218-227. https://doi.org/10.1016/j.wasman.2022.06.007
	Janssens, B., E. Knapen, P. Winkels, et G. Verbeeck. « Outcomes of a Student Research Project on Circular Building Systems - Focus on the Educational Aspect ». In IOP Conf. Ser. Earth Environ. Sci., édité par Passer A., Lutzkendorf T., Habert G., Kromp-Kolb H., et Monsberger M., Vol. 323. Institute of Physics Publishing, 2019. https://doi.org/10.1088/1755-1315/323/1/012138.
	MacKenbach, S., J.C. Zeller, et R. Osebold. « A Roadmap towards Circularity - Modular Construction as a Tool for Circular Economy in the Built Environment ». In IOP Conf. Ser. Earth Environ. Sci., édité par Wallbaum H., Hollberg A., Thuvander L., Femenias P., Kurkowska I., Mjornell K., et Fudge C., Vol. 588. IOP Publishing Ltd, 2020. https://doi.org/10.1088/1755-1315/588/5/052027.
	Mazzoli, C., R. Corticelli, L. Dragonetti, A. Ferrante, J. Van Oorschot, et M. Ritzen. « Assessing and Developing Circular Deep Renovation Interventions towards Decarbonisation: The Italian Pilot Case of "Corte Palazzo" in Argelato ». Sustainability (Switzerland) 14, no 20 (2022). https://doi.org/10.3390/su142013150.
	Nemeth, I., P. Schneider-Marin, H. Figl, M. Fellner, et C. Asam. « Circularity Evaluation as Guidance for Building Design ». In IOP Conf. Ser. Earth Environ. Sci., Vol. 1078. Institute of Physics, 2022. https://doi.org/10.1088/1755-1315/1078/1/012082.
	Rehfeldt, M., S. Porteron, et A. Herbst. « Modelling Circular Economy Action Impacts in the Building Sector on the EU Cement Industry ». In Eceee Ind. Summar Study Proc., 2020-September:133-43. European Council for an Energy Efficient Economy, 2020. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85123021970&partnerID=40&md5=0b818b13911c90532de1a43713c0c89b.
	Roberts, M., S. Allen, J. Clarke, J. Searle, et D. Coley. « Understanding the Global Warming Potential of Circular Design Strategies: Life Cycle Assessment of a Design-for-Disassembly Building ». Sustainable Production and Consumption 37 (2023): 331-43. https://doi.org/10.1016/j.spc.2023.03.001.
	Romnée, A., C. Vandervaeren, O. Breda, et N. De Temmerman. « A Greenhouse That Reduces Greenhouse Effect: How to Create a Circular Activity with Construction Waste? » In IOP Conf. Ser. Earth Environ. Sci., Vol. 225. Institute of Physics Publishing, 2019. https://doi.org/10.1088/1755-1315/225/1/012035.
	Sanchez, B., & Haas, C. (2018). A novel selective disassembly sequence planning method for adaptive reuse of buildings. Journal of Cleaner Production, 183, 998-1010. https://doi.org/10.1016/j.jclepro.2018.02.201
	Smol, M. (2023). Inventory and Comparison of Performance Indicators in Circular Economy Roadmaps of the European Countries. Circular Economy and Sustainability, 3(1), 557-584. https://doi.org/10.1007/s43615-021-00127-9
	Sun, Q., Q. Huang, Z. Duan, et A. Zhang. « Recycling Potential Comparison of Mass Timber Constructions and Concrete Buildings: A Case Study in China ». Sustainability (Switzerland) 14, no 10 (2022). https://doi.org/10.3390/su14106174.

(*continued on next page*)

(*continued*)

No.	Publication ajouté par les auteurs
	Vandervaeren, C., F. Denis, W. Galle, et N. De Temmerman. « Challenging Architectural Design Choices with Quantified Evaluations of the Generality and Adaptability of Plan Layouts ». In Smart Innov. Syst. Technol., édité par Littlewood J., Howlett R.J., Howlett R.J., Howlett R.J., Jain L.C., Jain L.C., et Jain L.C., 203:161-71. Springer Science and Business Media Deutschland GmbH, 2021. https://doi.org/10.1007/978-981-15-8783-2_13.
	Zhang, Z., et J.D. Lee. « Decision-Making Analysis for Pittsburgh's Deconstruction Pilot Using AHP and GIS ». Buildings and Cities 4, no 1 (2023): 292-314. https://doi.org/10.5334/bc.306.
Domaine du bâtiment mais pas ou peu de lien avec le sujet	
	Buildings | Free Full-Text | Construction Waste Audit in the Framework of Sustainable Waste Management in Construction Projects—Case Study. (s. d.). Consulté 5 juillet 2023, à l'adresse https://www.mdpi.com/2075-5309/11/2/61
	Buildings | Free Full-Text | Methods to Account for Design for Disassembly : Status of the Building Sector. (s. d.). Consulté 5 juillet 2023, à l'adresse https://www.mdpi.com/2075-5309/13/4/1012
	Chen, F., He, M., Li, M., Liu, J., Shu, Z., & Li, Z. (2023). Recovery testing of self-centering steel-timber hybrid beam-column connections. Construction and Building Materials, 365, 130,067. https://doi.org/10.1016/j.conbuildmat.2022.130067
	Corfar, D.-A., & Tsavdaridis, K. D. (2022). A comprehensive review and classification of inter-module connections for hot-rolled steel modular building systems. Journal of Building Engineering, 50, 104006. https://doi.org/10.1016/j.jobe.2022.104006
	Designing with reused building components : Some challenges. (s. d.). https://doi.org/10.1080/09613210701559499
	Fang, D., & Mueller, C. (2018). Joinery connections in timber frames : Analytical and experimental explorations of structural behavior. *Proceedings of IASS Annual Symposia, 2018*(20), 1-8.
	Giorgi, S., Lavagna, M., Wang, K., Osmani, M., Liu, G., & Campioli, A. (2022). Drivers and barriers towards circular economy in the building sector : Stakeholder interviews and analysis of five European countries policies and practices. Journal of Cleaner Production, 336, 130395. https://doi.org/10.1016/j.jclepro.2022.130395
	Incelli, F., & Cardellicchio, L. (2021). Progettare una connessione in acciaio con un alto grado di smontaggio : Un'esperienza basata sulla pratica. *Techne*, *22*, 104-113.
	Ismaeel, W. S. E., & Kassim, N. (2023). An environmental management plan for construction waste management. Ain Shams Engineering Journal, 102,244. https://doi.org/10.1016/j.asej.2023.102244
	Jahan, I., Zhang, G., Bhuiyan, M., & Navaratnam, S. (2022). Circular Economy of Construction and Demolition Wood Waste—A Theoretical Framework Approach. Sustainability, 14(17), Article 17. https://doi.org/10.3390/su141710478
	Jin, R., Yuan, H., & Chen, Q. (2019). Science mapping approach to assisting the review of construction and demolition waste management research published between 2009 and 2018. Resources, Conservation and Recycling, 140, 175-188. https://doi.org/10.1016/j.resconrec.2018.09.029
	Kabirifar, K., Mojtahedi, M., Wang, C., & Tam, V. W. Y. (2020). Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management : A review. Journal of Cleaner Production, 263, 121265. https://doi.org/10.1016/j.jclepro.2020.121265
	Kang, K., Besklubova, S., Dai, Y., & Zhong, R. Y. (2022). Building demolition waste management through smart BIM : A case study in Hong Kong. Waste Management, 143, 69-83. https://doi.org/10.1016/j.wasman.2022.02.027
	Liu, H., Qiu, C., Zhao, J., Li, W., Shi, J., Liu, H., & Chen, Z. (2023). Investigation on the mechanical behavior of glulam spliced joints connected with self-tapping screws and prestressed steel strips. Construction and Building Materials, 366, 130,190. https://doi.org/10.1016/j.conbuildmat.2022.130190
	Ness, D. A., & Xing, K. (2017). Toward a Resource-Efficient Built Environment : A Literature Review and Conceptual Model. Journal of Industrial Ecology, 21(3), 572-592. https://doi.org/10.1111/jiec.12586
	Ottenhaus, L.-M., Jockwer, R., Van Drimmelen, D., & Crews, K. (2021). Designing timber connections for ductility – A review and discussion. Construction and Building Materials, 304, 124621. https://doi.org/10.1016/j.conbuildmat.2021.124621
	Plug-and-Play Multistory Mass Timber Buildings : Achievements and Potentials | Journal of Architectural Engineering | Vol 26, No 2. (s. d.). Consulté 5 juillet 2023, à l'adresse https://ascelibrary.org/doi/full/10.1061/%28ASCE%29AE.1943-5568.0000394
	Rebouças, A. S., Mehdipour, Z., Branco, J. M., & Lourenço, P. B. (2022). Ductile Moment-Resisting Timber Connections : A Review. Buildings, 12(2), Article 2. https://doi.org/10.3390/buildings12020240
	Sandhaas, C., Munch-Andersen, J., & Dietsch, P. (2018). Design of Connections in Timber Structures. https://doi.org/10.2370/9783844061444
	Silvestre, J. D., & De Brito, J. (2011). Ceramic tiling in building façades : Inspection and pathological characterization using an expert system. Construction and Building Materials, 25(4), 1560-1571. https://doi.org/10.1016/j.conbuildmat.2010.09.039
	Smol, M., Kulczycka, J., Henclik, A., Gorazda, K., & Wzorek, Z. (2015). The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. Journal of Cleaner Production, 95, 45-54. https://doi.org/10.1016/j.jclepro.2015.02.051
	Zhang, A., Liu, J., Wang, J., Chen, Z., & Li, Y. (2023). Experimental and analytical behavior of light gauge steel-fast growing timber composite shear connections. Structures, 47, 1691-1709. https://doi.org/10.1016/j.istruc.2022.12.006
	Asdrubali, F., G. Grazieschi, M. Roncone, F. Thiebat, et C. Carbonaro. « Sustainability of Building Materials: Embodied Energy and Embodied Carbon of Masonry ». Energies 16, no 4 (2023). https://doi.org/10.3390/en16041846.
	Broniewicz, E., et K. Dec. « Environmental Impact of Demolishing a Steel Structure Design for Disassembly ». Energies 15, no 19 (2022). https://doi.org/10.3390/en15197358.
	Brütting, J., J. Desruelle, G. Senatore, et C. Fivet. « Design of Truss Structures Through Reuse ». Structures 18 (2019): 128-37. https://doi.org/10.1016/j.istruc.2018.11.006.
	Cambier, C., W. Galle, et N. De Temmerman. « Expandable Houses: An Explorative Life Cycle Cost Analysis ». Sustainability (Switzerland) 13, no 12 (2021). https://doi.org/10.3390/su13126974.
	Corfar, D.-A., et K.D. Tsavdaridis. « A Hybrid Inter-Module Connection for Steel Modular Building Systems with SMA and High-Damping Rubber Components ». Engineering Structures 289 (2023). https://doi.org/10.1016/j.engstruct.2023.116281.
	Costanzo, E., et P. Neri. « Certification of Building Eco-Compatibility and Durability: Application to New and Existing Buildings ». In Adv. Archit. Ser., 18:203-10, 2004. https://www.scopus.com/inward/record.uri?eid=2-s2.0-4644256160&partnerID=40&md5=918811b3db359305b62982e1e36cc94e.
	Daly, P. « A Critical Review of Circularity - 'Design for Disassembly' Assessment Methods Applied in the Development of Modular Construction Panels - an Irish Case Study ». E-Prime - Advances in Electrical Engineering, Electronics and Energy 5 (2023). https://doi.org/10.1016/j.prime.2023.100252.
	Denac, M., M. Obrecht, et G. Radonjič. « Current and Potential Ecodesign Integration in Small and Medium Enterprises: Construction and Related Industries ». Business Strategy and the Environment 27, no 7 (2018): 825-37. https://doi.org/10.1002/bse.2034.
	Eberhardt, L.C.M., H. Birgisdottir, et M. Birkved. « Potential of Circular Economy in Sustainable Buildings ». In IOP Conf. Ser. Mater. Sci. Eng., édité par Dabija A.-M., Str. Academiei 18-20 Ion Mincu University of Architecture and Urbanism Sec.1, Bucharest, Drusa M., Univerzitna 8215/1 University of Zilina Zilina, Segalini A., Parco Area delle Scienze 181/A University of Parma Parma, Coisson E., et al., Vol. 471. Institute of Physics Publishing, 2019. https://doi.org/10.1088/1757-899X/471/9/092051.
	Fernandes, J., et P. Ferrão. « A New Framework for Circular Refurbishment of Buildings to Operationalize Circular Economy Policies ». Environments - MDPI 10, no 3 (2023). https://doi.org/10.3390/environments10030051.
	Georgopoulos, C. « Evolution of Structural Design of Concrete Framed Buildings for Net Zero in the UK ». In Lect. Notes Civ. Eng., édité par Ilki A., Çavunt D., et Çavunt Y.S., 349 LNCE:349-58. Springer Science and Business Media Deutschland GmbH, 2023. https://doi.org/10.1007/978-3-031-32519-9_33.
	Gómez de Cózar, J.C., A.G. Martínez, Í.A. López, et M.R. Alfonsea. « Life Cycle Assessment as a Decision-Making Tool for Selecting Building Systems in Heritage Intervention: Case Study of Roman Theatre in Itálica, Spain ». Journal of Cleaner Production 206 (2019): 27-39. https://doi.org/10.1016/j.jclepro.2018.09.169.
	Huovila, P., et N. Westerholm. « Circularity and Sustainability in the Construction Value Chain ». In IOP Conf. Ser. Earth Environ. Sci., Vol. 1078. Institute of Physics, 2022. https://doi.org/10.1088/1755-1315/1078/1/012004.
	Joensuu, T., R. Leino, J. Heinonen, et A. Saari. « Developing Buildings' Life Cycle Assessment in Circular Economy-Comparing Methods for Assessing Carbon Footprint of Reusable Components ». Sustainable Cities and Society 77 (2022). https://doi.org/10.1016/j.scs.2021.103499.
	Kakkos, E., F. Heisel, D.E. Hebel, et R. Hischier. « Towards Urban Mining-Estimating the Potential Environmental Benefits by Applying an Alternative Construction Practice. A Case Study from Switzerland ». Sustainability (Switzerland) 12, no 12 (2020). https://doi.org/10.3390/su12125041.

(*continued on next page*)

(*continued*)

No.	Publication ajouté par les auteurs
	Keena, N., M. Raugei, M.-L. Lokko, M. Aly Etman, V. Achnani, B.K. Reck, et A. Dyson. « A Life-Cycle Approach to Investigate the Potential of Novel Biobased Construction Materials toward a Circular Built Environment ». Energies 15, no 19 (2022). https://doi.org/10.3390/en15197239.
	Lorenzo, T.M., B. Benedetta, C. Manuele, et T. Davide. « BIM and QR-Code. A Synergic Application in Construction Site Management ». In Procedia Eng., édité par Hajdu M. et Skibniewski M.J., 85:520-28. Elsevier Ltd, 2014. https://doi.org/10.1016/j.proeng.2014.10.579.
	Manelius, A.-M., S. Nielsen, et J. Schipull Kauschen. « Rebeauty - Artistic Strategies for Repurposing Material Components ». In IOP Conf. Ser. Earth Environ. Sci., Vol. 225. Institute of Physics Publishing, 2019. https://doi.org/10.1088/1755-1315/225/1/012023.
	Minunno, R., T. O'Grady, G.M. Morrison, et R.L. Gruner. « Exploring Environmental Benefits of Reuse and Recycle Practices: A Circular Economy Case Study of a Modular Building ». Resources, Conservation and Recycling 160 (2020). https://doi.org/10.1016/j.resconrec.2020.104855.
	Mollaei, A., C. Bachmann, et C. Haas. « A Framework for Estimating the Reuse Value of In Situ Building Materials ». In Constr. Res. Congr.: Proj. Manag. Deliv., Controls, Design Mater. - Sel. Pap. Constr. Res. Congr., édité par Jazizadeh F., Shealy T., et Garvin M.J., 3-C:666-76. American Society of Civil Engineers (ASCE), 2022. https://doi.org/10.1061/9780784483978.068.
	Morales-Beltran, M., P. Engür, Ö.A. Şişman, et G.N. Aykar. « Redesigning for Disassembly and Carbon Footprint Reduction: Shifting from Reinforced Concrete to Hybrid Timber–Steel Multi-Story Building ». Sustainability (Switzerland) 15, no 9 (2023). https://doi.org/10.3390/su15097273.
	Nakamura, S., et Y. Kondo. « A Waste Input-Output Life-Cycle Cost Analysis of the Recycling of End-of-Life Electrical Home Appliances ». Ecological Economics 57, no 3 (2006): 494-506. https://doi.org/10.1016/j.ecolecon.2005.05.002.
	Ness, D., J. Swift, D.C. Ranasinghe, K. Xing, et V. Soebarto. « Smart Steel: New Paradigms for the Reuse of Steel Enabled by Digital Tracking and Modelling ». Journal of Cleaner Production 98 (2015): 292-303. https://doi.org/10.1016/j.jclepro.2014.08.055.
	Nordby, A.S., B. Berge, F. Hakonsen, et A.G. Hestnes. « Criteria for Salvageability: The Reuse of Bricks ». Building Research and Information 37, no 1 (2009): 55-67. https://doi.org/10.1080/09613210802476023.
	Pialot, O., D. Millet, et N. Tchertchian. « How to Explore Scenarios of Multiple Upgrade Cycles for Sustainable Product Innovation: The "Upgrade Cycle Explorer" Tool ». Journal of Cleaner Production 22, no 1 (2012): 19-31. https://doi.org/10.1016/j.jclepro.2011.10.001.
	Pujadas-Gispert, E., M. Alsailani, K.C.A. van Dijk (Koen), A.D.K. Rozema (Annine), J.P. ten Hoope (Puck), C.C. Korevaar (Carmen), et S.P.G. Moonen (Faas). « Design, Construction, and Thermal Performance Evaluation of an Innovative Bio-Based Ventilated Façade ». Frontiers of Architectural Research 9, no 3 (2020): 681-96. https://doi.org/10.1016/j.foar.2020.02.003.
	Rajanayagam, H., K. Poologanathan, P. Gatheeshgar, G.E. Varelis, *P. Sherlock*, B. Nagaratnam, et P. Hackney. « A-State-Of-The-Art Review on Modular Building Connections ». Structures 34 (2021): 1903-22. https://doi.org/10.1016/j.istruc.2021.08.114.
	Redoutey, M., S. Ahlquist, J. Shaw, et E. Filipov. « Bending-Active Structures with a Variable Cross-Section Boundary ». In IASS Symp. - Anniv. Symp. Int. Assoc. Shell Spatial Struct.; Struct. Membr. - Int. Conf. Text. Compos. Inflatable Struct., FORM and FORCE, édité par Lazaro C., Bletzinger K.-U., et Onate E., 320-27. International Center for Numerical Methods in Engineering, 2019. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85085733326&partnerID=40&md5=70320b23c707c6fdd1fd5abeff5fd07c.
	Rennen, P., N. Khader, N. Hack, et H. Kloft. « A Hybrid Additive Manufacturing Approach: Combining Additive Manufacturing and Green-State Concrete Milling to Create a Functionally Integrated Loadbearing Concrete Panel System ». In Assoc. Comput. Aided Des. Archit. Annu. Conf., ACADIA, édité par Doe A.S. et Goode B. ACADIA, 2021. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85135327071&partnerID=40&md5=baf20b313ca40998dffedebade1f405e.
	Kremer, G. E., Haapala, K., Murat, A., Chinnam, R. B., Kim, K.-Y., Monplaisir, L., & Lei, T. (2016). Directions for instilling economic and environmental sustainability across product supply chains. Journal of Cleaner Production, 112, 2066-2078. Scopus. https://doi.org/10.1016/j.jclepro.2015.07.076
	Salvalai, G., M.M. Sesana, D. Brutti, et M. Imperadori. « Design and Performance Analysis of a Lightweight Flexible nZEB ». Sustainability (Switzerland) 12, no 15 (2020). https://doi.org/10.3390/su12155986.
	Schwede, D., et E. Störl. « Method for the analysis of the recyclability of building structures ». Bautechnik 94, no 1 (2017): 1-9. https://doi.org/10.1002/bate.201600025.
	Torgautov, B., A. Zhanabayev, A. Tleuken, A. Turkyilmaz, M. Mustafa, et F. Karaca. « Circular Economy: Challenges and Opportunities in the Construction Sector of Kazakhstan ». Buildings 11, no 11 (2021). https://doi.org/10.3390/buildings11110501.
	Vandervaeren, C., W. Galle, A. Stephan, et N. De Temmerman. « More than the Sum of Its Parts: Considering Interdependencies in the Life Cycle Material Flow and Environmental Assessment of Demountable Buildings ». Resources, Conservation and Recycling 177 (2022). https://doi.org/10.1016/j.resconrec.2021.106001.
	Juaristi, M., I. Sebastiani, et S. Avesani. « Timber-Based Façades with Different Connections and Claddings: Assessing Materials' Reusability, Water Use and Global Warming Potential ». Journal of Facade Design and Engineering 10, no 2 (2022): 71-85. https://doi.org/10.47982/jfde.2022.powerskin.5.

The spreadsheet list can be found in [12].

Appendix C. Literature review matrix

Méthode utilisée					
Lecture des introductions, résultats et discussions des articles de la short list.					
No.	**REFERENCE**	**STUDY PARAMETERS**	**FOCUS**	**GAP**	**FINDINGS**
1	Akanbi, L. A., Oyedele, L. O., Omoteso, K., Bilal, M., Akinade, O. O., Ajayi, A. O., Davila Delgado, J. M., & Owolabi, H. A. (2019). Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. Journal of Cleaner Production, 223, 386-396. https://doi.org/10.1016/j.jclepro.2019.03.172	* P = La performance de la construction dans le temps * RU = La fraction réutilisable des matériaux de construction * RC = La fraction recyclable * γ = La fraction de performance * t = Âge du bâtiment en année D15 * NC = Nombre total de connexions * ne = Nombre total d'éléments de construction possibles * ndc = Nombre de connexions démontables * nFb = Nombre d'ensemble préfabriqué * νSf = Volume de	Conception d'un système d'analyze de démontagne/ déconstruction (D-DAS: disassembly and deconstruction analytics system) afin de prendre en compte l'analyze des performances en fin de vie dès le processus de conception et de construction. Intergrer au BIM Fonctionalités developpées: - Analyze la peromance du bâtiment sur toute sa durée de vie - Analyze de la déconstruction des elements - Conseil pour la conception en vue de la déconstruction	Quantifie la quantité de matériaux pouvant être réutilisés, pas leur potentiel de désasemblage.	Cette technique permet aux concepteurs d'essayer plusieurs combinaisons. Fourni des données chiffrées. Le plug-in propose des alternatives pour optimiser la fin de vie du bâtiment. Quantifie la démontabilité via DAS [5]

(*continued on next page*)

(*continued*)

Méthode utilisée

Lecture des introductions, résultats et discussions des articles de la short list.

No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
		matériaux sans finitions secondaires * νm = Volume total des matériaux de construction * νhtt = Volume de matière sans contenu dangereux * α = Durée de vie du batiment * β = Facteur de pondération de l'importance de l'utilisation de connexions démontables sur la réutilisation des matériaux de construction en fin de vie * λ = Facteur de pondération de l'importance de l'utilisation d'ensembles préfabriqués sur la réutilisation des matériaux de construction en fin de vie * μ = Facteur de pondération pour l'importance de spécifier des matériaux sans finitions secondaires sur la réutilisation des matériaux de construction en fin de vie * ρ = Facteur de pondération pour l'importance de la spécification de matériaux sans contenu dangereux sur la réutilisation des matériaux de construction en fin de vie	Appliqué au BIM (plug-in BIM ou visioneuse BIM)		
2	Akinade, O. O., Oyedele, L. O., Bilal, M., Ajayi, S. O., Owolabi, H. A., Alaka, H. A., & Bello, S. A. (2015). Waste minimisation through deconstruction : A BIM based Deconstructability Assessment Score (BIM-DAS). Resources, Conservation and Recycling, 105, 167-176. https://doi.org/10.1016/j.resconrec.2015.10.018	* DAS = Score d'évaluation de la déconstructibilité * M = Ensemble de matériaux, c'est-à-dire M = {M 1, M2, …, Mn} * C = Ensemble de composants, c'est-à-dire C = {C 1, C2, …, Cn} * E = Ensemble de connecteurs, c'est-à-dire E = {E 1, E2, …, En} * DMD = Modèle de conception pour la déconstructabilité * r1 = Est vrai si l'échantillon est. réutilisable * r2 = Est vrai si l'échantillon est. recyclable * P = Est vrai si l'échantillon est. préfabriqué * c = Type de connexion; c = {cf., cb, cn, cd} * cf. = Connexion fixe * cb = Connexion Boulonnée * cn = Connexion clouée * cd = Connexion grace à des cheville	Création d'un model mathématique pour évaluer le potentiel d'un batiment par un score indicateur la déconstructibilité: Building information Modelling based Deconstructability Assessment Score (BIM-DAS) en phase de conception. 3 objectifs: -Identifier les principes de conception critiques qui assurent la déconstructibilité du bâtiment. -Développer un système objectif, i.e. BIM-DAS pour noter le degré de déconstuctibilité des bâtiments -Pour tester les performances et la convivialité du BIM-DAS	Même poids pour le score de déconstruction et de récupération. D'autres critères pourraient être considérés: manipulation du matérial, …	Méthode de calcul developée: - Variables: matériaux, composants, connexion, nombre,position, orientation, toxicité, … - Sortie: Perte, énergie perdue, éléments récupérables, … - > Somme pondérée de Score de déconstruction & Score de récupération = DAS Score Organization en sous-systèmes: couches. Conception de sous-systèmes indépendants Principes de conception DfD: - utilisation de boulon plutôt que de colle - matériaux durables - matériaux sans finitions secondaires - matériaux non toxiques - ensembles préfabriqués + minimise le nombre de type et le nombre de composants et de connexions Economiquement, (CoûtduDfD) < (ValeurdesMatériauxRecylcable) – (CoûtdeElimination)

(*continued on next page*)

(*continued*)

Méthode utilisée					
Lecture des introductions, résultats et discussions des articles de la short list.					
No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
		* n = Nombre totale d'échantillon * t = Type de materiaux de l'échantillon; t = {acier, béton, bois, etc.,} * tn = Rapport type-nombre de materiaux pour le sous-système * x = Est vrai si l'echantillon est. toxique * s = Est vrai si le materiau a des finitions secondaires * v = Volume de l'échantillon en mm3 * φ = Position spatile et orientation de l'échantillon * p = Position de l'échantillon dans l'espace 3D * r = Rotation de l'échantillon dans l'espace 3D * Ew = Le total des déchets en fin de vie * Bq = Nombre totale d'elements dans le batiments * Tr = Total d'élement récupérable dans Bq * ε = Résidus * Ee = L'énergie perdue en fin de vie * Ec = L'énergie grise totale et l'énergie nécessaire à la construction du batiment * Ed = L'énergie grise totale et l'énergie nécessaire à la déconstruction du batiment * Dscore = Score de déconstructibilité * Rscore = Score de récupération * dc = Rapport des connexions démontables			
3	CEN-TC 350-SC 1_N139_Gap consultation draft report	Pas de paramètre d'études puisque pas de mise en œuvre de méthode pour évaluer le potentiel de désassemblage	Passe en revue toute les lacunes des articles, normes, documents sur la circularité des batiments.	A part une section qui aborde le potentiel de désassemble avec le DfD et le Design for reuse, ce document ne fournit pas d'information sur les méthodes de caluls pour le déssassemblage. Ce n'est. qu'une revue des lacunes des normes et des études à propos de la circularité des batiments. Même si le sujet du désassemblage est. abordé puisqu'il fait parti de la circularité d'un batiment.	Les normes à propos du potentiel de réutilisation d'un building ne devraient pas être seulement sur la structure mais aussi sur l'ensemble du bâtiment. Il faudrait ajouter des design/conception avec une espérance de vie indéfinie. Dans l'ISO 20,887 il devrait ajouter des règles par catégories (acier, béton, bois …) Les études devraient prendre en compte la sécurité lors des démolition et déconstruction. Besoin d'un guide/normes et pour réutiliser les éléments de construction, pour écarter la « peur de réutiliser des parties de structure » La facilité et la capacité à déconstruire et réutilisé est. influencer par: - Le type de connexion - Le poids des matériaux - Si le bâtiment est. construit sur site ou avec des éléments préfabriquer H19
4	Cottafava, D., & Ritzen, M. (2021). Circularity indicator for residential buildings :	* BCIplein = Indicateur de circularité du bâtiment (version complète)	Ce concentre éssentiellement sur le développement d'une méthode de calcul servant à	Ne présente pas une méthode de calcul pour évaluer le potentiel de	Dans cette étude, il est. dit que de nos jours (en 2021) il n'existe pas de norme mondialement reconnue quant à la

(*continued on next page*)

(*continued*)

Méthode utilisée					
Lecture des introductions, résultats et discussions des articles de la short list.					
No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
	Addressing the gap between embodied impacts and design aspects. Resources, Conservation and Recycling, 164, 105120. https://doi.org/10.1016/j.resconrec.2020.105120	* BCIsimplifié = Indicateur de circularité du bâtiment (version simplifié) * ICE = Indice de circularité des éléments * Fd = Somme de tous les poids maximaux * Fje = Poids nominal * fj = Facteur pondéral du produit j dans la formulation PBCI * Frj = Fraction de materiau recyclé pour le produit j * Fuj = Fraction de materiau réutilisé pour le produit j * Je = Indice des critères de conception * IR = Recyclabilité intrinsèque * J = Nombre de composants pour l'ensemble du batiment * j = Indice de produit * Js = Nombre total de composants pour la couche s * Lav,j = Durée de vie moyenne d'un produit similaire sur le marché par rapport au produit j * Lj = Durée de vie du produit j * LFI = Indice de débit linéaire * LK = Niveau d'importance * LKs = Niveau d'importance pour les couches s * MCIp = Indicateur de circularité des materiaux pour le produit p * Mj = Masse totale du produit * MADAME = Score de réutilisation des materiaux * Ms. = Masse totale de tous les composants de la couche s * n = Nombre total de critères de conception * PBCI = Indicateur prédictif de circularité des batiments * PBCIplein = Indicateur prédictif de circularité des batiments (version complète) * PBCIsimplifié = Indicateur prédictif de circularité des batiments (version simplifié) * PCIp = Indicateur de circularité du produit * RC = Contenu recyclé * RPI = Indicateur du potentiel des ressources * S = Nombre total de couches de construction * s = Création d'un indice	quantifié la circularité d'une batiment. Il ne prends donc pas que en compte le désassemblage, mais aussi ca réutilisation.	désassemblage mais seulement une méthode pour calculer un indice de circulrité des batiments.	conception pour le désassemblage car ils existent énormément de méthodes. Akinade et al. (2017) ont identifié 15 facteurs regroupé en 3 groupes pour le DfD: - Les facteurs liés aux matériaux; - Les facteurs liés à la conception; - Les facteurs liés aux travailleurs du site. Ils ont également identifié 38 facteurs critiques regroupé en 5 catégories: - Les lois et les politiques rigoureuses - Les processus de conception de déconstruction et compétences - La conception en vue de la réutilisation des matériaux - La conception pour la réutilisation des matériaux - La conception pour la flexibilité du bâtiment Moffatt et Russell (2001) ont introduit quelques principes de DfAD: 1) durabilité, 2) polyvalence, 3) accès aux services, 4) redondance, 5) simplicité, 6) évolutivité, 7) indépendance et 8) information sur les bâtiments.

(*continued on next page*)

(*continued*)

Méthode utilisée

Lecture des introductions, résultats et discussions des articles de la short list.

No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
		de calque * SCI = Indicateur de circularité du système * SCIs = Indicateur de circularité du système * Uav,j = Marché intensité moyenne d'utilisation par an du produit j * Uj = Intensité d'utilisation par an du produit j * Vje = Valeur de l'évaluation * ERV = Efficacité des ressources basée sur la valeur * W0j = Déchets non valorisables provenant de l'écoulement linéaire pour le produit j * WFj = Déchets non valorisables issus du processus de valorisation du produit j * Wj Déchets non valorisabels pour le produit j * Xj = Utilitaire du produit pour le produit j			
5	Dams, B., Maskell, D., Shea, A., Allen, S., Driesser, M., Kretschmann, T., Walker, P., & Emmitt, S. (2021). A circular construction evaluation framework to promote designing for disassembly and adaptability. Journal of Cleaner Production, 316, 128,122. https://doi.org/10.1016/j.jclepro.2021.128122	Pas de paramètres d'étude puisque ce document est. un rapport de ce qu'il manque aux différentes études	Création de l'outil CCEF (Circular Construction Evaluation Framework) pour quantifier le niveau de circularité d'un projet. Application sur 4 cas d'étude de différent type (matériaux conventionnels, préfabrication avec matériaux conventionnels, préfabrication avec matériaux bio-sourcés, construction modulaire). Mise en application des directives internationnales, notamment ISO 20887:2020. Béton, acier, bois.	Notation peu précise: comment savoir avec précision dans quelle tranche de pourcentage se trouve le projet? Pas de pondération des critères.	Le CCEF prend en compte les critères: Conception (désassemblage, adaptibilité, simplicité), sécurité, durabilité, matériaux, traitement, connexions. Chaque critère est. noté de 0 (non circulaire) à 5 (circulaire). Si l'évaluation du critère est. oui ou non, oui=5 et non = 0. Si l'évaluation du critère se fait en %, le pourcentage est. traduit en une note de 0 à 5. Notation de 0 à 5: - 0: <10% - 1: 10–29% - 2: 30–49% - 3: 50–69% - 4: 70–89% - 5: > 90% Résultat sous forme de tableau, une section pour la globalité du bâtiment et une section pour les élements/composants. Le score maximal pouvant être obtenu est. 70, pouvant être converti en pourcentage pour donner unenote globale au bâtiment.
6	Denis, F., Vandervaeren, C., & Temmerman, N. D. (2018). Using network analysis and BIM to quantify the impact of Design for Disassembly. Buildings, 8(8). Scopus. https://doi.org/10.3390/buildings8080113	* Accessbibilité de la connexion, * Transportabilité (en lien avec le poids et le volume du matériaux), * Résistance (point de rupture pour deux éléments liés par une connexion irréversible), * Masse, * Reversibilité de la connexion, * Temps de désassemblage, * Dépendance séquentielle.	Developpement d'une méthode: DNA (Disassembly Network Analysis) pour quantifier l'impact du désassemblage sur les bâtiments. Etudie l'interdépendance des élements. Application de la méthode à 2 exemples: un assemblage linéaire et un assemblage complexe.	Méthode de calcul qui se concentre plus sur des résultats techniques: temps de désassmeblage estimé,transportabilité des composants extraits, … plutôt que sur une quantification du potentiel de désassemblage. Pourrait permettre d'avoir une note pour le potentiel de désassemblage en soustrayant le nombre d'élements récupérés et le nombre d'élements perdus?	Méthode divisée en 4 étapes: - vérification rapide (détermine si l'élement peut être déconnecté) - définition des chemins potentiels (liste des moyens d'accéder de rompre la connexion) - quantification des paramètres (temps de désassemblage, nombre d'élements perdus, …) - résultats
7	Durmisevic, E. (2006). Design for disassembly as a way to introduce sustainable		Etudie les design de conception pour les bâtiments transformables.		2 critères clés: indépendance (fonctionnelle: design) et échangeabilité (technique: ordre hiérachique et physique: connexions)

(continued on next page)

(*continued*)

Méthode utilisée

Lecture des introductions, résultats et discussions des articles de la short list.

No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
	engineering to building design & construction.				Resultat: diagramme radial. KPI for transformation: - décomposition fonctionnelle - systématisation et regroupement - relations hierarchiques entr éléments -spécification de l'élement de base - séquence d'assemblage - géométrie de l'interface - type de connection - coordination du cycle de vie assemblage/ désassemblage+G36 Décompositionn technique - schéma relationnel - spécification de l'élement de base Décomposition physique - géométrie desbords - séquence d'assemblage - connexion - coordination du cycle de vie assemblage/ désassemblage Décomposition fonctionnelle - Indépendance fonctionelle - systématisation
8	Grüter, C. et al. (not published) Design for and from Disassembly with Timber Elements: Strategies based on two Case Studies from Switzerland				
9	ISSO 110250 Circulariteit in referentiedetails. (s. d.). ISSO. Consulté 7 juillet 2023, à l'adresse https://open.isso.nl/publicatie/isso-rapport-110250-circulariteit-in-referentiedetails/2021				
10	Roithner, C., Cencic, O., Honic, M., & Rechberger, H. (2022). Recyclability assessment at the building design stage based on statistical entropy : A case study on timber and concrete building. Resources, Conservation and Recycling, 184. Scopus. https://doi.org/10.1016/j.resconrec.2022.106407	* le nombre de materiaux (Nm), * le nombre d'élément (Ne), * la masse de chaque materiau (Mi), * la masse total du produit (Mp), * les parts massiques des composants (mj; mj = Mj / Mp) Ce qui va permettre de caluler: * la concentration de chaque matériaux (cij) * l'entropie statique (Hj) de chaque partie, * l'entropie statique total (Hp) Grace à l'entropie statique hypothétique maximal (Hmax), on calcule la « recyclabilité inhérente au produit relatif » RPR.	Revoit la technique de Honic et al. [39]. Le document se base sur un seul batiment, qui à été concu pour etre par la suite désassemblé. Technique de calcul appelé RPR (« recyclabilité inhérente au produit relatif ») qui consiste à calculer le taux de recyclabilité d'un batiment en fonction de sa composition et de sa structure. Elle prends en compte ses composants, sous composant et SSC. En appliquant cette méthode, le résultat dinal est. un pourcentage de recyclabilité. Démonstration de la méthode sur un batiment designé et modéliser grace à un logiciel BIM en bois ou en béton. Utilisation d'un passeport pour les différent composant.	Ne prends en compte que les structure en bois et en béton. (voir si il y en à d'autre meme peu utilisée) Etude réalisée seulement sur un batiment concu pour etre désassemblé. Pas de vérification sur d'autres batiments, déjà construit.	Le batiment en béton est. d'avantage recyclable si aucune déconstruction précise n'est. réalisé (= démolition brut), or comme le batiment en bois utilise un nombre de materiaux plus elevé, au niveau des SC et même des SSC, cela permet d'avoir un taux de recyclabilité plus élevé. Le RPR diminue à mesure que les matériaux d'un bâtiment sont mélangés.
11	Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements and guidance ISO 20887:2020. Consulté le 7 juillet 2023.		Vise à fournir un cadre pour les principes de DfD/A et les points clés qui necessitent d'être questionnées par les acteurs de la construction, permettant ainsi d'integrer ces principes au projet. Applicable à tout type de bâtiment et d'ouvrage de génie civil et à tout type de projet (construction neuve, rénovation, …) Les principes décrits dans le document doivent être appliqués aux	Le document n'a pas pour vocation d'établir une méthode de calcul du potentiel de désassemblage. Il dresse un guide succint avec des notations simples (oui/no ou 0 à 5). Il n'a aucune hierarchisation des citères ni note globale.	Les principes à privilegier varient en fonction du scénario d'étude. Par exemple, un principe sera à privilegier plutôt qu'un autre en fonction de la durée de service du bâtiment d'étude. 3 principes de design pour adaptibilité: - versatilité (accueillir diverse fonctions avec peu de changement) - convertibilité (anticiper la possibilité de changement de besoin des utlisateurs) - extensibilité (permet l'ajout de nouveaux espaces, capacité, …) 7 principes de design pour le désassemblage:

(*continued on next page*)

(*continued*)

Méthode utilisée

Lecture des introductions, résultats et discussions des articles de la short list.

No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
			élements et composants principaux, (négliger les élements qui pourraient être obsolètes ex: système de vetilation). Traite des aspects environnementaux, sociaux, economiques, techniques et fonctionnels		- facilité d'accès aux composants - indépendance - éviter les traitements et finitions inutiles - soutien des modèles économiques de réutilisation - simplicité - standardization - sécurité de désassemblage 5 niveaux d'étude: système, élements, composants et assemblage, sous-composant, matériaux. Annexe C: Guide succcint pour mesurer le DfD sans hiérachisation entre les critères. Critère qui penvent être groupée sous forme de check-list dans une matrice. - facilité d'accès aux composants (0 à 5) - indépendance (0 à 5) - éviter les traitements et finitions inutiles (yes/no) - soutien des modèles économiques de réutilisation (% or yes/no) - simplicité - standardization (% par catégorie dimension, composant, connexion, modularité, interopérablité) - sécurité de désassemblage (0 à 5)
12	van der Zwaag, M. (2022). Data-Driven Decision-Making for Circular Building Design : Development of an automated decision-support framework for an improved circular design workflow. https://repository.tudelft.nl/islandora/object/uuid%3Ad4752ebd-7d70-4136-b0d7-685fc070ac56				
13	Van Vliet, M., Van Grinsven, J., Teunizen, J. (2021). Circular Buildings Meetmethodiek Losmaakbaarheid version 2.0. Alba Concepts.	* Type de connexions, * accessibilité de la connexion, * indépendance, * géométrie,	Methode de calcul du potentiel de désassemblage en construction Champ d'application: - pour developper des connexions facilement désassemblables Version anméliorée par rapport à celle de 2019 grâce aux retours et recommandations	Méthode de calcul qui semble être la plus précise.	Le potentiel de détachabilité n'est. pas une indication de circularité à lui seul. La méthode doit donc être appliquée en relation avec d'autres principes de circularité. Attribution d'un score compris entre 0 et 1 pour chaque paramètre en fonction du tableau de référence fourni. Mise en place d'une équation reprenant tous les paramètres (pondérés) pour calculer le potentiel de désassemblage de chaque ensemble plus du bâtiment dans sa globalité.
14	van Vliet. (s. d.). *Disassembling the steps towards Building Circularity*.	* Accessibility to connection * Type of relational pattern * Assembly sequence * Method of fabrication * Independency * Assenmbly shape *Type of connection * Deconstruction safety * Dasassembly instructions * Disassembler expertise * Number of operations * Disassembly costs	une révision de la méthode de calcul l'indicateur de circularité BCI (Building Circularité Indicator) (Verdener, 2016). L'étude se concentre sur l'indicateur « disassembly possibility of a building » qui représente à lui seul 50% sur résultat BCI. Elle tend à valider les hypothèses faites lors de l'élaboration du BCI et à affiner la méthode de calcul du potentiel de désassemblage.		
15	Xiao, J., Zeng, L., Ding, T., Xu, H., & Tang, H. (2023). Deconstruction evaluation method of building structures based on digital technology. Journal of Building Engineering, 66, 105901. https://doi.org/10.1016/j.jobe.2023.105901	* Ddéconstruction * Ed = énergie totale libéré au cours du processes de déconstruction * Eq = énergie nécessaire à la déconstruction * Er = ressource énergétique des objets déconstruits	Développement d'une méthode pour évaluer la déconstruction des structures des bâtiments grâce à l'utilisation d'une technique de balayage laser. Cette technique de balayage sans contact permettrait d'évaluer la déconstruction, améliorer la sécurité et faciliter la		

(*continued on next page*)

(*continued*)

Méthode utilisée					
Lecture des introductions, résultats et discussions des articles de la short list.					
No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
		* ε = énergie libéré pour d'autres raison (pertes) * Dr. = mesure dans laquelle l'élémetn de structure du batiment peut etre déconstruit * Rr = N qui peuvent etre recyclé * Or = enironnement ou se situe le batiment * ti = rapport des différentes formes de structure * di = rapport du mode de connexion des composants * ri = rapport entre les éléments préfabriqués ou les unités directement décomposables *pi = rapport entre les composants ou les unités et la position dans la structure du bâtiment à déconstruire * R1…Rn = forme de ressource de chaque élément structurel après avoir été déconstruit * tm et sm = conditions exterieurs (toxique ou suffisant) * hm = facteurs humains * pm = processus technique * mm = méthodes de construction * i = type de facterus d'influence pertinents * n = nombre total de parties structurelles * CCi = cout de la déconstruction * RPRi = cout de materiaux directement recyclables et déconstruit * CDL = cout économisé par l'élimination de déchet * ACCi = le coût de modification de l'utilisation secondaire des composants après la déconstruction de la structure, * CTi = cout de transport engendré par l'utilisation des ressources * CDi = cout de déconstruction * CRi = cout de l'utilisation des ressources * Cde = cout de la déconstruction * Vu = valeur d'utilisation * Cdi = cout de l'elimination	transformation de la démolition destructrice en une démolition optimale		

The spreadsheet list can be found in [12].

Appendix D. Explanations for key non-English references

Author(s)	Report Title
[23]	***Circular buildings: Meetmethodiek Losmaakbaarheid versie 1.1. the Hague, The Netherlands.***
The document is developed by the Dutch Circular Building with Disassembly Details Guide. This guideline goes a step further and offers concrete tools to design releasable details as well as possible, both in the building sector. The study of Dutch Circular Building builds on the ISSO report and DGBC method and provides a constructive feedback and guidance on how to improve the disassembly potential of building connections. In this case, the study goes one step further to improve the details rather than just evaluating them.	
[42]	***Rapport 110,250 Circulariteit in referentiedetails. Rotterdam, The Netherlands.***
The ISSO (2020) Reference Details report provide examples of dismantlable building products and components connections through detailed section drawings. The drawings are colored and represent the different building materials. The construction details are based on the EU CPR definition for products with CE marking. The report shows different types of connections and compositions for building products and evaluates the ease of disassembly to reuse the dismantle building components or products. The disassembly evaluation is based on characterizing the type of connection and the accessibility to the connection during the demolition process. The disassembly potential calculation approach is based on the DGBC (2022) method developed together with Alba Concepts. The ISSO report, written in Dutch, does discuss the disassembly potential of existing construction details, but not how those details can be improved in terms of disassembly. The document is therefore a good start, but not yet sufficiently useful for those who want to design and build for disassembly in practice.	
van Vliet et al. [62].	***Circular buildings: Meetmethodiek Losmaakbaarheid versie 1.1.***
This document is an early version of the Dutch Circular buildings: Disassembly potential measurement method version that was published in November 2019, the report 'Circular Buildings – a measuring methodology for releasability' has been published containing the first five practical examples. These are calculated using the Detachability measurement method v1.0. One of the practical examples is the Temporary Court on the Zuidas in Amsterdam. Various circular design principles were used in this project. Most of the document is embedded in DGBC v2. [24]	
Platform CB'23 [50]	***Losmaakbaar detailleren. Delft, Netherland.***
This guideline provides concrete tools for releasable details as well possible to design, both in the building construction and civil engineering sector. The guide builds on this existing initiatives, such as the aforementioned measurement methods, the ISSO report and the Platform CB'23-guidelines Facilitating future reuse (2023) and Circular design (2021), both of which address disassembly. The guide states that the type of connection and the accessibility and replaceability of connections in existing buildings are often not drawn but are essential for the disassembly. Also recording information about the materials, construction products and elements, so that later it is known what can and should be done with it (for example in a materials passport). Broad disassembly of building components principles is formulated. The purpose of this guideline is to encourage designers to provide releasable detailing. Therefore, the guidance contains many example details. The guide includes valuable terms and definitions of disassembly and related concepts in circulation.	
Teunizen et al. [58]	***Meetmethodiek losmaakbaarheid—Casestudy Tijdelijke Rechtbank. Dutch Green Building Council.***
Based on the disassembly calculations method of DGBD (2021) this report presents a case study for a courthouse in Amsterdam. A building inspection concluded that the disassembly index v2.0 of the Temporary Court is 62% and therefore lower than the dismantling index v1.0 of 88%. The main reasons for this lower score are the factors 'intersections' and 'form containment' of the connections that are of little use where it is the main supporting structure and facade, which means: the disassembly is positively influenced by a proportional weighting of the four releasability indicators included in the formula at v1.0. During the building inspection it turned out that spacious 90% of the products match exactly the way with the as the built drawings. The quality/lifespan, where disassembly influences both elements. After all, is loosening a bolt or nut requires more labor, and non-detachable products provide consequential damage to underlying products and therefore a limited reuse value.	
Witteveen+Bos [68]	***Beoordelingsmethode Losmaakbaarheid in de GWW. Versie 1.0***
The Witteveen+Bos [68] Evaluation method for buildings disassembly provides designers with relevant insights to design structures that are more modular/demountable. The method report, written in Dutch, is based on a hierarchical classification system for building components and materials associated with the life expectancy. Discusses the disassembly potential of existing construction details, but not how those details can be improved in terms of disassembly. The method is purely theoretical and is focused on the technical aspects of disassembly, for example the connection types or materials binding. These methods to measure detachability are already widely used. However, these publications do not discuss the practice of architectural detachable details, while that is the most important topic for designers and builders.	

References

[1] H. Abu-Ghaida, M. Ritzen, A. Hollberg, et al., Accounting for product recovery potential in building life cycle assessments: a disassembly network-based approach, International Journal of Life Cycle Assessment (2024), https://doi.org/10.1007/s11367-024-02324-8.

[2] ADEPT, Rasmus Hjortshøj—COAST · The Braunstein Taphouse · Divisare, Available from: https://divisare.com/projects/432510-adept-rasmus-hjortshoj-coast-the-braunstein-taphouse, 2023. accessed: 24.01.2024.

[3] L.A. Akanbi, L.O. Oyedele, K. Omoteso, M. Bilal, O.O. Akinade, A.O. Ajayi, J. M. Davila Delgado, H.A. Owolabi, Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy, Journal of Cleaner Production 223 (2019) 386–396, https://doi.org/10.1016/j.jclepro.2019.03.172.

[4] N.G. Akhimien, E. Latif, S.S. Hou, Application of circular economy principles in buildings: a systematic review, Journal of Building Engineering 38 (2021) 102041, https://doi.org/10.1016/j.jobe.2020.102041.

[5] O.O. Akinade, L.O. Oyedele, M. Bilal, S.O. Ajayi, H.A. Owolabi, H.A. Alaka, S. A. Bello, Waste minimisation through deconstruction: a BIM based Deconstructability assessment score (BIM-DAS), Resources, Conservation and Recycling 105 (2015) 167–176, https://doi.org/10.1016/j.resconrec.2015.10.018.

[6] A.S. Allam, M. Nik-Bakht, Supporting circularity in construction with performance-based deconstruction, Sustainable Production and Consumption 45 (March 2024) (2023) 1–14, https://doi.org/10.1016/j.spc.2023.12.021.

[7] M. Al-Obaidy, L. Courard, S. Attia, A parametric approach to optimizing building construction systems and carbon footprint: a case study inspired by circularity principles, Sustainability 14 (6) (2022) 3370, https://doi.org/10.3390/su14063370.

[8] K. Anastasiades, J. Goffin, M. Rinke, M. Buyle, A. Audenaert, J. Blom, Standardisation: an essential enabler for the circular reuse of construction components? A trajectory for a cleaner European construction industry, Journal of Cleaner Production 298 (2021) 126864, https://doi.org/10.1016/j.jclepro.2021.126864.

[9] S. Attia, Regenerative and Positive Impact Architecture, Springer International Publishing, 2018, https://doi.org/10.1007/978-3-319-66718-8.

[10] S. Attia, Content Analysis, ULiege, IFRES, 2020. Available from: https://tinyurl.com/qorc2x3. accessed: 24.01.2024.

[11] S. Attia, M. Al-Obaidy, Design Criteria for Circular Buildings, Crossing Boundaries, Parkstadt, The Netherlands, 2021. https://orbi.uliege.be/handle/2268/258348.

[12] S. Attia, M. Al-Obaidy, M. Mori, C. Campain, Review lists and publications on disassembly calculation methods and criteria for buildings, 2024, https://doi.org/10.7910/DVN/SHLD4D. Harvard Dataverse, V1 [dataset].

[13] S. Brand, How Buildings Learn: What Happens after they're Built, Penguin, New York, USA, 1995. ISBN : 978-1-101-56264-2.

[14] C. Campain, Evaluation du potentiel de désassemblage des batiments en bois en vue d'une réutilisation [MSc Thesis], ENTPE, Lyon, France, 2023.

[15] CEPEZED, Demontage tijdelijke rechtbank amsterdam nadert einde, 2022. Available from: https://www.cepezed.nl/en/news/dismantling-temporary-court-amsterdam-is-nearing-completion/91458/. accessed: 24.05.2024.

[16] CEPEZED, The Green house, 2024. Available from: https://www.cepezed.nl/nl/project/the-green-house/22172/. accessed: 24.05.2024.

[17] Circl, A completely circular and innovative pavilion, 2017, September 20. MaterialDistrict. Available from: https://materialdistrict.com/article/circl-circular-pavilion/. accessed: 24.05.2024.

[18] Circulaire BouwEconomie, Demontage Tijdelijke Rechtbank Amsterdam, Available from: https://www.youtube.com/watch?v=PfHJrUoT7Gc, 2023. accessed: 24.05.2024.

[19] 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.

[20] 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.

[21] P. Crowther, Exploring the Principles of Design for Disassembly through Design-led Research 1101(6), Scopus, 2022, https://doi.org/10.1088/1755-1315/1101/6/062031.

[22] B. Dams, D. Maskell, A. Shea, S. Allen, M. Driesser, T. Kretschmann, P. Walker, S. Emmitt, A circular construction evaluation framework to promote designing for disassembly and adaptability, Journal of Cleaner Production 316 (2021) 128122, https://doi.org/10.1016/j.jclepro.2021.128122.

[23] DGBC, Circular Buildings: Meetmethodiek Losmaakbaarheid Versie 1.1. The Hague, the Netherlands, Available from: https://www.dgbc.nl/publicaties/circula

r-buildings-een-meetmethodiek-voor-losmaakbaarheid-v11-26, 2019. Accessed: 30.05.2024.
[24] DGBC, Circular Buildings: Disassembly Potential Measurement Method Version 2.0. The Hague, the Netherlands, Available from: https://www.dgbc.nl/publicaties/circular-buildings-een-meetmethodiek-voor-losmaakbaarheid-v20-41, 2021. accessed: 24.05.2024.
[25] C. Díaz-López, M. Carpio, M. Martín-Morales, M. Zamorano, Defining strategies to adopt level (s) for bringing buildings into the circular economy. A case study of Spain, Journal of Cleaner Production 287 (2021) 125048, https://doi.org/10.1016/j.jclepro.2020.125048.
[26] P. Dräger, P. Letmathe, L. Reinhart, F. Robineck, Measuring circularity: evaluation of the circularity of construction products using the ÖKOBAUDAT database, Environmental Sciences Europe 34 (1) (2022) 13, https://doi.org/10.1186/s12302-022-00589-0.
[27] E. Durmisevic, Transformable building structures: design for dissassembly as a way to introduce sustainable engineering to building design & construction, 2006. PhD dissertation, Delft, the Netherlands, available from: https://repository.tudelft.nl/islandora/object/uuid%3A9d2406e5-0cce-4788-8ee0-c19cbf38ea9a. accessed: 24.01.2024.
[28] E. Durmisevic, P.R. Beurskens, R. Adrosevic, R. Westerdijk, Systemic view on reuse potential of building elements, components and systems: Comprehensive framework for assessing reuse potential of building elements, in: International HISER Conference on Advances in Recycling and Management of Construction and Demolition Waste 21–23 June 2017, Delft University of Technology, Delft, The Netherlands, 2017, pp. 275–280. https://research.utwente.nl/en/publications/systemic-view-on-reuse-potential-of-building-elements-components-.
[29] L.C.M. Eberhardt, H. Birgisdottir, M. Birkved, Potential of Circular Economy in Sustainable Buildings vol. 471(9), Scopus, 2019, https://doi.org/10.1088/1757-899X/471/9/092051.
[30] EISMEA, Study on Measuring the Application of Circular Approaches in the Construction Industry Ecosystem, European Innovation Council and SMEs Executive Agency. European Commission, Brussels, Belgium, 2023, https://doi.org/10.2826/488711. ISBN: 978-92-9469-579-6.
[31] Ellen MacArthur Foundation, Circularity indicators: An approach to measuring circularity, 2015. Circularity-Indicators_Project-Overview_May2015.pdf. Available from: https://www.ellenmacarthurfoundation.org/assets/downloads/insight/. accessed: 24.05.2024.
[32] L. Enzio Pozzi, Design for Change: An Adaptable Housing Complex which Deals with the Impermanence of Architecture, MSc Thesis, TU-Delft, Delft, The Netherlands, 2020.
[33] 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 built environment, sec, Sustainable Building Design and Construction 9 (2023), https://doi.org/10.3389/fbuil.2023.1239757.
[34] M. Gorgolewski, Designing with reused building components: some challenges, Building Research and Information 36 (2) (2008), https://doi.org/10.1080/09613210701559499. Article 2.
[35] C. Grüter, M. Gordon, M. Muster, F. Kastner, P. Grönquist, A. Frangi, S. Langenberg, C. De Wolf, Design for and from disassembly with timber elements: strategies based on two case studies from Switzerland, Frontiers in Built Environment 9 (2023), https://doi.org/10.3389/fbuil.2023.1307632.
[36] B. Guy, N. Ciarimboli, B. Guy, N. Ciarimboli, Design for disassembly in the built environment: a guide to closed-loop design and building, Pennsylvania State University, 2007. Available from: https://www.lifecyclebuilding.org/docs/DfDseattle.pdf. accessed 31.05.2024.
[37] Harmonic Mean, Available from: https://en.wikipedia.org/wiki/Harmonic_mean, 2024. accessed 31.05.2024.
[38] Hedgehog Company, Expressing environmental impact in euros (or dollars) for the ECI, 2023, November 20. Available from: https://www.hhc.earth/knowledge-base/the-eci-explained. accessed 24.01.2024.
[39] M. Honic, I. Kovacic, H. Rechberger, Improving the recycling potential of buildings through material passports (MP): an Austrian case study, Journal of Cleaner Production 217 (2019) 787–797, https://doi.org/10.1016/j.jclepro.2019.01.212.
[40] P. Hradil, A. Talja, V. Ungureanu, H. Koukkari, L. Fülöp, Reusability indicator for steel-framed buildings and application for an industrial hall, Ce/Papers 1 (2–3) (2017), https://doi.org/10.1002/cepa.511. Article 2–3.
[41] ISO, ISO 20887:2020, Sustainability in Buildings and Civil Engineering Works — Design for Disassembly and Adaptability — Principles, Requirements and Guidance, 2020. Geneva, Switzerland.
[42] ISSO, Rapport 110250 Circulariteit in referentiedetails, 2023. Rotterdam, the Netherlands. Available from: https://open.isso.nl/publicatie/isso-rapport-110250-circulariteit-in-referentiedetails/2021. accessed 31.05.2024.
[43] H. Li, H. Johra, F. de Andrade Pereira, T. Hong, J. Le Dréau, A. Maturo, M. Wei, Y. Liu, A. Saberi-Derakhtenjani, Z. Nagy, A. Marszal-Pomianowska, D. Finn, S. Miyata, K. Kaspar, K. Nweye, Z. O'Neill, F. Pallonetto, B. Dong, Data-driven key performance indicators and datasets for building energy flexibility: a review and perspectives, Applied Energy 343 (2023) 121217, https://doi.org/10.1016/j.apenergy.2023.121217.
[44] T. Lukianova, C. Kayaçetin, L. Lefevre, A. Versele, R. Klein, BIM-based circular building assessment and design for demountability, in: CLIMA 2022 Conference. 22–25 May, Rotterdam, The Netherlands, 2022, https://doi.org/10.34641/clima.2022.291.
[45] J. Mingers, L. Leydesdorff, A review of theory and practice in scientometrics, European Journal of Operational Research 246 (1) (2015) 1–19, https://doi.org/10.1016/j.ejor.2015.04.002.
[46] Müller Sigrist Architekten, Design for disassembly—Building Social Ecology, Available from: https://www.buildingsocialecology.org/patterns/design-for-disassembly/, 2022. accessed: 24.05.2024.
[47] Architekten, Solares Direktgewinnhaus N11—Building Social Ecology, Available from: https://www.buildingsocialecology.org/projects/solares-direktgewinnhaus-n11-zweisimmen/, 2022. accessed: 24.05.2024.
[48] OECD, Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences, OECD Publishing, Paris, France, 2019, https://doi.org/10.1787/9789264307452-en.
[49] L.-M. Ottenhaus, R. Jockwer, D. van Drimmelen, K. Crews, Designing timber connections for ductility – a review and discussion, Construction and Building Materials 304 (2021) 124621, https://doi.org/10.1016/j.conbuildmat.2021.124621.
[50] Platform CB'23, Losmaakbaar detailleren, 2023. Delft, Netherland. Available from: https://platformcb23.nl/wp-content/uploads/PlatformCB23_Leidraad_Losmaakbaar-detailleren.pdf. accessed 31.05.2024.
[51] RAU, Triodos Bank, Thonet, Gispen. Archello, Available from: https://archello.com/fr/project/triodos-bank, 2023, November 22. accessed: 02.05.2024.
[52] C. Roithner, O. Cencic, M. Honic, H. Rechberger, Recyclability assessment at the building design stage based on statistical entropy: a case study on timber and concrete building. Resources, conservation and recycling 184, Scopus, 2022, https://doi.org/10.1016/j.resconrec.2022.106407.
[53] C. Roithner, O. Cencic, M. Honic, H. Rechberger, Recyclability assessment at the building design stage based on statistical entropy: a case study on timber and concrete building. Resources, conservation and recycling 184, Scopus, 2022, https://doi.org/10.1016/j.resconrec.2022.106407.
[54] W. Salama, Design of concrete buildings for disassembly: an explorative review, International Journal of Sustainable Built Environment 6 (2) (2017) 617–635, https://doi.org/10.1016/j.ijsbe.2017.03.005.
[55] Y. Sandin, E. Shotton, M. Cramer, K. Sandberg, S.J. Walsh, J. Östling, A. Zabala Mejia, Design of Timber Buildings for Deconstruction and Reuse—Three Methods and Five Case Studies, 2022. Göteborg, Sweden. RISE report 2022:52; ISBN 978-91-89561-92-2.
[56] K. Sandberg, Y. Sandin, A. Harte, E. Shotton, M. Hughes, D. Ridley-Ellis, C. Cristescu, Summary Report InFutUReWood–Innovative Design for the Future–use and Reuse of Wood (Building) Components, 2022. RISE Rapport, 08. Göteborg, Sweden. ISBN: 978-91-89561-23-6.
[57] S. Schaubroeck, R. Dewil, K. Allacker, Circularity of Building Stocks: Modelling Building Joints and their Disassembly in a 3D City Model vol. 105, Scopus, 2022, pp. 712–720, https://doi.org/10.1016/j.procir.2022.02.119.
[58] J. Teunizen, M. van Vliet, R. Zonnevijlle, Meetmethodiek losmaakbaarheid—Casestudy Tijdelijke Rechtbank. Dutch Green Building Council, Rotterdam, the Netherlands, available form: https://www.dgbc.nl/publicaties/meetmethodiek-losmaakbaarheid-casestudy-tijdelijke-rechtbank-51, 2021. accessed 31.05.2024.
[59] C. Thormark, Recycling Potential and Design for Disassembly in Buildings, Lund Institute of Technology, Lund, Sweden, 2001 (ISSN 1103-4467).
[60] UKGBC, Circular economy metrics for buildings: a deep dive into best practice approaches for measuring circular economy principles in the built environment, UK Green Building Council, 2023. Available from: https://ukgbc.org/resources/circular-economy-metrics-for-buildings/. accessed 31.05.2024.
[61] M. van Vliet, Disassembling the steps towards building circularity: redeveloping the building disassembly assessment method in the building circularity indicator, Eindhoven University of Technology, Eindhoven, the Netherlands, 2018. Available from: https://pure.tue.nl/ws/portalfiles/portal/122509202/Vliet_0946226_thesis.pdf. accessed 31.05.2024.
[62] M. van Vliet, J. van Grinsven, J. Teunizen, Circular buildings: Meetmethodiek Losmaakbaarheid versie 1.1, 2019. Rotterdam, The Netherlands.
[63] M. van Vliet, J. van Grinsven, J. Teunizen, Circular buildings: disassembly potential measurement method version 2.0, 2021. Available from: https://www.dgbc.nl/publicaties/circular-buildings-een-meetmethodiek-voor-losmaakbaarheid-v20-41. accessed: 24.04.2024.
[64] C. Vandervaeren, W. Galle, A. Stephan, N. De Temmerman, More than the sum of its parts: considering interdependencies in the life cycle material flow and environmental assessment of demountable buildings, in: Resources, Conservation and Recycling 177, Scopus, 2022, https://doi.org/10.1016/j.resconrec.2021.106001.
[65] Vandkunsten Architects, Social Housing designed for reuse, 2023, November 21. Available from: https://vandkunsten.com/en/projects/circle-house. accessed: 24.04.2024.
[66] J.J.H. Verberne, Building circularity indicators: an approach for measuring circularity of a building, Master Thesis, Eindhoven University of Technology, Eindhoven, the Netherlands, 2016. Available from: https://pure.tue.nl/ws/portalfiles/portal/46934924/846733-1.pdf. accessed 31.05.2024.
[67] A. Welch, T Centrum Westerlo, Belgium: Kamp C Building. E-Architect, Available from: https://www.e-architect.com/belgium/t-centrum-westerlo-kamp, 2022, May 22. accessed 30.04.2024.
[68] Witteveen+Bos, Beoordelingsmethode Losmaakbaarheid in de GWW. Versie 1.0. Een tool voor 1283 ontwerpers, voor het meten van losmaakbaarheid, Witteveen+Bos, Deventer, The Netherlands, 2023.
[69] J. Xiao, L. Zeng, T. Ding, H. Xu, H. Tang, Deconstruction evaluation method of building structures based on digital technology, Journal of Building Engineering 66 (2023) 105901, https://doi.org/10.1016/j.jobe.2023.105901.
[70] C. Zhang, M. Hu, F. Di Maio, B. Sprecher, X. Yang, A. Tukker, An overview of the waste hierarchy framework for analyzing the circularity in construction and

demolition waste management in Europe, Science of The Total Environment 803 (2022) 149892, https://doi.org/10.1016/j.scitotenv.2021.149892.

Chapter 04. *Expert system for building disassembly potential evaluation and inspection – Journal paper*

Abstract: In architectural and construction practices, there is a need for decision support systems that include disassembly evaluations in the early design and deconstruction stages of buildings. Despite the growth of simulation programs over the past decade, there is a lack of ready-to-use applications for evaluating the deconstruction potential of buildings. Furthermore, most available tools focus on analyzing the environmental performance of a building while ignoring the technical issues of connection disassembly. In this study, an expert system was developed to classify the connections in demountable buildings and applied to case studies of newly constructed circular buildings to evaluate their disassembly potential. Disassembly criteria and barriers were identified by reviewing the literature. The fieldwork included the observation of more than 2500 connection systems in these circular buildings via standardized inspections. A statistical analysis of the disassembly barriers observed during these inspections was conducted, and their ability to dismantle the most probable connections was evaluated. The interpretation of these data allowed the creation of an inventory of measures to be implemented to ensure the ease and quality of disassembly, helping the practicing engineer and the disassembly team in their practice. This proposed expert system is considered the first step toward a thorough understanding of the impact of design on the disassembly criteria of and barriers to circularity. Its further development will contribute to the accurate forecasting of the disassembly potential of buildings and material recoverability.

Role of Ph.D. candidate: As first author, the Ph.D. candidate originated the expert-system concept and inspection protocol (conceptualization/methodology, Lead), coordinated fieldwork and dataset assembly (investigation/data curation/project administration, Lead), implemented the scoring prototype (software, Lead), performed statistical analyses and validation (formal analysis/validation, Lead), prepared workflows and result graphics (visualization, Lead), and wrote the first full draft (writing – original draft, Lead). Co-authors contributed supervision and writing – review & editing (Equal).

Journal: Building Engineering (Elsevier)

Journal impact factor: Current Impact Factor: 7.4

5-Year Impact Factor: 7.5

Citations: Google Scholar: 8

Reference: Al-Obaidy, M., Carens, H., Campain, C., Giannasi, E., Mori, M., van Vliet, M., & Attia, S. (2025). Expert system for building disassembly potential evaluation and inspection. Journal of Building Engineering, 103, 112148. https://doi.org/10.1016/j.jobe.2025.112148 & https://hdl.handle.net/2268/328510

Journal of Building Engineering 103 (2025) 112148

Contents lists available at ScienceDirect

Journal of Building Engineering

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

Expert system for building disassembly potential evaluation and inspection

Muheeb Al-Obaidy [a,b,*], Hilde Carens [b], Clémentine Campain [a,c], Enola Giannasi [d], Maxime Mori [d], Mike van Vliet [e], Shady Attia [a]

[a] Sustainable Building Design Laboratory, Department. Urban and Environmental Engineering, School of Engineering, Université de Liège, 4000, Liège, Belgium
[b] Sustainable Building Materials, Construction Department, Colruyt Group, 1500, Halle, Belgium
[c] ENTPE, University of Lyon, 3 rue Maurice Audin Vaulx-en-Velin, 69120, France
[d] EPF Graduate School of Engineering, 2 Rue Fernand Sastre, Rosières-près-Troyes, 10430, France
[e] Alba Concepts and BCI Gebouw, 's-Hertogenbosch, the Netherlands

ARTICLE INFO

Keywords:
Decision support
Deconstruction
Design for disassembly
Building connections
Circular buildings

ABSTRACT

In architectural and construction practices, there is a need for decision support systems that include disassembly evaluations in the early design and deconstruction stages of buildings. Despite the growth of simulation programs over the past decade, there is a lack of ready-to-use applications for evaluating the deconstruction potential of buildings. Furthermore, most available tools focus on analyzing the environmental performance of a building while ignoring the technical issues of connection disassembly. In this study, an expert system was developed to classify the connections in demountable buildings and applied to case studies of newly constructed circular buildings to evaluate their disassembly potential. Disassembly criteria and barriers were identified by reviewing the literature. The fieldwork included the observation of more than 2500 connection systems in these circular buildings via standardized inspections. A statistical analysis of the disassembly barriers observed during these inspections was conducted, and their ability to dismantle the most probable connections was evaluated. The interpretation of these data allowed the creation of an inventory of measures to be implemented to ensure the ease and quality of disassembly, helping the practicing engineer and the disassembly team in their practice. This proposed expert system is considered the first step toward a thorough understanding of the impact of design on the disassembly criteria of and barriers to circularity. Its further development will contribute to the accurate forecasting of the disassembly potential of buildings and material recoverability.

Abbreviations:

BAMA	Buildings As Material Banks	DPBc&s	Disassembly Potential of the building's core and shell
BIM	Building Information Modelling	DPcpn	Disassembly Potential of the Composition of Element
BPS	Building Performance Simulation	DPCn	Disassembly Potential of the Connection
C&D	Construction and Demolition	DPcn	Disassembly Potential of the Connection of Element

(*continued on next page*)

* Corresponding author. Sustainable Building Design Laboratory, Department. Urban and Environmental Engineering, School of Engineering, Université de Liège, 4000, Liège, Belgium.
E-mail address: muheeb.al-obaidy@uliege.be (M. Al-Obaidy).

https://doi.org/10.1016/j.jobe.2025.112148
Received 22 October 2024; Received in revised form 2 February 2025; Accepted 16 February 2025
Available online 18 February 2025

(continued)

CAn	Connection Accessibility of Element	ECI	Environmental Cost Indicator
CDW	Construction and demolition waste	EU	European Union
CE	Circular Economy	FCRBE	Facilitating the circulation of reclaimed building elements in Northwestern Europe
CLT	Cross-Laminated timber	GDPR	General Data Protection Regulation
CTn	Connection Type of Element	GPEn	Geometry of Product Edge of element
DBn	Disassembly Barriers	HELEN	Holistic design of taller timber buildings
DfD	Design for Disassembly	IDn	Independency of Element
DfD&A	Design for Disassembly and Adaptability	LCA	Life Cycle Assessment
DfF	Design for Flexibility	MFA	Material Flow Analysis
DfR	Design for Reuse/Recycling	PDEs	Potential Ductile Elements
DIC	Disassembly Index of the Connection	SBD	Sustainable Building Design lab
DMP	Data Management Plan	SUS	System Usability Scale
DPBc	Disassembly Potential of the building's core		
DPBs	Disassembly Potential of the building's shell		
DPBc/s	Disassembly Potential of the building's core or shell		

1. Introduction

The construction sector consumes 40 % of raw materials [1] and generates 50 % of waste worldwide [2] owing to the decades-old linear economic model of "take–make–dispose." Circular economy (CE) has evolved as a new strategy for creative practices to attain sustainable economic development in response to issues such as resource shortages, environmental crises, and other challenges [3]. Disassembly potential is defined as "the ability of a building's structure to be selectively taken apart with the intention of reusing and up-cycling some (or all) of its constituent parts" [4,5]. Therefore, "design for deconstruction" is being developed in response to the need to reduce waste and move toward CE [6].

However, little consideration has been given to design for deconstruction owing to the lack of supporting tools and technical knowledge. Although there is an increasing awareness of building deconstruction [7], the problem of quantifying their disassembly potential remains in the literature [8]. In addition, it is generally believed that the lifespan of a building may not be significantly longer [9]. It is estimated that less than 1 % of building materials have been reused after demolition and their first application [10]. The literature on the circularity gap indicates a high uncertainty associated with the evaluation of the disassembly potential of buildings [8, 11]. Without measuring the disassembly potential of buildings and incorporating science into standards, such as the standardization in evaluating circular constructions [12] conducted by CEN/TC350 [13], practitioners will not be able to overcome cradle-to-grave construction practices (an extensive literature review on the methods and tools used to evaluate the disassembly potential of buildings is presented in Section 2).

The latest draft requirements of the European Union (EU) taxonomy for circularity [14], which is set to become effective in late 2024, state that at least 90 % (by weight) of the nonhazardous construction and demolition waste must be prepared for reuse or recycling [15]. Furthermore, construction designs and techniques must support circularity by incorporating the concepts of design for disassembly (DfD) and adaptability. The benefits of building deconstruction outweigh the costs if the value of building components is preserved after the end-of-life and reused [2]. The Ellen MacArthur Foundation [16] identified three important principles of a CE, all of which are driven by design: elimination of waste and pollution, circulation of products and materials, and renewal of nature through the enhancement of natural resources. However, it remains unclear which CE principle is related to building design [17]. The European Commission's Directorate-General for Internal Market, Industry, Entrepreneurship, and SMEs [18] conducted a study to try to answer

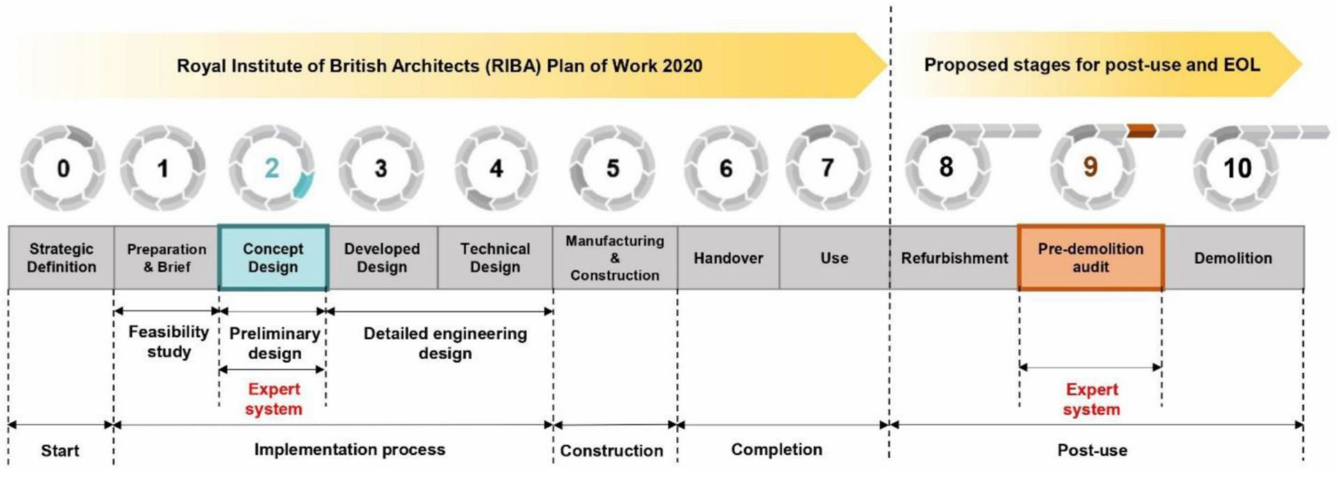


Fig. 1. Use of the expert system according to a design process inspired by the RIBA Plan of Work 2020 with post-use and end-of-life stages.

this important question.

Therefore, in this study, an expert system was developed to evaluate the disassembly potential of buildings. Furthermore, an audit sheet of the connections was established, listing their anomalies and the most probable causes. An expert system is a decision-support method represented by rules to solve complex problems by reasoning through bodies of knowledge [19]. The expert system is part of the DeConstruct [20] Project developed in collaboration with Liege University, Colruyt Group, and COST Action Circular-B on Implementation of Circular Economy in the Built Environment. An expert system is intended to be used during two life stages of a building: first, during the early design stage to improve the disassembly potential of the new construction design and, second, during the pre-demolition stage of a building's lifespan to assess its disassembly potential to recover existing building components and products for reuse (see Fig. 1). The beneficiaries of the expert system are architects, building engineers, insurance companies, and demolition contractors. In this study, the pathological characterization of structural connections was performed using this expert system. This expert system was applied to two case study projects representing circularity-inspired buildings to evaluate their disassembly potential. Based on the above discussion, this study aims to answer three main research questions.

i. How to evaluate the disassembly potential of a building?
ii. To what extent the design of a building is circular and reusable?
iii. What is the effect of design on the disassembly ability?

As an added value, the developed expert system is a starting point for the development of a widely used tool to evaluate the disassembly potential of buildings.

2. Literature review

Herein, previous studies that attempted to classify connections and determine the criteria to evaluate the disassembly potential of a building were investigated. More than 180 papers were reviewed and filtered in a previous study by Attia and Al-Obaidy (2024) as part of the expert system development in this study [8].

2.1. Connection disassembly inspection systems

The construction industry has the potential to support the principles of CE, including eco-friendly technologies, as this aids in the use of waste materials generated during production processes to reduce construction costs and preserve embodied energy [21]. Abdul Nasir et al. [22] argued for integrating CE ideals into the theory and practice of supply chain management, citing a case study that showed the benefits of adopting CE principles over linear systems, including reductions in emissions such as carbon and nitrogen oxides. Although the concept of CE is not new [23], it gained more attention after the EU's July 2014 communication on a "Zero Waste Program for Europe" emphasized the need for its adoption [24].

According to various European studies and projects, efforts have been made to create circularity indicators for assessing the environmental impact of building materials [25], and life cycle assessment (LCA) has influenced these approaches [26]. However, new groups of scientists have sought to broaden the methods used to define circularity and extend the reuse of building materials [25–28]. For example, research projects aimed at enabling a systemic shift in the building sector have been conducted, and one such project is the "Buildings As Material Banks" project [29]. This project focused on developing and integrating tools, such as material passports and reversible building designs [30,31]. The Flemish Public Waste Agency has also implemented the "Design for Change" project, which involves a consortium of Flemish institutions that published guidance documents promoting adaptability [32] and design principles for closed material loops in the building sector [33]. One of the project reports [34] provided a comprehensive overview of the technical lifespan of building construction components and reviewed more than 70 references, including the Ecology of Building Materials book [35]. The project also published 24 technical design leaflets on change-oriented building design [36]. In this project, nine disassembly criteria for circular buildings have been recommended, along with suggestions for developing a policy and transition framework [37].

One of the main problems with the LCA standards, including EN 15804-A2 and EN 15978, is the assumption regarding the number of replacements in buildings [38]. The standards ignore the influence of such replacements on the surroundings of interdependent building sections. Thus, it fails to reflect the potential advantages of DfD [39]. In light of this limitation, Vandervaeren et al. (2022) [39] presented a method for predicting the fluxes of building parts triggered by building deconstruction, both during the operation and end-of-life stages. This modeling technique considers the structural stability, accessibility, and utilization of detachable connections. It provides a time-based bottom-up material flow analysis of the entire building that can be combined with the LCA. The results of this method were compared with those obtained using EN 15978, and nine design variations were considered. The projected life cycle environmental effect using this method was up to 162 % greater than that predicted using EN 15978 for a pavilion with non-detachable connections, demonstrating the relevance of this design parameter.

The reference details are highly suitable for showing how products can be dismantled at the end of a building's lifespan; therefore, the Dutch private standardization organization ISSO [40] is developing a method to provide insights into the detachability of construction details and nodes. The standard reference details [40] offer parties who design, implement, and supervise a practical handle for excellent and sound construction as well as compliance with the minimum legal building regulations for partition constructions. Similarly, Kroll et al. (1996) [41] suggested a spreadsheet to measure the ease of disassembly. A few design factors, such as accessibility, location, force, time, and unique features of each component of the device, were subjectively evaluated, with scores ranging from 1 (easy) to 4 (difficult).

In addition, the Belgian Building Research Institute developed a deconstruction protocol [42] to organize the deconstruction process in Brussels [43]. This protocol is part of the FCRBE project, which aims to facilitate the circulation of reclaimed building components in Northwestern Europe [44]. This protocol consists of five phases occurring successively: (1) completion of the deconstruction inventory (before construction), (2) drafting the call for tenders (before construction), (3) drafting the demolition waste management plan (before construction), (4) execution and monitoring of the demolition (during construction), and (5) reporting (at the end of construction). This protocol covers all activities related to a total or partial deconstruction (renovation), from the preparation for deconstruction to the reporting of deconstruction activities. However, it does not cover the transport and waste treatment/recovery links or the production of new construction products. This protocol aims to obtain clean (inert) waste streams to be recycled into high-quality recycled aggregates.

Another study [45] discussed the design and use of a pre-demolition mapping tool to assess and promote construction and demolition waste recycling. In their study, the use of three-dimensional (3D) scanning and building information modeling was discussed in the form of case studies to estimate the type and quantity of waste generated during building demolition. Disassembly using digital tools has become very important for inventory support, material recovery strategies, and disassembly planning; therefore, Durmisevic et al. [46] developed a conceptual digital deconstruction tool to support decision-making and facilitate a CE. While the construction industry has made significant strides in developing Design for Disassembly (DfD) methodologies, valuable insights can be drawn from the manufacturing sector, which has long-established practices in disassembly, remanufacturing, and repurposing. Recent studies in manufacturing have focused on quantifying disassembly capacity through standardized metrics, such as disassembly time, ease of separation, and material recovery rates, which could be adapted to evaluate construction-specific connection types like bolts, adhesives, and interlocking mechanisms [47]. Additionally, the manufacturing industry has leveraged modular designs and standardized interfaces to enhance scalability and efficiency, principles that could be integrated into construction practices to improve DfD outcomes [48,49]. Techniques such as Product Lifecycle Management (PLM) and disassembly sequencing algorithms, widely used in manufacturing, offer the potential for adaptation to address construction-specific challenges, such as the complexity of building systems and the variability of material flows [50].

Over time, pre-demolition and deconstruction audits have gained great importance and have become mandatory in some countries

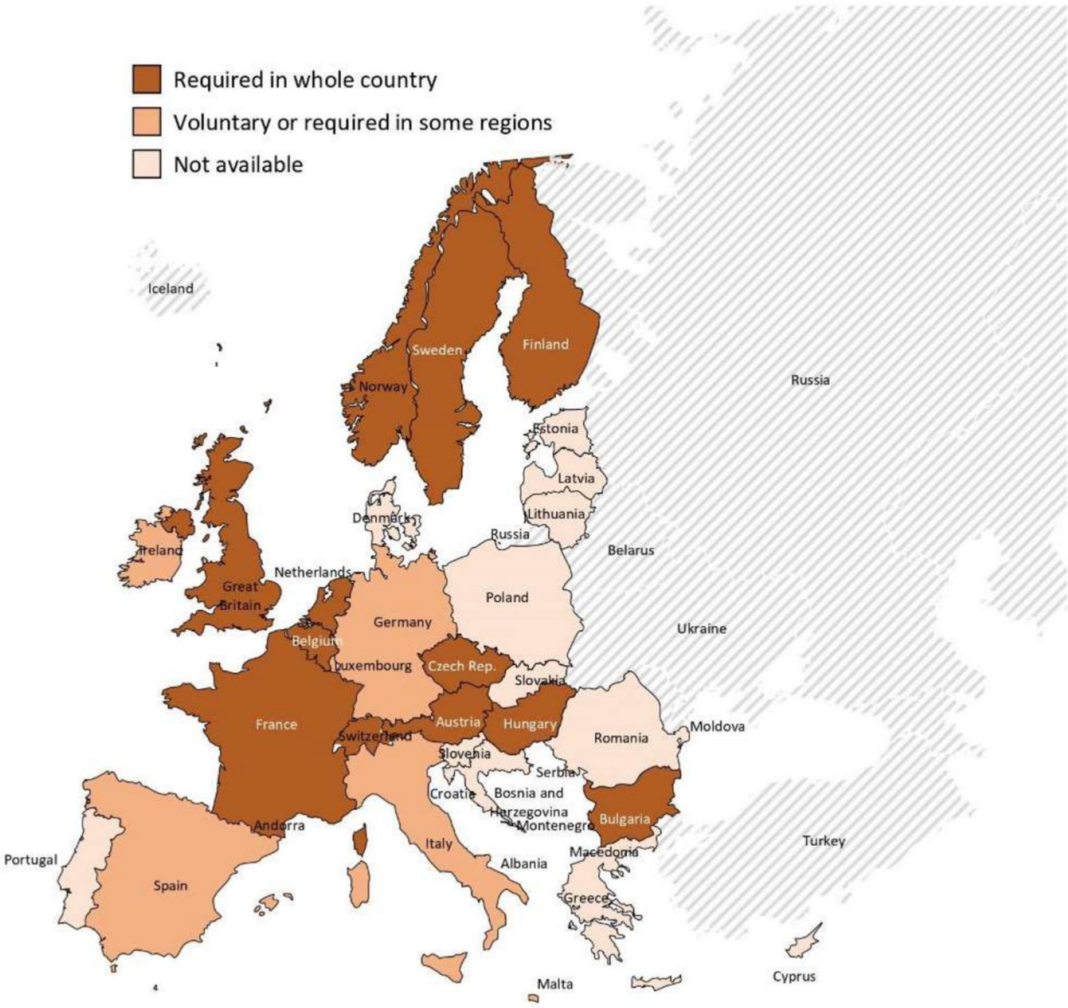


Fig. 2. Use of pre-demolition audits in the EU based on a literature review.

of the EU [51,52], as shown in Fig. 2, and this was updated by the authors based on 2023 data [8]. Pre-demolition or deconstruction audits consist of preparatory actions to collect information about the quality and quantity of building materials that will be produced during the deconstruction process [52]. This can help identify reusable and recyclable materials that are assessed based on the specific details of quality, quantity, and accessibility. This enormous number of tools is one of the reasons why establishing a unique standard is difficult, as disassembly evaluation is still dependent on the expertise of the expert performing the demolition audit and assessing the disassembly potential of a building.

2.2. Disassembly classification and criteria

According to Smeyers et al. (2023) [10], less than 1 % of all existing buildings can be completely dismantled and their materials can be reused after demolition and their first application. Researchers and practitioners have recently begun to focus on the design criteria to increase the disassembly potential of building components. Consequently, it is critical to design for flexibility, adaptability (DfAD), disassembly (DfD), and reuse/recycling to replace single components or materials without compromising other parts or layers.

Currently, there is no globally recognized standard for quantitatively evaluating the disassembly potential of buildings [8]. Researchers have proposed various methodologies and criteria [47,53]. For example, Akinade et al. (2017) [2] identified 15 determinants

Table 1
Disassembly criteria and their associated scores. Adapted from "Transformable Building Structures" by Durmisevic, E. (2006) [56] and the Dutch Green Building Council and Alba Concepts (2021) [54].

ID	Criteria	Sub criteria	Score
CT	**Connection type**		
D.c	**Dry Connection**		
D.c1		Loose (no fastening material)	1.0
D.c2		Click connection	1.0
D.c3		Velcro connection	1.0
D.c4		Magnetic connection	1.0
C.e	**Connection with added elements**		
C.e1		Bolt and nut connection	0.8
C.e2		Spring connection	0.8
C.e3		Corner connections	0.8
C.e4		Screw connection	0.8
C.e5		Connections with added connection elements	0.8
D.i	**Direct integral connection**		
D.i1		Pin connection	0.6
D.i2		Nail connection	0.6
S.c	**Soft chemical connection**		
S.c1		Caulking connection	0.2
S.c2		Foam connection (PUR)	0.2
H.c	**Hard chemical connection**		
H.c1		Adhesive connection	0.1
H.c2		Dump connection	0.1
H.c3		Weld connection	0.1
H.c4		Cementitious connection	0.1
H.c5		Chemical anchors	0.1
H.c6		Hard chemical connection	0.1
CA	**Connection accessibility**		
C.a	**Connection accessibility**		
C.a1		Freely accessible without additional actions	1.0
C.a2		Accessible with additional actions that do not cause damage	0.8
C.a3		Accessible with additional actions with fully repairable damage	0.6
C.a4		Accessible with additional actions with partially repairable damage	0.4
C.a5		Not accessible — irreparable damage to the product or surrounding products	0.1
ID	**Independency**		
I.d	**Independency**		
I.d1		No independency — modular zoning of products or elements from different layers.	1.0
I.d2		Occasional independency of products or elements from different layers.	0.4
I.d3		Full integration of products or elements from different layers.	0.1
GPE	**Geometry of the product edge**		
G.b	**Geometry of the product edge**		
G.b1		Open — no obstacle to the (interim) removal of products or elements.	1.0
G.b2		Overlapping — partial obstruction to the (interim) removal of products or elements.	0.4
G.b3		Closed — complete obstruction to the (interim) removal of products or elements.	0.1

of DfD that were aggregated into three main groups: material-related, design-related, and site worker–related factors. They identified 38 key DfD components using expert focus groups, which were classified into five categories: (1) strict regulation and policy, (2) deconstruction design process and competencies, (3) design for material recovery, (4) design for material reuse, and (5) design for building flexibility. Guy and Ciarimboli (2008) [54] described 10 essential DfD principles, and Moffatt and Russell (2001) [55] developed eight DfAD concepts: durability, adaptability, service access, redundancy, simplicity, upgradability, independence, and building information.

According to Durmisevic (2018) [31], design for deconstruction is described by three domains: (1) the functional domain is concerned with functional decomposition and separating functions into different materials; (2) technical decomposition is concerned with the hierarchical organization of construction materials as well as linkages and hierarchical interconnections between material layers; and (3) the physical domain is concerned with the interfaces that determine the physical integrity and dependencies of a building structure. As determined in a previous study [56], the weights of the seven DfD criteria are (1) functional decomposition, (2) lifecycle coordination, (3) relational pattern, (4) systematization, (5) assembly, (6) geometry, and (7) connections. Furthermore, Attia and Al-Obaidy (2021) considered the type of connection and the time of disassembly as important criteria to evaluate the disassembly potential of a building [17].

A study by the Dutch Green Building Council and Alba Concepts [57] determined four technical criteria for disassembly along with their weight factors, all of which are related to the design and determination of the physical ability to disassemble components. Each category consists of several subcategories with a certain score, where 1.00 represents the highest score and 0.10 is the lowest score. Components or products can be connected to multiple elements. To ensure that the determination of the disassembly potential does not become an unnecessarily complex calculation, it is necessary to delineate which connection is decisive in determining the disassembly potential. Table 1 presents the four technical criteria that have been proposed with associated categorical values, that is, the "fuzzy variables," to determine the disassembly potential of buildings: (1) connection type, (2) connection accessibility, (3) crossing, and (4) form containment. This is in line with the results of a previous study in which the most important factors were identified using a survey of 122 respondents.

Research on the mechanical performance and geometric potential of joinery connections in timber buildings is scarce. Therefore, a

Table 2
Main and sub-barriers of disassembly in the construction sector based on the reported barriers in the literature and the most common barriers according to the SBD Lab database.

ID	Barriers	Sub-barriers	Score
B.d	**Design barriers**		
1B.d		Design errors	0.1
2B.d		Incompatible, omitted, or unsuitable choice of materials	0.1
3B.d		Incorrect design of the connections	0.1
4B.d		Areas inaccessible to disassembly	0.1
5B.d		Deficient care in detailing connections	0.1
6B.d		Defects in peripheral elements	0.1
7B.d		Excessive deformations	0.1
E.e	**Execution errors**		
E.e1		Use of non-prescribed and/or incompatible materials	0.08
E.e2		Application in extreme environmental conditions	0.08
E.e3		Disregard of the connection's default lifespan	0.08
E.e4		Use of misplaced connections	0.08
E.e5		Incomplete contact between the elements	0.08
E.e6		Joints of an insufficient width or depth/missing joints	0.08
E.e7		Metal accessories unprotected in the connections	0.08
E.e8		Lack of maintenance	0.08
A.a	**Accidental actions**		
A.a1		Vandalism	0.06
A.a2		Stress concentration on the connections	0.06
A.a3		Deformation	0.06
A.a4		Fire and burnt connections	0.06
E.a	**Environmental actions**		
E.a1		Damp within connections	0.04
E.a2		Mold within connections	0.04
E.a3		Water leakage inside the connections	0.04
E.a4		Biological action	0.04
E.a5		Air pollution	0.04
M.i	**Management issues**		
M.i1		Rules or standards to organize the construction of reused materials or elements	0.02
M.i2		Limited demand for reusing materials in the construction market	0.02
M.i3		Deconstruction time compared with mechanical demolition	0.02
M.i4		Deconstruction costs compared with mechanical demolition	0.02
M.i5		Deconstruction contractual issues	0.02
M.i6		Manufacturers' lack of interest and responsibility in reducing waste	0.02

study was conducted to develop a performance-driven design framework for the geometry of joinery connections [58]. In timber buildings, connections have a significant effect on the overall structural performance. Connections are considered potential ductile elements (PDEs) that significantly contribute to the overall ductility in the case of overloading [59]. Connections must be designed as "fuses" to avoid brittle failure, which causes the building to progressively collapse [60]. Therefore, a previous study [59] focused on the design principles of timber connections for ductility, with a particular emphasis on laterally loaded dowel-type fasteners. Timber connections are critical components of timber construction because they not only join or connect members but also affect the load capacity, stiffness, and construction ductility of the overall system.

2.3. Classification of the probable barriers to disassembly

The design process is the primary impediment to disassembly [61–63]. Buildings are designed and constructed without considering the end of life or the procedure for recovering their components and elements. Srour et al. (2010) emphasized the importance of design for deconstruction and stated that designers should be on the front lines to ensure that salvaged materials are reused [62].

There are no rules or standards for organizing the construction of reused materials or components [64,65]. Conversely, the expansion of DfD has a direct impact on the prospective improvement of standards and regulations in this sector. Building standards and regulations began to address the difficulties associated with the application of such materials through government and public involvement [66].

Material reuse is one of the most difficult challenges [24] that can be overcome as more designers start adopting DfD methods and using new techniques. Another important barrier to deconstruction is time [54,67,68]. Compared with mechanical demolition, the time required for disassembly can be three to eight times longer [14]. Deconstruction may not be a practical alternative to demolition when time is a critical factor.

Deconstruction may also be hampered by costs [54,67,68]. There is a widespread misconception that deconstruction is more expensive than demolition or disposal. However, research has revealed that this is not always the case [9,54,62,68]. Costs are influenced by variables such as material storage before the final destination; local and regional market and demand for used materials; higher labor costs; higher costs with workers' insurance; hazardous material removal; training expenses; material conditions; debris transportation; and landfill fees. Therefore, certain components can help save money.

Another important barrier to deconstruction is the contractual issue. Normally, demolition contracts do not require the reuse or recycling of materials. However, terms can also be incorporated to address and encourage these practices [66]. More time and planning are required to improve the contract, and one of the most important barriers to overcome is the lack of interest and accountability of manufacturers in reducing waste [66,67,69]. Therefore, members of the Sustainable Products Purchasers Coalition [70] used their technical expertise to persuade companies to include life cycle analysis data in their products [69]. Table 2 summarizes the probable barriers to disassembly identified in the literature and during demolition missions.

Finally, the literature review indicated a knowledge gap related to the quantification of the disassembly potential of buildings during the early design and pre-demolition stages. None of the investigated studies combined connection disassembly criteria with connection disassembly barriers to assess the disassembly potential of newly designed or existing buildings. Therefore, evaluation methods and decision support systems are needed to bridge this gap.

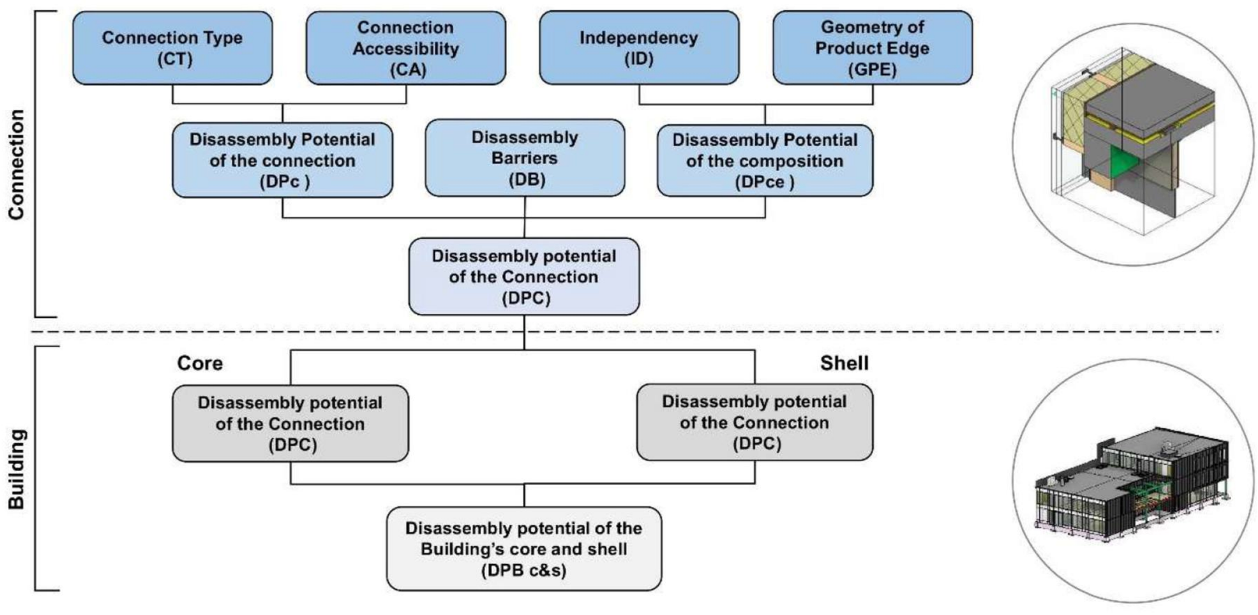


Fig. 3. Decision tree for assessing the disassembly potential of a building at the core and shell levels.

3. Methodology

3.1. Analytical approach

First, more than 180 publications were reviewed by the authors in a previous study to determine the adopted disassembly criteria and barriers to disassembly [8]. The present study focused on four main DfD criteria and 31 sub-criteria, with five main barriers and 30 sub-barriers, to evaluate the disassembly potential of buildings. The results of this review are presented in Section 2.

Second, the authors consulted the Sustainable Building Design (SBD) lab [71] database of the University of Liege for circular buildings and construction details. The database includes more than 15 buildings and 400 connection details and images [72]. The database was developed in 2016 and includes lessons learned on the most common disassembly barriers according to demolition contractors and insurance companies in Northwest Europe. The database inputs were developed and validated through participation activities of the FCRBE project (2018–2023) [10] and COST Action CA20139 HELEN (2021–2025) [73]. With the help of the literature review [8], experts from both projects were consulted, and focus group discussions were conducted to expand the bank of circular buildings and the representativeness of building junctions and connections. Access to the private database was granted with permission from the last author.

Third, an algorithm evaluation and decision tree were developed to evaluate the dismantling of the building at the core and shell levels. The authors focused on the most important connections between various components and components, as shown in Fig. 3.

Fourth, an audit sheet was developed. The audit sheet comprises all the steps that need to be performed when a building is evaluated and is filled up by an auditor. Therefore, when an expert system is used, inputs from the audit sheet should be used to feed the expert system with the necessary data. The audit sheet can be found in Appendix 3, and the expert system interface (step-by-step tutorial) and the final report can be found in Appendix 4.

Finally, for the application, three actions were performed: a case study, focus group discussions, and usability testing. Two projects were chosen as case studies (*'t Centrum* and *Green Office* buildings) to test the expert system. These buildings were chosen because they are compatible with the concepts of CE and DfD. A focus group discussion was conducted through technical meetings with experts to discuss the DfD criteria and barriers. Usability testing was performed to determine the extent to which this expert system could be used to evaluate the disassembly potential of a building (see Fig. 4).

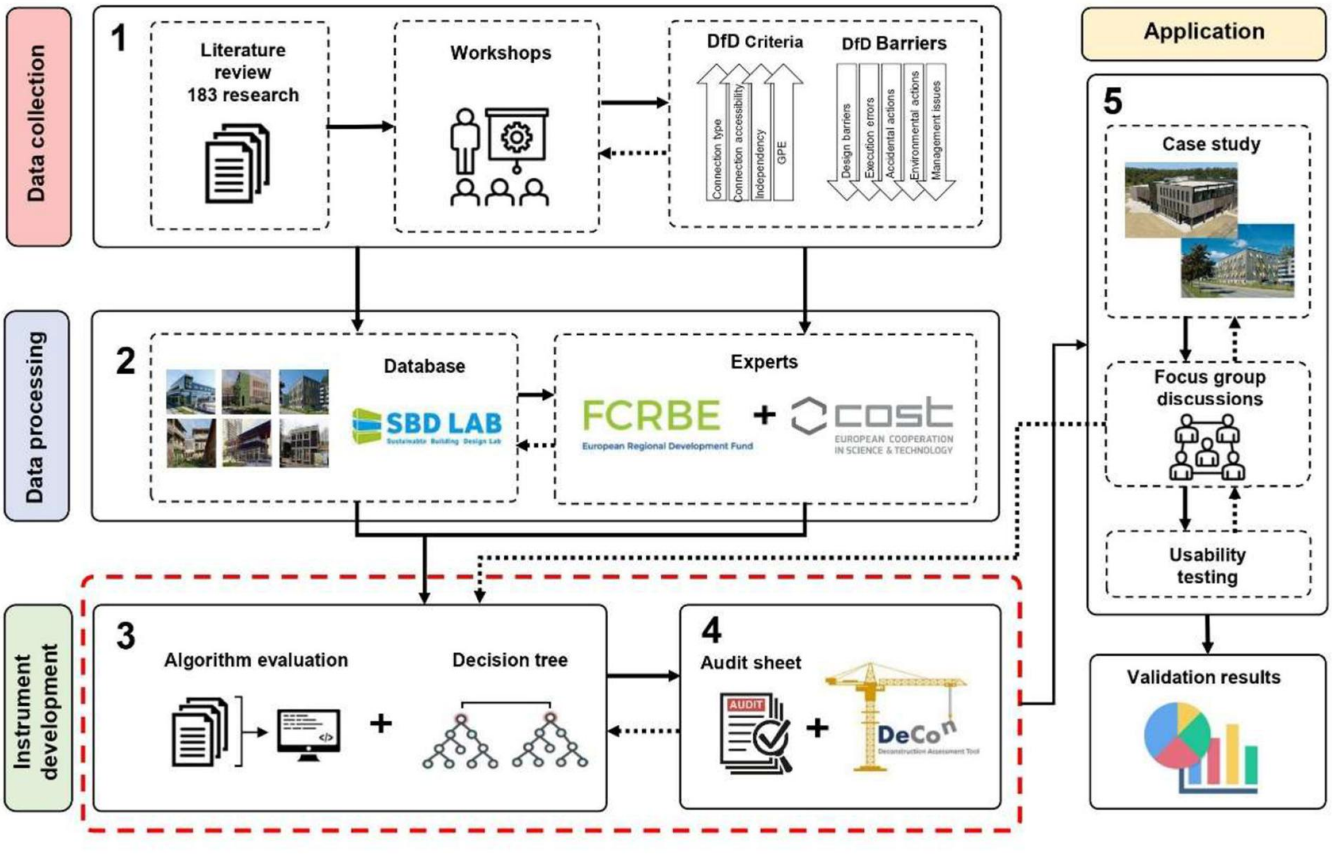


Fig. 4. Methodology framework of the study.

3.2. Inventory and inspection campaign

Demolition contractors were consulted, and an inventory of construction details for different types of buildings, such as steel, concrete, and timber, was made to observe a wide sample of connections. A complete inventory of construction connections emerged from these consultations. Moreover, the types of connections were identified and inventoried, and the disassembly potential was evaluated based on a previous study by the authors [17] that addressed the disassembly criteria for six different buildings in Belgium, the Netherlands, and Switzerland, as shown in Fig. 5. The data were collected for each project through the bill of materials with the help of experts, and focus groups were organized during technical meetings to discuss the DfD criteria.

The inspection campaign was based on an audit sheet and the creation of a database. A database was developed and programmed to collect details, images of connections, and the most common disassembly barriers. The first database (COST Action database) collects data from COST Action CA20139 (HELEN) experts [73]. By contrast, the second database, that is, the SBD lab [71] database at the University of Liege (SBD Lab database), collects data from engineers and demolition companies.

3.3. Characterization and statistical analysis

In this study, the methodology used by the Dutch Green Building Council and Alba Concepts [57] was adapted and developed in the form of a scenario describing the buildings and their disassembly potential, based on the criteria mentioned in the literature. This research is technical; therefore, the environmental cost indicator of the component was omitted from the method and a list of barriers to the disassembly process was added with their impact weights, which the authors developed based on a literature review. Barriers were included in the evaluation equations because of the lack of an important and sensitive factor for dismantling.

This research focused on four main DfD criteria and 31 sub-criteria, with five main DfD barriers and 30 sub-barriers that were developed and considered in the final evaluation results. The abbreviated IDs indicate the criteria and barriers and are presented in Tables 1 and 2, respectively.

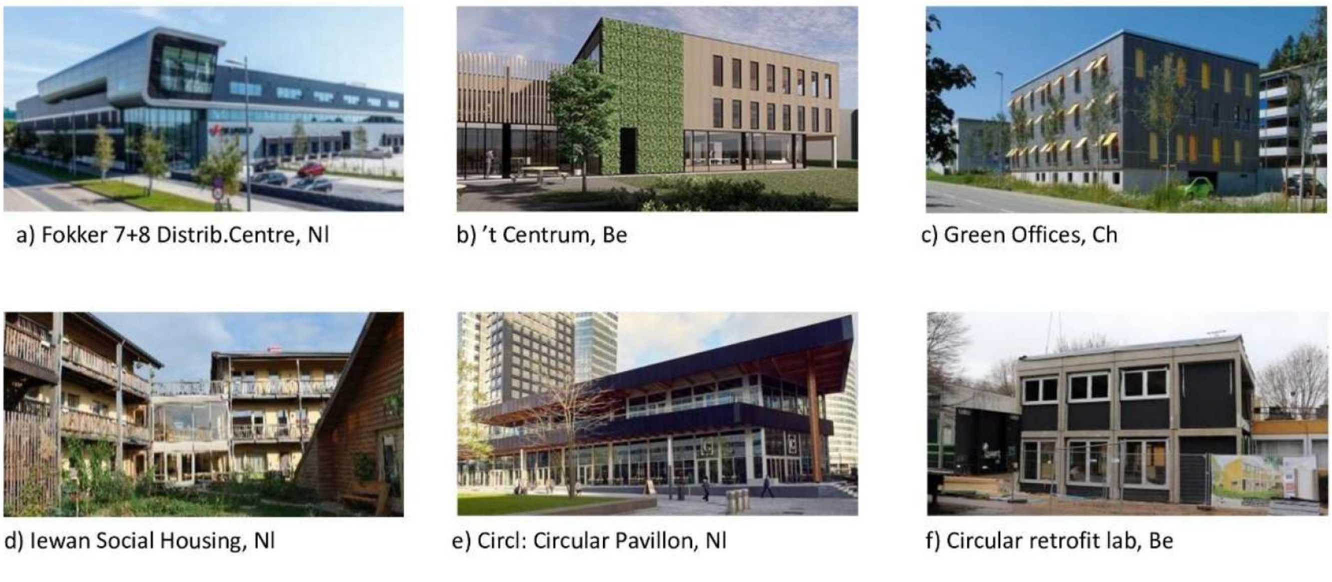
As presented in Table 1, the first criterion is the *connection type*. Various types of connections are used to connect the elements. For disassembly, dry connections, connections with added elements, and direct integral bonds prevail over soft and hard chemical compounds.

The second criterion is *connection accessibility*. The accessibility of connections refers to the physical possibility of accessing the connecting elements and the extent to which this causes damage to the surrounding elements. When accessibility is high and it is easy to reach the connecting element without causing damage to the surrounding building parts, disassembly is positively affected.

The third criterion is *independency*. This creates the integration and interweaving of objects and elements. This creates a dependence of the elements on each other. When the elements do not physically cross each other, they remain independent and disassemble more easily.

The fourth criterion is the *geometry of the product edge*. This deals with the physical containment of objects or elements and creates an inseparable connection through containment. The elements must remain open on at least one side and should not be physically enclosed to ensure disassembly. Consequently, they can be separated from each other without affecting the surrounding elements.

Table 2 presents the main DfD barriers adopted in this research, which are the five major barriers listed in the literature review section: (1) design barriers or errors, (2) execution errors, (3) accidental actions, (4) environmental actions, and (5) management issues. These barriers were examined, and their weights were determined based on a literature review and database [72] developed for



a) Fokker 7+8 Distrib.Centre, Nl b) 't Centrum, Be c) Green Offices, Ch

d) Iewan Social Housing, Nl e) Circl: Circular Pavillon, Nl f) Circular retrofit lab, Be

Fig. 5. Examples of the buildings that have been investigated to define the connection's disassembly potential and barriers based on a previous publication by the authors [17,74] and the SBD lab database [72].

this purpose.

The methodology adopted distinguishes between two types of criteria: those influenced by the connection between elements (connection type) and those influenced by the assembly of elements (connection accessibility). For each element *e*, the disassembly potential of the connection DPc_n and the disassembly potential of the composition $DPcp_n$ are determined. Together, these form the disassembly index of the connection in the core or shell of the building (Equations (1) and (2)).

$$= \frac{2}{\frac{1}{CT_n} + \frac{1}{CA_n}} \tag{1}$$

DPc_n = Disassembly potential of the connection of element *n*
CT_n = Connection type of element *n*
CA_n = Connection accessibility of element *n*

$$DPcp_n = \frac{2}{\frac{1}{ID_n} + \frac{1}{GPE_n}} \tag{2}$$

$DPcp_n$ = Disassembly potential of the composition of element n
IDn = Independency of element n
GPEn = Geometry of product edge of element *n*

$$DPC_n = \frac{2}{\frac{1}{DPc_n} + \frac{1}{DPcp_n}} \tag{3}$$

DPC_n = Disassembly potential of the connection
DPcn = Disassembly potential of the connection of element n
DPcpn = Disassembly potential of the composition of element *n*

Disassembly barriers are an integral part of evaluating the disassembly of connections. Therefore, Equation (4) was developed to evaluate the disassembly potential of the connections of the core or shell of the building.

$$= \left(\sum_{i=1}^{n} \frac{DPC_n - DB_n}{n} \right) X\,100 \tag{4}$$

$DPB_{c/s}$ = Disassembly potential of the building's core or shell
DPC_n = Disassembly potential of the connection n = number of connections in the building's core or shell

Finally, Equation (5) was used to calculate the total disassembly potential of the core and shell of the building.

$$DPB_{c\&s} = \frac{DPBc + DPBs}{2} \tag{5}$$

$DPB_{c\&s}$ = Disassembly potential of the building's core and shell
DPBc = Disassembly potential of the building's core
DPBs = Disassembly potential of the building's shell

3.4. Usability testing

Usability testing is an important procedure for validating the performance of the developed method. The primary aim of this test was to assess the usability of the expert system (DeCon) and its decision-making abilities by conducting usability tests on various prototype versions. Usability testing was based on the USER-FIT framework described by Attia (2023) [75] and Attia et al. (2024) [76]. The participants were selected according to the EU General Data Protection Regulation [77] and asked for their consent. Ethical approval was not required because the responses were anonymized and an intervention was not performed. A data management plan [78] was developed to collect and consistently file all answers.

Two major iterations of usability testing were conducted during the creation of expert system (DeCon) prototypes 1 and 2 to obtain inputs from designers and potential users. Each usability iteration comprised two different types of tests. The first test was a paper-based usability satisfaction questionnaire. A system usability scale (SUS) was used to improve and validate the expert system [79]. A set of 10 conventional (predefined) SUS questions were used to ensure the internal validity of the test. A reporting structure [80] was used to analyze the replies. The second test was a usability metric test with 20 users, comprising architects, engineers, and architectural students, who measured the success of the task.

The objective was to assess the efficiency with which users could accomplish a set of tasks. A Likert scale was used for the paper-based surveys. Users answered the questionnaire on a scale of 1 (strongly disagree) to 5 (strongly agree). Scores from the survey were added, and the total was multiplied by 2.5. The mean score, ranging from 0 to 100, was calculated from the selected replies. The higher the score, the more user-friendly the website. A rating of 70 or higher indicated good usability. The SUS can be found in Appendix 5.

4. Results and validation

4.1. Case study

The case study buildings were selected after a thorough analysis of the case studies performed in a previous paper by the first author [17]. A selection list was created that included the inclusion and exclusion criteria to ensure that the case study building was constructed following the concepts and principles of CE [81].

4.1.1. ‘t Centrum building

The first case study was the *'t Centrum* building, an office building located in Belgium, Westerlo, Kamp C [82]. The building was designed by West Architecture [83] and was constructed by Beneens [84]. The building has three floors, with an area of 2200 m^2. It is considered carbon neutral and implements circularity principles. Moreover, this building acts as a catalyst for modular and circular buildings in the region. The construction was finished in March 2022. This is an example of a recent circular building designed to be dismantled 5 years after its construction and reassembled on the same site with a different design to assess its disassembly ability [85]. The building has a modular office arrangement with transformable workspaces. Consequently, the building may be completely disassembled when it becomes outdated. *'t Centrum* was built using Cross-Laminated Timber CLT, a type of connection that relies on dry fastening mechanisms. The ceiling, flooring, and internal walls were all made of timber, with partitions and floor tiles fastened using dry connections to increase the disassembly potential.

The project data were collected through technical meetings with the project consortium. The author was provided with the required drawings, necessary data, and a 3D scan view to conduct this research. The author regularly monitored the assembly process during the construction phase (see Fig. 6 and Appendix 1).

4.1.2. Green office building

The second case study was the *Green Office* building. The building was designed by Lutz Architects [86] as an ecologically optimal building with a positive impact. The building is to be disassembled and its components to be reused in the future. The Green Office building is located in Givisiez, Switzerland. It was constructed in 2005 by Vonlanthen Holzbau AG [87]. As a sustainable office building, it provides commercial spaces for companies specializing in sustainable development. The building has three floors, with a total area of 5391 m^2, and it is Switzerland's first MINERGIE-P-ECO [88]. The design of the building was based on using the smallest amount of energy possible — less is more. This construction obtained the first label for an administrative building in Switzerland and the Watt d'Or 2008 prize [89].

The building aims not only to consume a minimum amount of energy during its operation but also during its construction by choosing materials that consume little embodied energy. Each construction material was analyzed and selected based on its environmental impact. In principle, only the so-called ecological materials were used for the entire construction, such as untreated wood for the façade, natural interior paint, thermal insulation made from waste paper, and frames made entirely of native wood. The ecological balance sheet for the entire building is very positive. Each company working in this building aims to optimize electricity use by installing, for example, low-energy lamps, flat screens, presence detectors, and a timer on the coffee machine (see Fig. 7 and Appendix 2).

4.2. Expert system and disassembly potential evaluation

The expert system was designed as a web tool called DeCon [90]. This web tool was designed in the JavaScript programming language [91] and consists of four steps. It takes 10–15 min to feed the tool with the necessary data to obtain the final result. In this web

Fig. 6. Photograph of the first case study building, *'t Centrum* [82].

Fig. 7. Second case study, the *Green Office* building [86].

tool, the evaluation process takes the form of scenarios based on a decision tree (see Section 3.1.) to help engineers avoid performing calculations or using mathematical equations. Answering some questions will be sufficient to determine the results of the disassembly potential, which is based on a group of case studies. By inputting the number of connections, connection type, component connection relationships, and disassembly barriers, the disassembly potential can obtained at the connection, core, and shell levels of the building. Using the expert system (DeCon), the final report of the disassembly potential can be downloaded at the end of the assessment. Fig. 8 shows the interface and final report of the expert system (DeCon).

After visiting and auditing the buildings and obtaining an inventory of the number and connection types using an audit sheet (see Appendix 3), the expert system (DeCon) was fed with all the necessary data to assess the disassembly potential of the buildings [90]. Fig. 9 illustrates the disassembly sequence of some components of 't Centrum building and their disassembly scores according to the expert system. As shown in Fig. 10a and b, for the *'t Centrum* building, the total disassembly potential for all connections in the core and shell was 92 %. The results of the column and foundation connections showed a decrease of up to 88 % owing to the use of prefabricated foundation blocks underground, which will require additional actions that do not cause damage to reach and remove them completely.

By contrast, the disassembly potential of the *Green Office* building was 72 %. The results of the column connection with the foundation showed a decrease of up to 18 % owing to the use of concrete buried underground (not prefabricated), which cannot be accessed or extracted, except by destroying it. In addition, another 10 % decrease was found after calculating the factor of disassembly barriers, considering that using this type of foundation is a design error when designing a building for disassembly. The evaluation of the connection disassembly depends on the ease of disassembling and isolating the components from each other and their surroundings.

As shown in Fig. 11a and b, the *'t Centrum* building at the core level achieved the highest disassembly potential in the geometry of the product edge and independence criteria, reaching 100 %, followed by connection accessibility at 97 % and the connection type at 80 %.

At the shell level, *'t Centrum* had the highest disassembly potential in the geometry of the product edge, independence, and connection accessibility criteria, reaching 100 %, followed by the connection type at 80 %. The decrease in disassembly potential to 80 % in the connection type at the core and shell levels is attributed to the use of dry connections with added connection components. The total number of barriers to disassembly potential in the core and shell was 0 %. The building is new and does not contain design barriers. It is perfectly designed for disassembly and does not even contain other barriers that hinder the disassembly process resulting from a long period of use. By contrast, the *Green Office* building at the core level achieved the highest disassembly potential in the independence criterion of 100 %, followed by the connection accessibility and geometry of product edge criteria at 82 %, and the connection type at 80 %.

At the shell level, *Green Office* had the highest disassembly potential in the geometry of product edge, independence, and connection accessibility criteria, reaching 100 %, followed by the connection type at 80 %. The total number of barriers to disassembly potential in this building was 10 % owing to the use of hard chemical connections and a classic concrete foundation buried underground (not prefabricated), which cannot be accessed except by destroying it completely.

Through a comparison between the two buildings shown in Fig. 12, the expert system (DeCon) demonstrated the superiority of the *'t Centrum* building over the *Green Office* building, with a total disassembly potential of 92 % compared with 72 % for the *Green Office* building at the core and shell levels. This comparison was made according to the disassembly criteria and barriers described in the methodology of this study.

4.3. Usability test results

According to the usability test results, the initial prototype achieved high usability for the nine questions, as shown in Fig. 13. However, for the final question, participants stated that they needed to understand how the expert system (DeCon) functioned. In addition, after the usability test, each participant was interviewed to gain useful insights into the limits of the expert system. The results were inputted into expert system (DeCon) prototype 2 before the second round of usability testing.

The second phase of usability testing was completed by organizing workshops at the SBD lab. Two user focus groups evaluated the

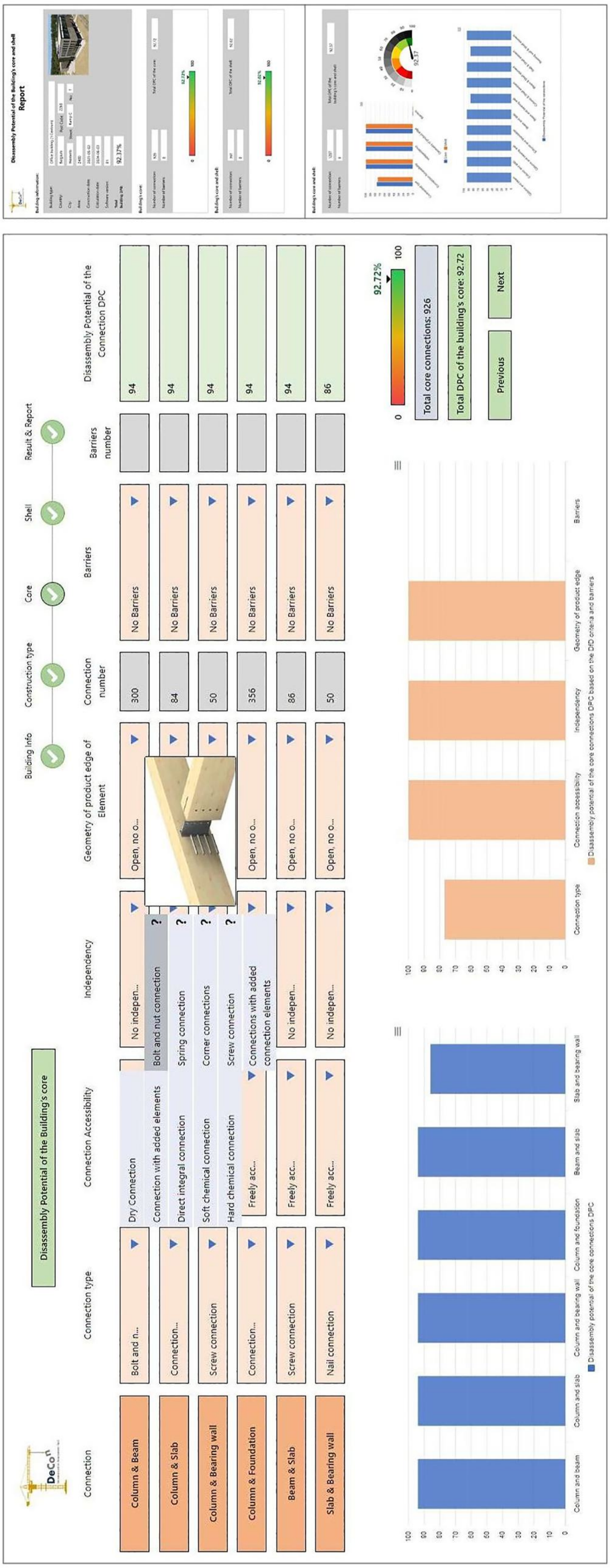


Fig. 8. Interface and final report of the expert system (DeCon) [90].

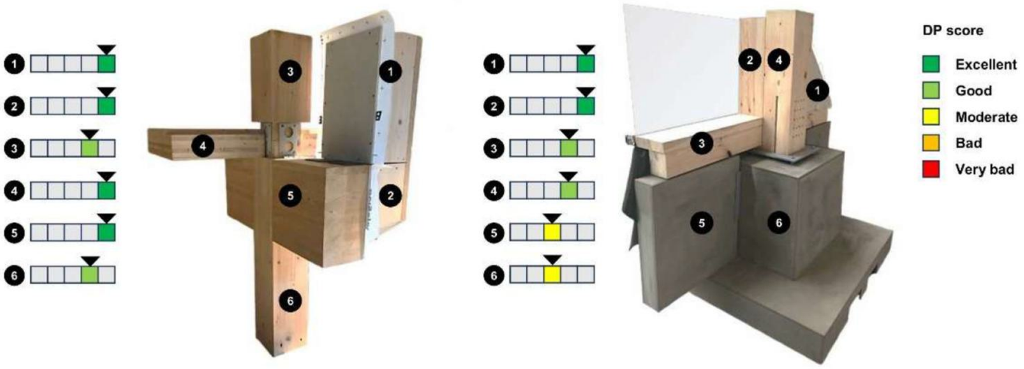


Fig. 9. The disassembly sequence of some components of ’t Centrum building and their disassembly potential DP scores according to the expert system.

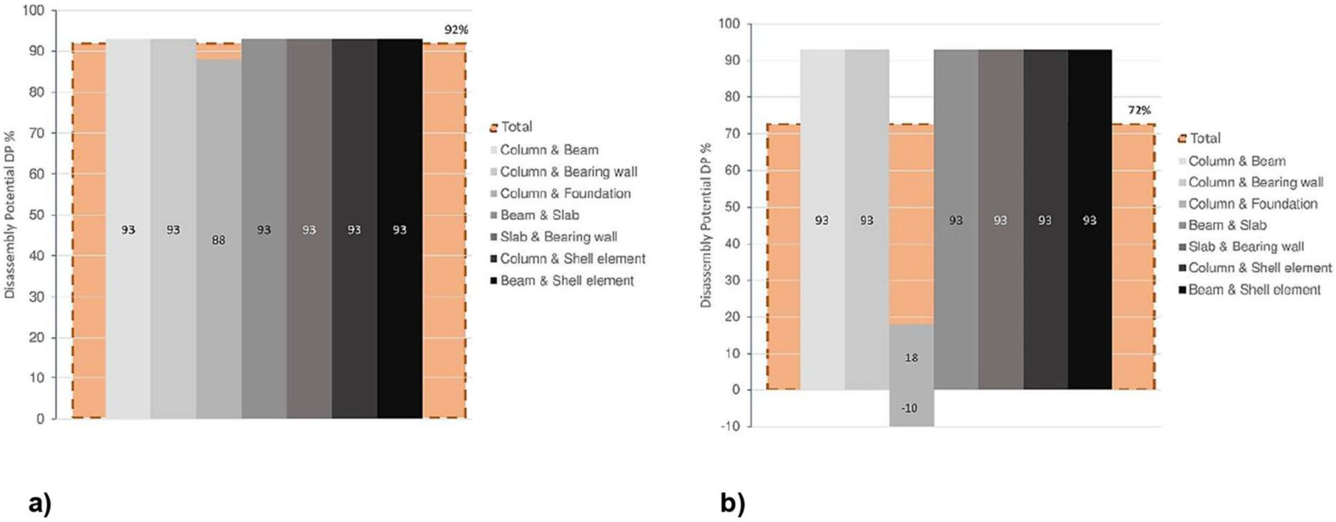


Fig. 10. Disassembly potential of connections in the a) *’t Centrum* and b) *Green Office* buildings.

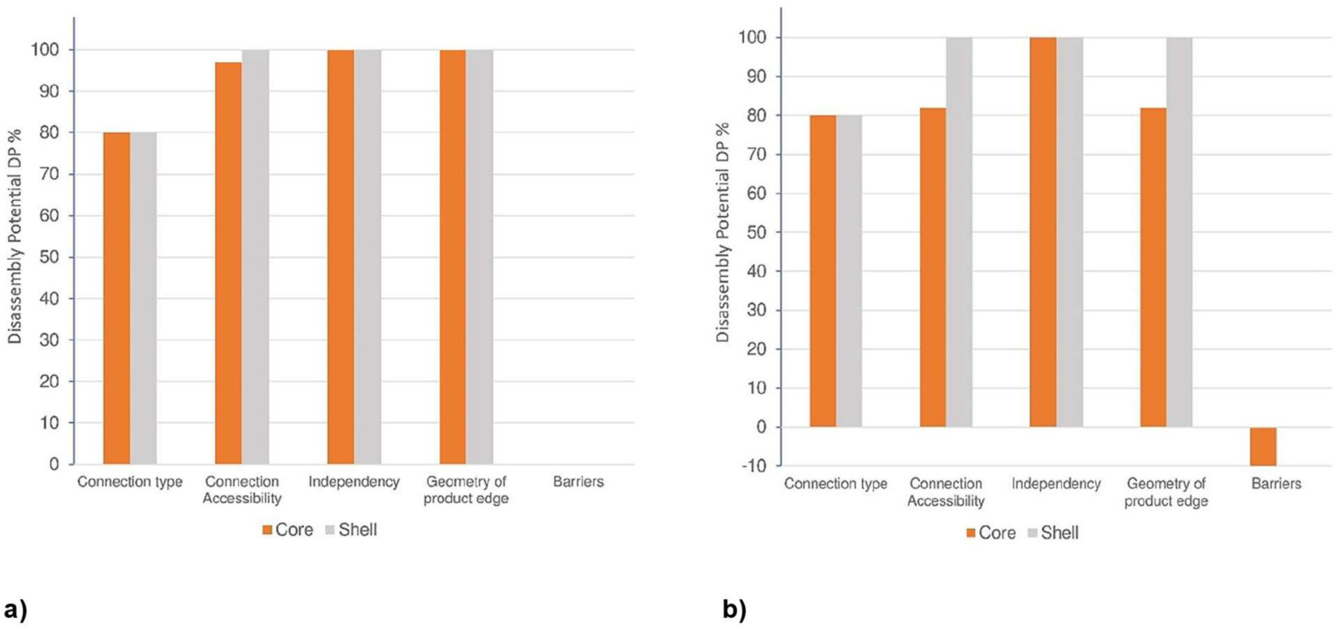


Fig. 11. Disassembly potential of the core and shell of the buildings based on the DfD criteria and barriers: a) *’t Centrum* building and b) *Green Office* building.

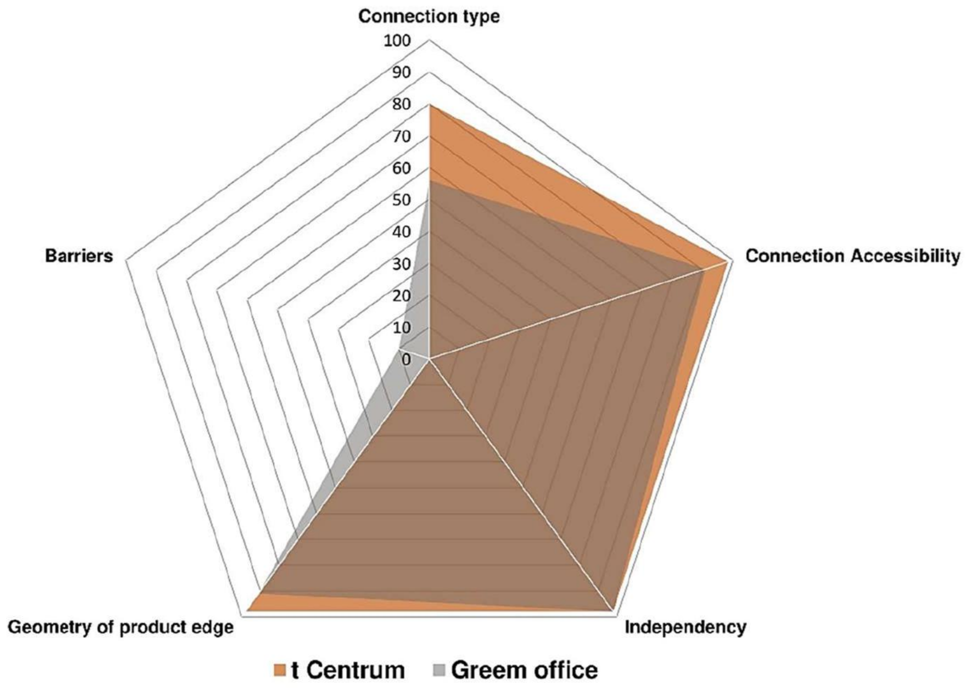


Fig. 12. Disassembly potential of *'t Centrum* and *Green office* buildings based on the DfD criteria and barriers.

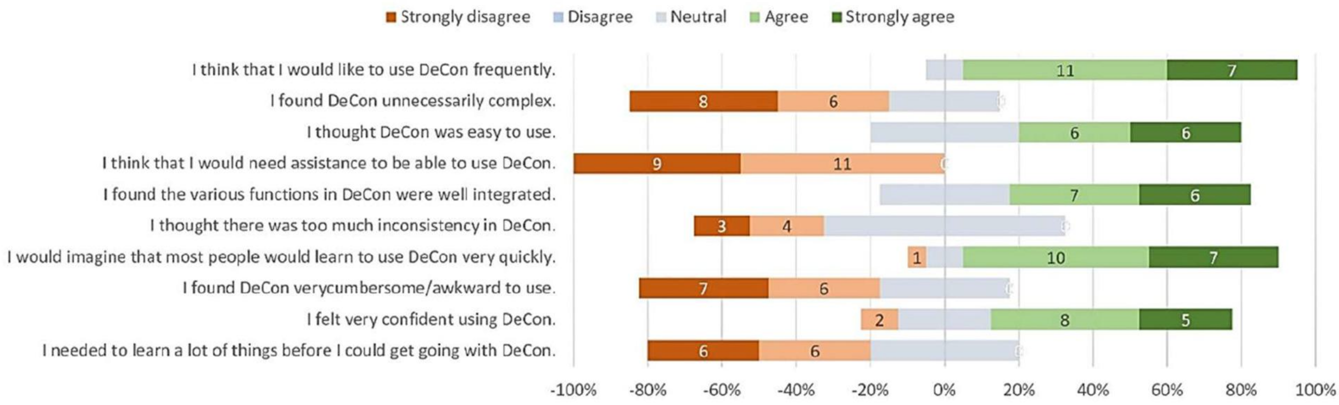


Fig. 13. Results of the usability test of expert system (DeCon) prototype 1 using the SUS.

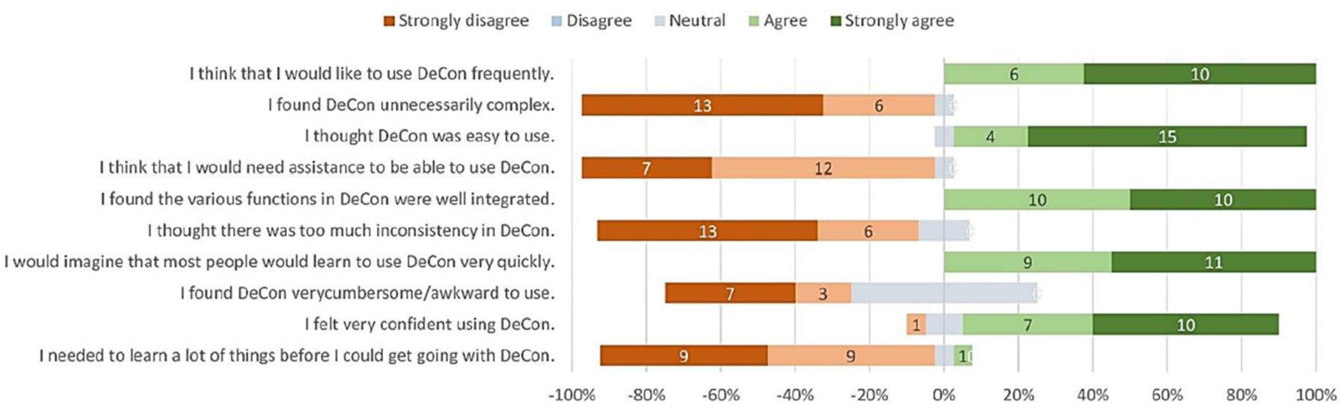


Fig. 14. Results of the usability test of expert system (DeCon) prototype 2 using the SUS.

expert system. The testing groups of architects, architectural engineers, and architectural students (20 users) were given a set of assignments outlining the steps necessary to utilize the expert system (DeCon).

Fig. 14 shows the inputs of users after gathering 20 responses. Overall, the usability of prototype 2 increased compared with that of prototype 1. The participants appeared to be more confident in using the instrument (prototype 2 vs. prototype 1: 86 % vs. 75 %). Therefore, the latest version of the expert system (DeCon) was adopted to evaluate the disassembly potential of the buildings.

5. Discussion

5.1. Summary and main findings

During the early design and deconstruction stages, the simulation-based design assistance expert system was found to promote informed decision-making regarding DfD. This boosts the understanding of DfD and reduces decision-making ambiguity. Participants who used the expert system (DeCon) reported a high level of expertise and employed an informational decision support method rather than an evaluative trial-and-error technique in their design. This alignment of decision-making and design purposes in the context of greater knowledge is consistent with our notion of informed DfD decision-making. However, based on the interface usability testing, the current prototype has not achieved a degree of usefulness that satisfies the demands of designers to address all building components. At this stage, the work of this expert system was limited to evaluating the disassembly potential of the core and shell of the buildings; therefore, this web tool is a starting point for developing a widely useable expert system with more details and many new features.

5.2. Strengths and limitations of this research

This is the first simulation-based expert system to support decision making in the early design and deconstruction stages. The strength of the expert system (DeCon) is its ability to inform design before decision making while managing huge sensitivity simulations and presenting complicated data in readily accessible, quick, and comparable scenarios. This web tool is very easy to use and has a simple interfacial structure. The web tool assists in achieving the disassembly target while investigating several ranges of disassembly designs to achieve the performance goal.

One of the reasons for the strength of this expert system is that it is a Duch-local approach and was developed based on the methodology used by the Dutch Green Building Council and Alba Concepts [57].

This expert system is purely technical; therefore, the environmental cost indicator of the component was omitted from the mentioned method, and a list of barriers to the disassembly process was added with their impact weights, which the author developed based on a literature review, to be used globally.

Informed decisions made during the early design stage and deconstruction enhance the DfD. It is envisaged that the current design trials of the expert system (DeCon) will have a greater influence on architects' decision-making and real design outputs, allowing the integration of building performance simulation tools to extend beyond the decision support level of this research.

However, the usability test results revealed that the expert system seemed more useful when used with the support of an expert or specialist in DfD. In addition, the decision-making support of the current prototype can only handle the connections between the core and shell of the building, although many users expect the system to handle more details and features. One of the main limitations identified during the workshops was the geometry input. The evaluation process took two weeks for the *'t Centrum* building to inventory the connections using the Revit model and 3 weeks for the *Green Office* building to inventory the connections from an AutoCAD file. Users suggested linking the audit sheet to the expert system (DeCon) to automatically feed the web tool by uploading the audit sheet instead of manually filling it.

5.3. Future work and possible applications

The expert system (DeCon) is a starting point for improved DfD decision making. The current version of the web tool has considerable limitations, and designers require additional information to make more educated decisions.

An expert system can be developed to include all buildings, such as hybrid or non-timber buildings, in full detail. It also includes other building configurations in terms of form, function, and connection types. Moreover, it can be developed to include additional products and components, such as doors, windows, and partitions. The interface could also be modified to include additional building systems. Future research should focus on integrating advanced data collection and processing techniques to enhance DeCon's scalability and automation. Real-time data acquisition and integration with Building Information Modeling (BIM) or Digital Twin platforms could reduce reliance on manual inputs in DeCon. Additionally, applying AI-driven predictive analytics for disassembly planning and anomaly detection would improve decision-making efficiency. In terms of usability testing, this study addressed the efficiency and effectiveness of the web tool as a supplement to satisfaction testing. At the level of decision assistance, future developments of the web tool can include economic indicators to mention the different costs and times during the deconstruction stage. Additionally, environmental indicators can be added to address the reduction in carbon emissions through efficient disassembly. For example, web tool development will continue as part of the new working group SC1/WG5 of CEN 350 for the circularity assessment of construction. These developments will be important for designers, academics, and CE policymakers.

The expert system (DeCon) could benefit from insights from the manufacturing sector, where standardized metrics like disassembly time and material recovery rates enhance efficiency. Adapting modular designs and digital tools such as Product Lifecycle Management

(PLM) could improve DeCon's accuracy in assessing construction-specific connections and material flows. Integrating these approaches would strengthen its role in promoting circular construction practices.

Finally, further investigations are required to learn more about the potential of DfD principles to accurately forecast the disassembly potential of buildings and material recoverability. Buildings must have a high level of standardization to design a building for disassembly. For the optimal completion of the disassembly process, the skills of the demolition contractors, as well as the type of workers and their availability, should be considered. This expert system would have no value if it remained within the theoretical framework and was not used practically by demolition experts or trained and specialized workers in the deconstruction of a building. Detailed guidelines for practitioners are still required, and there is a need to formalize and define the main steps of the disassembly process to be performed according to an approved protocol.

6. Conclusion

The development of the expert system (DeCon) represents a significant advancement in evaluating the building disassembly potential. By transforming complex data into quick and comparable scenarios, the expert system (DeCon) aids stakeholders in making informed decisions regarding building deconstruction. Through the literature review, the author identified critical DfD criteria and barriers, providing a foundation for the framework for the expert system. Validation through two case studies demonstrated the effectiveness of DeCon, with the system successfully quantifying the disassembly potential of the *'t Centrum* building at 92 % and that of the *Green Office* building at 72 %. These results highlight the utility of the expert system (DeCon) in promoting sustainable building practices and supporting its adoption for future projects aimed at enhancing CE principles in construction.

CRediT authorship contribution statement

Muheeb Al-Obaidy: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hilde Carens:** Writing – review & editing, Validation. **Clémentine Campain:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Enola Giannasi:** Visualization, Validation, Software, Investigation, Data curation. **Maxime Mori:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Mike van Vliet:** Writing – review & editing, Validation. **Shady Attia:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research is part of the Ph.D. research project DeConstruct: A circularity evaluation framework for office building design, supported by the University of Liege. We wish to acknowledge the Sustainable Building Design Lab for the use of data processing software in this research and its valuable support during focus group discussions and content analysis of the data. This research was supported by the EU Cost Action 21103–Implementation of Circular Economy in the Built Environment (Circular B), EU COST Action 20139–Holistic Design of Taller Timber Buildings (HELEN), and CEN/TC 350: Sustainability of Construction works, SC1 and SC5 on circularity assessment. We thank our colleagues from the COST Action Workgroups and CEN 350 committees, under the leadership of Prof. Lisbeth M. Ottosen from Denmark Technical University who provided insights and expertise that greatly assisted in screening review papers. The authors would also like to gratefully acknowledge Kamp C team and the companies consortium of 't Centrum project under the leadership of Joeri Beneens for sharing information about the case study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2025.112148.

Data availability

The data that has been used is confidential.

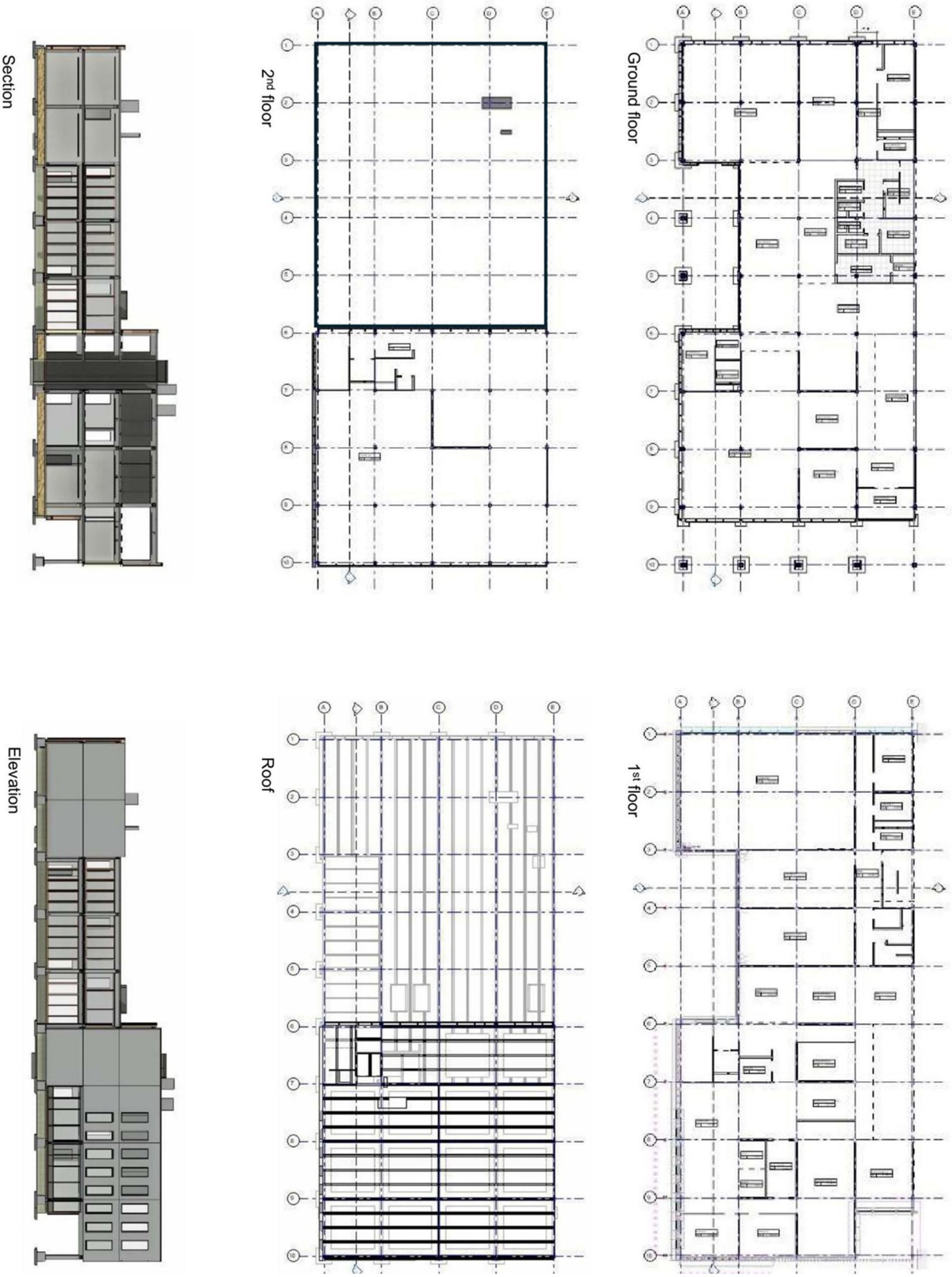
References

[1] D.A. Ness, K. Xing, Toward a resource-efficient built environment: a literature review and conceptual model: towards a resource efficient built environment, J. Ind. Ecol. 21 (3) (Jun. 2017) 572–592, https://doi.org/10.1111/jiec.12586.
[2] O.O. Akinade, et al., Design for Deconstruction (DfD): critical success factors for diverting end-of-life waste from landfills, Waste Management 60 (Feb. 2017) 3–13, https://doi.org/10.1016/j.wasman.2016.08.017.
[3] M. Anttonen, M. Lammi, J. Mykkänen, P. Repo, Circular economy in the triple helix of innovation systems, Sustainability 10 (8) (Aug. 2018), https://doi.org/10.3390/su14063370. Art. no. 8.
[4] E. Durmisevic, O. Ciftcioglu, C.J. Anumba, Knowledge model for assessing disassembly potential of structures, in: *Deconstruction And Materials Reuse Proceedings Of the 11th Rinker International Conference*, Conference, 2003. Delft, The Netherlands.
[5] ISO, ISO 20887:2020(en), Sustainability in buildings and civil engineering works - Design for disassembly and adaptability - Principles, requirements and guidance. https://www.iso.org/obp/ui/en/#iso:std:iso:20887:ed-1:v1:en. (Accessed 2 August 2024).
[6] P. Crowther, Design for Disassembly : an Architectural Strategy, Queensland University of Technology Winter Colloquium, Brisbane, Australia, 1999, pp. 27–33.
[7] B. Addis, Briefing: design for deconstruction, Proc Inst Civ Eng - Waste Resour Manag (May 2015), https://doi.org/10.1680/warm.2008.161.1.9.
[8] S. Attia, et al., Disassembly calculation criteria and methods for circular construction, Autom. ConStruct. 165 (Sep. 2024) 105521, https://doi.org/10.1016/j.autcon.2024.105521.
[9] B. Guy, S. Shell, H. Esherick, Design for deconstruction and materials reuse, in: *Proceedings Of the CIB Task Group*, Rotterdam, The Netherlands: Citeseer, 2006, pp. 189–209.
[10] T. Smeyers, M. Deweerdt, M. Mertens, Fcrbe - facilitating the circulation of reclaimed building elements in Northwestern Europe, Report (2023). Brussels, Belgium.
[11] Metabolic, Circularity in the built environment in Europe, Report (2024). Amsterdam, The Netherlands.
[12] ISO 59004:2024, "Circular economy — Vocabulary, principles and guidance for implementation." Geneva, Switzerland. Accessed: August. 2, 2024. [Online]. Available: https://www.iso.org/standard/80648.html.
[13] A. Jenet, M. Jenet, A. Lamperti Tornaghi, G. Tsionis, A. Sejersen, P. Moseley, Circular Technologies in Construction. Putting Science into Standards, publications office of the European Union, Luxembourg, 2024. Report.
[14] European Commission, "Sustainable investment – EU environmental taxonomy." Accessed: June. 4, 2023. [Online]. Available: http://rb.gy/j2fgdq.
[15] G. Pristerà, D. Tonini, M. Lamperti Tornaghi, D. Caro, S. Sala, Taxonomy of design for deconstruction options to enable circular economy in buildings, Resour Environ Sustain 15 (Mar. 2024) 100153, https://doi.org/10.1016/j.resenv.2024.100153.
[16] Ellen MacArthur Foundation, "What is a circular economy?" Accessed: January. 9, 2022. [Online]. Available: https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview.
[17] S. Attia, M. Al-Obaidy, Design criteria for circular buildings. Presented at the Crossing Boundaries 2021, Parkstadt, The Netherlands: Zuyd Uninversity, Mar. 2021, p. 11.
[18] DG Internal Market, Industry, Entrepreneurship and SMEs' (DG GROW)." Accessed: March. 28, 2023. [Online]. Available: http://rb.gy/sbu1zr.
[19] P. Jackson, Introduction to Expert Systems, third ed., Addison-Wesley, Michigan, USA, 2002. Book.
[20] SBD Lab, Project DeConstruct, A circularity evaluation framework for office buildings design. https://rb.gy/z1tt2n. (Accessed 30 July 2024).
[21] M. Smol, J. Kulczycka, A. Henclik, K. Gorazda, Z. Wzorek, The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy, J. Clean. Prod. 95 (2015) 45, https://doi.org/10.1016/j.jclepro.2015.02.051.
[22] M.H.A. Nasir, A. Genovese, A.A. Acquaye, S.C.L. Koh, F. Yamoah, Comparing linear and circular supply chains: a case study from the construction industry, Int. J. Prod. Econ. 183 (Jan. 2017) 443–457, https://doi.org/10.1016/j.ijpe.2016.06.008.
[23] L. Akanbi, et al., Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy, J. Clean. Prod. 223 (Mar) (2019), https://doi.org/10.1016/j.jclepro.2019.03.172.
[24] European Commission, "COM(2014)398 - Towards a circular economy: A zero waste programme for Europe." Accessed: February. 28, 2023. [Online]. Available: https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vjl4tamjogxb.
[25] D. Cottafava, M. Ritzen, Circularity indicator for residential buildings: addressing the gap between embodied impacts and design aspects, Resour. Conserv. Recycl. 164 (Jan. 2021) 105120, https://doi.org/10.1016/j.resconrec.2020.105120.
[26] M. Vandenbroucke, W. Galle, N. De Temmerman, W. Debacker, A. Paduart, Using life cycle assessment to inform decision-making for sustainable buildings, Buildings 5 (2) (Jun. 2015), https://doi.org/10.3390/buildings5020536.
[27] S. Attia, M.C. Santos, M. Al-Obaidy, M. Baskar, Leadership of EU member States in building carbon footprint regulations and their role in promoting circular building design. Presented at the Crossing Boundaries 2021, Parkstadt, The Netherlands: Zuyd Uninversity, Mar. 2021, p. 13.
[28] European Commission, Circular economy - principles for building design, Report (2020). Brussels, Belgium.
[29] L.M. Luscuere, Materials Passports: optimising value recovery from materials, Proc Inst Civ Eng - Waste Resour Manag 170 (1) (Feb. 2017) 25–28, https://doi.org/10.1680/jwarm.16.00016.
[30] W. Debacker, S. Manshoven, M. Peters, A. Ribeiro, Y. De Weerdt, Circular economy and design for change within the built environment: preparing the transition. Presented at the International HISER Conference, 2017. Delft, The Netherlands, https://rebrand.ly/booqhvd.
[31] E. Durmiševic, Reversible Building Design, University of Twente, Report, Enschede, The Netherlands, Mar. 2018.

[32] M. Vandenbroucke, S. Brancart, Catalogus veranderingsgericht bouwen, Functionele lagen. OVAM, Report, 2020. Brussels, Belgium.
[33] OVAM, Design for change: development of a policy and transitional framework, Report (2015). Brussels, Belgium.
[34] M. Vandenbroucke, Rapport -Technische levensduur van gebouwcomponenten. OVAM, Report, Nov. 2018. Brussels, Belgium.
[35] B. Berge, The Ecology of Building Materials, second ed., Routledge, London, UK, 2009. Book.
[36] M.L. Vandenbroucke, W.C. Lam, W. Debacker, W. Galle, Ontwerpfiches: Veranderingsgericht Bouwen, Openbare Vlaamse Afvalstoffenmaatschappij, OVAM, 2015. Report, Brussels, Belgium.
[37] W. Galle, M. Vandenbroucke, Veranderingsgericht bouwen: ontwikkeling van een beleids- en transitiekader. Samenvatting, OVAM, Report (Apr. 2015). Brussels, Belgium.
[38] M. Orbelians, Design for Disassembly in Life Cycle Assessment and Circularity Evaluation, Norwegian University of Science and Technology, Trondheim, Norway, 2023. Master thesis.
[39] C. Vandervaeren, W. Galle, A. Stephan, N. De Temmerman, More than the sum of its parts: considering interdependencies in the life cycle material flow and environmental assessment of demountable buildings, Resour. Conserv. Recycl. 177 (Feb. 2022) 106001, https://doi.org/10.1016/j.resconrec.2021.106001.
[40] ISSO, "Beter weten, beter bouwen," ISSO. Accessed: March. 3, 2023. [Online]. Available: https://www.isso.nl/.
[41] E. Kroll, B. Beardsley, A. Parulian, A methodology to evaluate ease of disassembly for product recycling, IIE Trans. 28 (10) (Oct. 1996) 837–846, https://doi.org/10.1080/15458830.1996.11770736.
[42] Buildwise, Protocole d'identification et de gestion des déchets de démolition en vue de leur valorisation, in: Buildwise, Report, Brussels, Belgium, 2023.
[43] T. Smeyers, M. Mertens, The reclamation audit: a guide to creating an inventory before demolition of potentially reusable construction products, Brussels Environment (2022). Report, Brussels, Belgium.
[44] G. Emilie, G. Michael, A. Paduart, C. Bernair, A roadmap to foster reuse practices in the construction sector A collection of inspiring actions for public authorities, Report (Nov. 2021). Brussels, Belgium.
[45] R. Mestdagh, S. Vanhullebusch, Design and Use of Pre-demolition Mapping Tool to Evaluate and Enhance Recycling of Construction and Demolition Waste, Faculty of Engineering Technology, KU Leuven, 2019. Master thesis, Leuven, Belgium.
[46] E. Durmisevic, A. Guerriero, C. Boje, B. Domange, G. Bosch, Development of a conceptual digital deconstruction platform with integrated Reversible BIM to aid decision making and facilitate a circular economy. Presented at the CIB W78 & LDAC, Oct. 2021. Luxemburg.
[47] B. Dams, et al., A circular construction evaluation framework to promote designing for disassembly and adaptability, J. Clean. Prod. 316 (Sep. 2021) 128122, https://doi.org/10.1016/j.jclepro.2021.128122.
[48] Z. Yang, W. Lu, Facility layout design for modular construction manufacturing: a comparison based on simulation and optimization, Autom. ConStruct. 147 (Mar. 2023) 104713, https://doi.org/10.1016/j.autcon.2022.104713.
[49] S. Montazeri, N. Odo, S.A.W. Naqvi, Z. Lei, Integrating design for manufacturing and assembly principles in modular home construction: a comprehensive framework for enhanced efficiency and sustainability, Buildings 15 (1) (Jan. 2025), https://doi.org/10.3390/buildings15010103.
[50] J.R. Jupp, Cross industry learning: a comparative study of product lifecycle management and building information modelling, Int. J. Prod. Lifecycle Manag. 9 (3) (Jan. 2016) 258–284, https://doi.org/10.1504/IJPLM.2016.080502.
[51] P. Hradil, M. Wahlström, PRE-DEMOLITION audits in EU countries. VTT Technical Research Centre, Report, Finland, Espoo, 2019.
[52] Bre, et al., Resource Efficient Use of Mixed Wastes Improving Management of Construction and Demolition Waste: Final Report, Publications Office of the European Union, Brussels, Belgium, 2017. Report.
[53] C. Lausselet, O.A. Dahlstrøm, M. Thyholt, A. Eghbali, P. Schneider-Marin, Methods to account for design for disassembly: status of the building sector, Buildings 13 (4) (Apr. 2023), https://doi.org/10.3390/buildings13041012.
[54] B. Guy, N. Ciarimboli, DfD: design for disassembly in the built environment : a guide to closed-loop design and building, Hamer Center, Report, Seattle, USA (2008).
[55] S. Moffatt, P. Russell, Assessing the adaptability of buildings, Energy-Related Environmental Impact of Buildings 31 (2001). Birmingham, UK.
[56] E. Durmisevic, Transformable Building Structures: Design for Dissassembly as a Way to Introduce Sustainable Engineering to Building Design and Construction, Dissertation, Delft, The Netherlands, 2006.
[57] M. Van Vliet, J. Van Grinsven, J. Teunizen, Circular Buildings - een meetmethodiek voor losmaakbaarheid v2.0 - Dutch Green Building Council, Report (2021). Rotterdam, The Netherlands.
[58] D. Fang, C. Mueller, Joinery connections in timber frames: analytical and experimental explorations of structural behavior, Conference, Boston, USA (Jul. 2018).
[59] L.-M. Ottenhaus, R. Jockwer, D. van Drimmelen, K. Crews, Designing timber connections for ductility – a review and discussion, Constr. Build. Mater. 304 (Oct. 2021) 124621, https://doi.org/10.1016/j.conbuildmat.2021.124621.
[60] I. Smith, A. Asiz, M. Snow, Design method for connections in engineered wood structures, Conference (2006). Fredericton, Canada.
[61] L. Liu, Tracking The Life Cycle Of Construction Steel: The Development of A Resource Loop, University of Kansas, Kansas, USA, 2009. Master thesis.
[62] I. Srour, W. Chong, F. Zhang, Sustainable recycling approach: an understanding of designers' and contractors' recycling responsibilities throughout the life cycle of buildings in two US cities, Sustainable Development - SUSTAIN DEV 20 (Sep) (2012), https://doi.org/10.1002/sd.493.
[63] M. Webster, D.T. Costello, Designing structural systems for deconstruction: how to extend a new building's useful life and prevent it from going to waste when the end finally comes, Conference (2005) 1–14. Atlanta, USA.
[64] C.J. Kibert, A.R. Chini, J. Languell, Deconstruction as an essential component of sustainable construction. Presented at the CIB World Building Congress, Conference, 2001. Wellington, New Zealand.
[65] C. Kibert, A.R. Chini, Overview of deconstruction in selected countries, Report (2000). Rotterdam, The Netherlands.
[66] F.C. Rios, W.K. Chong, D. Grau, Design for disassembly and deconstruction - challenges and opportunities, Procedia Eng. 118 (Jan. 2015) 1296–1304, https://doi.org/10.1016/j.proeng.2015.08.485.
[67] R.A. Bohne, E. Wærner, Barriers for Deconstruction and Reuse/Recycling of Construction Materials in Norway, vol. 397, CIB Publication, Ontario, Canada, 2014, pp. 89–107.
[68] C. Kibert, Deconstruction as an essential component of sustainable construction. Proceedings of International Conference Sustainable Building, 2000, pp. 89–91.
[69] B. Milani, Building Materials in a Green Economy: Community-Based Strategies for Dematerialization, University of Toronto, Dissertation, Toronto, Canada, 2005.
[70] BuildingGreen, "Sustainable Products Purchasers Coalition SPPC." Accessed: April. 16, 2023. [Online]. Available: https://www.buildinggreen.com/newsbrief/sustainable-products-purchasers-coalition.
[71] SBD Lab, "Sustainable Building Design SBD Lab," University of Liege. Accessed: July. 2, 2023. [Online]. Available: https://www.sbd.uliege.be/cms/c_7641680/en/sbdlab.
[72] S. Attia, Sustainable buildings and connections database, Harvard Dataverse (2024), https://doi.org/10.7910/DVN/S33AGK [Online]. Available:.
[73] COST, "Action CA20139 Holistic design of taller timber buildings (HELEN)," COST. Accessed: June. 20, 2023. [Online]. Available: https://www.cost.eu/actions/CA20139.
[74] S. Attia, Regenerative and positive impact architecture, in: SpringerBriefs in Energy, Springer International Publishing, London, UK, 2018, https://doi.org/10.1007/978-3-319-66718-8.
[75] S. Attia, M. Attia, USER-FIT: A Framework to Evaluate the Usability of Building Performance Simulation Tools in the Architectural Design Process, Report, SBD Lab, University of Liege, Liege, Belgium, 2023.
[76] S. Attia, A. El-Degwy, M. Attia, Usability and fitness testing for building performance simulation tools, Journal of Building Performance Simulation 17 (4) (Jul. 2024) 460–479, https://doi.org/10.1080/19401493.2024.2341089.
[77] European Commission, Data protection in the EU - European commission. https://commission.europa.eu/law/law-topic/data-protection/data-protection-eu_en. (Accessed 3 August 2024).
[78] KU Leuven, Data management plan DMP. https://www.kuleuven.be/rdm/en/guidance/dmp/dmp. (Accessed 3 August 2024).

[79] ISO, ISO 9241-11:2018 Ergonomics of human-system interaction — Part 11: usability: Definitions and concepts. https://www.iso.org/standard/63500.html. (Accessed 24 September 2023).
[80] ANSI/INCITS 354-2001, Common Industry Format for Usability Test Reports (formerly ANSI INCITS 354-2001) (2001).
[81] CEN, Circular Economy in the Construction Sector - Terminology, Principles and Framework for Implementation, vol. 7, Standard Draft, Geneva, Switzerland, 2025.
[82] Kamp C, "Circular building: 't Centrum," Kamp C. Accessed: July. 19, 2021. [Online]. Available: https://www.kampc.be/tcentrum/circulair-bouwen-t-centrum.
[83] WEST architectuur, "KANTOOR - C." Accessed: September. 25, 2023. [Online]. Available: https://westarchitectuur.be/realisaties/kampc.
[84] Beneens, "We build camp circular." Accessed: July. 19, 2021. [Online]. Available: https://www.beneens.be/circulair.
[85] M. Al-Obaidy, L. Courard, S. Attia, A parametric approach to optimizing building construction systems and carbon footprint: a case study inspired by circularity principles, Sustainability 14 (6) (Jan. 2022), https://doi.org/10.3390/su14063370.
[86] LUTZ architectes, Green Offices, premier bâtiment administratif Minergie-P-Eco. https://www.lutz-architectes.ch/realisation/green-offices-premier-batiment-administratif-minergie-p-eco. (Accessed 25 September 2023).
[87] Vonlanthen Holzbau AG – Holz in Topform, "Innovativ – Bauend Auf Generationen." Accessed: September. 25, 2023. [Online]. Available: https://www.vonlanthenholzbau.ch/.
[88] Minergie, Minergie international - sustainable buildings. https://www.minergie.com/. (Accessed 25 September 2023).
[89] Swiss Federal Office of Energy, Winners of the 2008 Watt d'Or awards. https://cl.gy/MXmHO. (Accessed 25 September 2023).
[90] M. Al-Obaidy, S. Attia, DeCon, Deconstruction assessment tool. Beta Version 1, SBD Lab, University of Liege, Belgium, 2024 [Online]. Available: https://orbi.uliege.be/handle/2268/313887. (Accessed 9 March 2024).
[91] W3 Schools, "What is JavaScript." Accessed: August. 3, 2024. [Online]. Available: https://www.w3schools.com/whatis/whatis_js.asp.

Appendix 1. ’t Centrum building drawings



Appendix 2. Green office building drawings

Appendix 3. The audit sheet

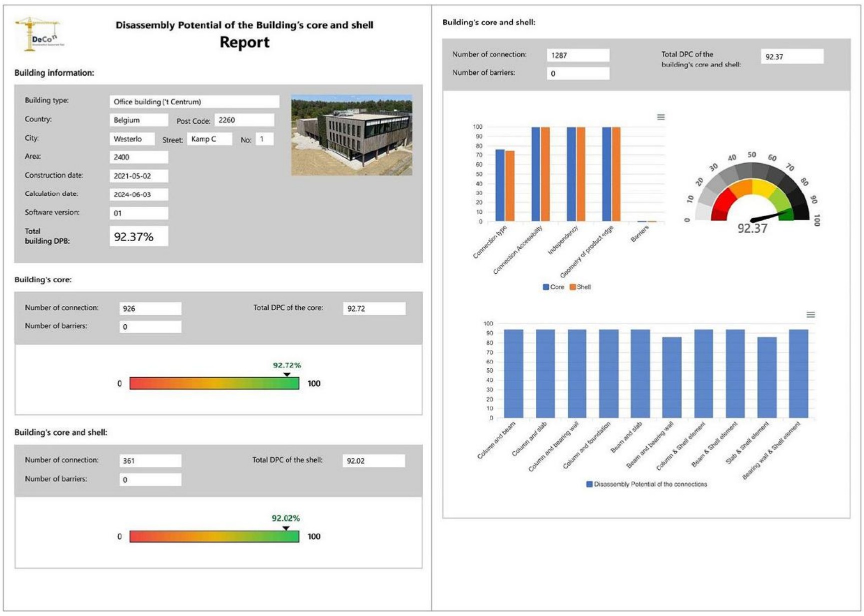
Audit sheet to evaluate the disassembly potential ('t Centrum)

		DfD Criteria					DfD Barriers					Number
1	Core	Composition type	Connction type	Connection accessibility	Independency	Geometry of product edge	Design barriers	Execution errors	Accidental actions	Environmental actions	Management issues	
	1.1.	Column & Beam	Connections with	Freely accessible without	Occasional	Open, no obstacle to the						
	1.2.	Column & Slab	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	1.3.	Column & Bearing wall	Connections with	Accessible with additional	Occasional	Open, no obstacle to the						
	1.4.	Column & Foundation	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	1.5.	Beam & Slab	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	1.6.	Slab & Bearing wall	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
2	Shell											
	2.1.	Column & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	2.2.	Beam & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	2.3.	Slab & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	2.4.	Bearing wall & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						

Audit sheet to evaluate the disassembly potential (Green Office)

		DfD Criteria					DfD Barriers					
1	Core	Composition type	Connction type	Connection accessibility	Independency	Geometry of product edge	Design barriers	Execution errors	Accidental actions	Environmental actions	Management issues	
	1.1.	Column & Beam	Connections with	Freely accessible without	Occasional	Open, no obstacle to the						
	1.2.	Column & Slab	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	1.3.	Column & Bearing wall	Connections with	Accessible with additional	Occasional	Open, no obstacle to the						
	1.4.	Column & Foundation	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	1.5.	Beam & Slab	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	1.6.	Slab & Bearing wall	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
2	Shell											
	2.1.	Column & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	2.2.	Beam & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	2.3.	Slab & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	2.4.	Bearing wall & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						

Appendix 4. The expert system (DeCon) interface (step-by-step tutorial) and final report



Appendix 5. The System Usability Scale (SUS)

Participant ID: _____ Site: ________ Date: ___/___/___

System Usability Scale

Instructions: For each of the following statements, mark <u>one</u> box that best describes your reactions to the **DeCon** tool.

	Strongly Disagree				Strongly Agree
1. I think that I would like to use DeCon frequently.					
2. I found DeCon unnecessarily complex.	☐	☐	☐	☐	☐
3. I thought DeCon was easy to use.	☐	☐	☐	☐	☐
4. I think that I would need assistance to be able to use DeCon.	☐	☐	☐	☐	☐
5. I found the various functions in DeCon were well integrated.	☐	☐	☐	☐	☐
6. I thought there was too much inconsistency in DeCon.	☐	☐	☐	☐	☐
7. I would imagine that most people would learn to use DeCon very quickly.	☐	☐	☐	☐	☐
8. I found DeCon very cumbersome/awkward to use.	☐	☐	☐	☐	☐
9. I felt very confident using DeCon.	☐	☐	☐	☐	☐
10. I needed to learn a lot of things before I could get going with DeCon.	☐	☐	☐	☐	☐

Please provide any comments about **DeCon** tool:

This questionnaire is based on the System Usability Scale (SUS), which was developed by John Brooke while working at Digital Equipment Corporation. © Digital Equipment Corporation, 1986.

Chapter 05. *BCEF: Early design framework for circular and low-impact buildings – Journal paper*

Abstract: The transition to a circular economy in construction demands robust frameworks to assess circularity across the building life cycle. Most existing methods lack methodological depth, fail to support early design, and overlook strategies for disassembly, reuse, and service. This paper presents the Building Circularity Evaluation Framework (BCEF), a multi-criteria framework integrating six indicators: Global Warming Potential, Land-Use Footprint, Reused Content, Disassembly Potential, Functional Adaptation, and Product-Service Systems. Aligned with EN 15804+A2, EN 15978, and ISO 20887, BCEF uses digital tools (Brightway2, DeCon) for semi-automated scoring. Validation is conducted using the Circl Pavilion in the Netherlands; one of the few fully disassemblable buildings. Three scenarios with varying circular strategies are modeled to demonstrate BCEF's ability to quantify trade-offs, support early-stage decision-making, and benchmark circularity. Results confirm their robustness, replicability, and relevance for designers, engineers, and policymakers aiming to implement circular construction practices.

Role of Ph.D. candidate: As first author, the Ph.D. candidate developed the framework architecture and indicator set (conceptualization, Lead), defined normalisation/weighting and scoring logic (methodology, Lead), implemented the computation pipeline and data structures (software/resources, Lead), ran case applications and collated evidence (investigation/data curation, Lead), tested robustness/sensitivity (formal analysis/validation, Lead), prepared all framework diagrams and dashboards (visualization, Lead), and drafted the manuscript (writing – original draft, Lead). Co-authors supported supervision and writing – review & editing (Equal)

Journal: Results in Engineering (Elsevier)

Journal impact factor: Current Impact Factor: 7.9

5-Year Impact Factor: 7.4

Citations: Google Scholar: 3

Reference: Al-Obaidy, M., Courard, L., Passarelli, R., Giannasi, E., & Attia, S. (2026). BCEF: Early Design Framework for Circular and Low-Impact Buildings. Results in Engineering, 110824. https://doi:10.1016/j.rineng.2026.110824 & https://hdl.handle.net/2268/344633

Results in Engineering 30 (2026) 110824

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Research paper

BCEF: Early design framework for circular and low-impact buildings

Muheeb Al-Obaidy [a,b,*], Luc Courard [c], Rafael Passarelli [d], Enola Giannasi [e], Shady Attia [a]

[a] Sustainable Building Design Laboratory, Department, Urban and Environmental Engineering, School of Engineering, Université de Liège, Liège 4000, Belgium
[b] Sustainable Building Materials, Construction Department, Colruyt Group, Halle 1500, Belgium
[c] GeMMe Building Materials, Department of Urban and Environmental Engineering, Faculty of Applied Science, Université de Liège, Liège 4000, Belgium
[d] Faculty of Architecture and Arts, Hasselt University, Hasselt 3500, Belgium
[e] ENTPE, University of Lyon, 3 Rue Maurice Audin, Vaulx-en-Velin 69120, France

ARTICLE INFO

Keywords:
Decision support
Design for disassembly (DfD)
Building connections
Circular buildings
Life cycle impact assessment
Performance indicators

ABSTRACT

The transition to a circular economy in construction demands robust frameworks to assess circularity across the building life cycle. Most existing methods lack methodological depth, fail to support early design, and overlook strategies for disassembly, reuse, and service. This paper presents the Building Circularity Evaluation Framework (BCEF), a multi-criteria framework integrating six indicators: Global Warming Potential, Land-Use Footprint, Reused Content, Disassembly Potential, Functional Adaptation, and Product-Service Systems. Aligned with EN 15804+A2, EN 15978, and ISO 20887, BCEF uses digital tools (Brightway2, DeCon) for semi-automated scoring. Validation is conducted using the Circl Pavilion in the Netherlands; one of the few fully disassemblable buildings. Three scenarios with varying circular strategies are modeled to demonstrate BCEF's ability to quantify trade-offs, support early-stage decision-making, and benchmark circularity. Results confirm their robustness, replicability, and relevance for designers, engineers, and policymakers aiming to implement circular construction practices.

1. Introduction

1.1. Background

The building sector is among the most resource- and carbon-intensive industries worldwide, accounting for 36.4 % of material waste in the European Union (EU) [1,2] and nearly 50 % globally [3]. It is also responsible for approximately 40 % of global CO_2 emissions [4], arising from energy-intensive material production, construction activities, building operation, and end-of-life (EoL) processes. A fundamental structural driver of these impacts is the prevailing linear economic model, characterized by a "take–make–dispose" logic that largely neglects strategies for material reuse, recovery, and disassembly during the design phase [5]. As a result, opportunities to reduce embodied emissions and extend material service life remain systematically underexploited.

In response to these challenges, the circular economy (CE) has emerged as a guiding paradigm for reducing resource depletion and environmental burdens. CE aims to maintain products, components, and materials at their highest utility and value over time, supporting restorative and regenerative material cycles [6]. Within the construction sector, this paradigm is reflected in design strategies such as material reuse, design for disassembly (DfD) [7], functional adaptability, and service-based procurement models, which collectively aim to minimize virgin resource input and enhance recovery at EoL [8,9]. At the regulatory and standardization level, CEN/TC 350 [10] provides a European framework defining principles, boundaries, and assessment methods to support the integration of circular economy concepts into construction practice.

Circular construction, therefore, seeks to deliver buildings that

Abbreviations: BCEF, Building Circularity Evaluation Framework; BCIs, Building circularity indicators; CBA, Circular building assessment; CDW, Construction and demolition waste; CE, Circular economy; CLT, Cross-laminated timber; DfD, Design for disassembly; DfD&A, Design for disassembly and adaptability; DfF, Design for flexibility; EC, European Commission; EoL, End of life; EPD, Environmental product declaration; EU, European Union; FCRBE, Facilitating the circulation of reclaimed building elements in Northwestern Europe; GHG, Greenhouse gas; GWP, Global warming potential; HVAC, Heating, ventilation, and air conditioning; ISO, International Organization for Standardization; KPIs, Key performance indicators; LCIA, Life cycle impact assessment; LU, Land-Use footprint; PSS, Product-service systems; RC, Reused content; RES, Renewable energy systems; TQM, Total quantity of materials.

* Corresponding author at: Sustainable Building Design Laboratory, Department Urban and Environmental Engineering, School of Engineering, Université de Liège, Liège 4000, Belgium.
E-mail address: muheeb.al-obaidy@uliege.be (M. Al-Obaidy).

https://doi.org/10.1016/j.rineng.2026.110824
Received 10 August 2025; Received in revised form 29 April 2026; Accepted 30 April 2026
Available online 30 April 2026

incorporate reused or recycled materials [11], adapt to changing functional requirements over time, and act as material reservoirs at the end of their service life [12]. By reducing dependence on virgin resources, such approaches are expected to mitigate material scarcity risks and exposure to price volatility [13,14]. In this context, the effective management of Construction and Demolition Waste (CDW) has been identified as a critical enabler of circular transition, highlighting the importance of integrated, life-cycle-oriented resource recovery strategies [15].

To operationalize these principles, a growing number of frameworks and tools have been developed over the past decade, including Level(s), BREEAM, Madaster, and the Whole Building Circularity Indicator (WBCI). These approaches have contributed valuable qualitative and quantitative indicators for assessing aspects of building circularity, particularly material efficiency and disassembly potential. However, they remain heterogeneous in scope and methodology, with limited consistency in life-cycle coverage, indicator integration, and early-stage applicability [16,17]. In particular, environmental life-cycle impacts are not always systematically integrated with circularity metrics, and methodological assumptions are often implicit or tool-specific. These limitations motivate further research into structured approaches that can link circular design strategies with life-cycle impact assessment in a transparent and design-relevant manner.

1.2. Research gap

Despite increasing policy attention and a rapidly expanding body of academic work, standardized and analytically consistent methods for evaluating building circularity across the full life cycle remain limited. Existing approaches are characterized by methodological heterogeneity, including divergent definitions of circularity, inconsistent indicator sets, and varying system boundaries, which together hinder transparency and comparability across projects [18]. In practice, many frameworks focus on specific aspects of circularity, such as individual material flows or recycled content, while relying on qualitative or checklist-based assessment methods that lack quantitative rigor and reproducibility [19].

Although recent studies have attempted to quantify circular construction strategies, many frameworks still struggle to operationalize circularity assessment at the whole-building scale in a life-cycle-consistent manner [20,21]. In particular, the systematic coverage of life-cycle stages defined in EN 15804 and EN 15978; namely Modules A (product stage), B (use stage), C (end-of-life), and D (benefits beyond the system boundary); is often incomplete or implicit, limiting alignment with standardized environmental assessment practice. This fragmentation complicates the interpretation of circularity outcomes and their integration with life-cycle impact assessment results.

Furthermore, empirical evidence suggests that increased circularity does not automatically translate into improved environmental or economic performance [22,23]. Reuse and recycling strategies may shift impacts across life-cycle stages or introduce new trade-offs, underscoring the need for evaluation frameworks that can explicitly relate circular design strategies to quantified life-cycle outcomes. While existing tools such as the Material Circularity Indicator (MCI) and Level (s) provide valuable insights [24], they typically do not integrate disassembly potential, functional adaptability, and service-based models within a unified, quantitative framework at the whole-building level [25]. Moreover, they rarely make explicit how circularity indicators interact with environmental impacts across Modules A–D [26,27].

Taken together, the research gap addressed in this study is not the absence of circularity metrics per se, but the lack of a structured, transparent, and early-stage-oriented evaluation framework that explicitly links circular design strategies with life-cycle assessment principles while acknowledging potential trade-offs.

1.3. Objectives and contributions

This study introduces the Building Circularity Evaluation Framework (BCEF) as a structured, multi-indicator evaluation framework for assessing building circularity and selected environmental impacts during early design stages. BCEF is not intended as a predictive model or optimization tool, but as a transparent evaluative structure that formalizes how circularity-related indicators can be selected, mapped to life-cycle stages, normalized, and aggregated at the whole-building level. The framework was developed through a systematic review of the literature, alignment with EN and ISO standards, and expert consultation within EU-funded projects and technical committees.

BCEF integrates six indicators; Global Warming Potential (GWP), Land-Use Footprint (LU), Reused Content (RC), Disassembly Potential (DP), Functional Adaptation (FA), and Product–Service Systems (PSS); each explicitly linked to life-cycle modules defined in EN 15804 and EN 15978 (Modules A–D). The novelty of BCEF lies in being among the first frameworks to explicitly integrate LCIA indicators (GWP, LU) with circular design indicators (DP, RC, FA, PSS) within a unified early-stage engineering evaluation structure. Existing systems such as DGNB, BREEAM, Level(s), and Madaster either lack early-stage engineering applicability, integrated weighting logic, or explicit disassembly assessment; BCEF addresses all three within a single, standards-aligned framework.

To support operationalization, BCEF combines digital tools, including the Brightway life-cycle assessment software for environmental modeling and a semi-automated expert system (DeCon tool) for assessing disassembly potential. This integration enhances transparency and replicability of calculations, while acknowledging the constraints of early design information.

The research addresses the following questions:

1. How can building circularity be evaluated in a structured and transparent manner during early design stages using a life-cycle-based perspective?
2. How can circularity-related indicators be consistently mapped and aggregated across life-cycle Modules A, B, C, and D to support comparative design assessment?

The novelty of BCEF relative to existing international frameworks is threefold. First, it is the first framework to explicitly map six circularity-related indicators–including qualitative dimensions such as Functional Adaptation (FA) and Product–Service Systems (PSS); to life-cycle modules A–D as defined in EN 15804 and EN 15978, enabling joint interpretation of circular design strategies and quantified environmental impacts. Second, BCEF integrates a semi-automated expert system (DeCon) for disassembly potential assessment, making scoring transparent and reproducible rather than judgment-based. Third, it is validated through a real stress-test case (ABN AMRO Circl Pavilion) across three scenario scopes, exposing scope-dependent trade-offs that prior frameworks such as BCI, WBCI, and Level(s) do not model [27,28,30]. Unlike these frameworks, BCEF couples circularity proxies (DP, RC, FA, PSS) with LCIA-based pressures (GWP, LU) within a single normalized composite index, enabling trade-off visualization at the early design stage rather than isolated optimization of either dimension.

The framework is demonstrated through application to the ABN AMRO Circl Pavilion in the Netherlands [26], an information-rich case selected to test internal coherence, indicator behavior, and methodological consistency under real design conditions. The case study is not intended to represent typical building practice, nor to establish generalizable benchmarks, but to illustrate how BCEF can be applied in practice and to identify strengths and limitations of the framework.

Overall, this work contributes a standards-aligned and transparent methodological structure for early-stage circularity evaluation. By explicitly acknowledging trade-offs, methodological assumptions, and current limitations, BCEF provides a foundation for future refinement, comparative testing against alternative frameworks (e.g., Level(s) [28], BCI [29], Madaster [30]), and broader validation across building types and contexts [27,31].

This work aligns with the aims and scope of this journal by addressing a concrete engineering problem: the absence of a structured, quantitative framework for evaluating building circularity during early design–and by developing and validating an engineering solution grounded in life-cycle assessment (EN 15804+A2, EN 15978) and structural performance principles (ISO 20887). BCEF is operationalized through digital engineering tools (Brightway2, DeCon) and validated on a real, constructed, and subsequently deconstructed building. The contribution is methodological and engineering-focused: it produces reproducible, quantitative outputs; GWP in kg CO_2eq, disassembly potential in percentage, and a composite BCEF index; that directly support design engineers and building performance practitioners. This positions BCEF firmly within the domain of structural and environmental engineering, addressing performance engineering challenges rather than management, economics, or social science questions.

2. Relation to recent literature (2020–2025)

A rapidly expanding body of work published between 2020 and 2025 has advanced circularity assessment in the built environment, with BCEF directly building upon and differentiating itself from this recent literature. Khadim et al. [16,27] proposed the Whole Building Circularity Index (WBCI), which advances building-level scoring but does not integrate life-cycle impact assessment (LCIA) indicators or explicit module mapping across Modules A–D. Van Stijn et al. [17] introduced a CE-LCA approach linking material flows to environmental impacts, yet without a disassembly potential indicator or product–service system dimension. Studies by Durmisevic [16] and Slobbe et al. [22] further reinforced the need for early-stage, quantitative evaluation frameworks integrating both circularity and environmental performance dimensions. At the standardization level, the ongoing development of prEN 17998 (design for circularity) and prEN 18177 (framework and definitions) within CEN/TC 350/SC 1 signals institutional convergence toward harmonized European approaches; BCEF is explicitly structured to align with these emerging standards [52,53]. In contrast to the contributions above, BCEF provides an integrated, normalized, and digitally operable structure that simultaneously addresses material circularity, environmental impact (GWP, LU), functional adaptability, and service models within a single composite index–a combination not achieved by any single prior framework. Critically, the Circl Pavilion validation was conducted following the building's actual deconstruction in 2024, providing empirical grounding against real disassembly outcomes that earlier studies could not access [78,79]. This positions BCEF as a methodological contribution directly responsive to the unresolved gaps identified in the most recent literature.

This study makes a direct contribution to building engineering practice by providing a structured, quantitative decision-support framework applicable at the early design stage. The BCEF framework integrates engineering design principles, lifecycle performance assessment, and material circularity metrics into a coherent evaluation methodology. As such, it advances the field of sustainable building engineering by translating high-level environmental goals into actionable, performance-oriented design criteria that can be operationalized by engineers and architects during the pre-design and schematic phases. The framework has been validated through application to a real, constructed, and subsequently deconstructed building, demonstrating its practical utility and reproducibility in engineering contexts.

3. Literature review

The literature on circular economy (CE) assessment in the building sector has expanded rapidly over the past decade, driven by European policy initiatives, standardization efforts, and growing concern over the environmental impacts of construction. Numerous frameworks, indicators, and tools have been proposed to operationalize circularity concepts at material, component, and building scales. However, this body of work is characterized less by convergence than by diversification, resulting in a fragmented assessment landscape with significant variation in scope, methodological rigor, and intended use.

Rather than reviewing these approaches descriptively, this section critically examines how existing frameworks conceptualize circularity, which life-cycle stages and design decisions they address, and where methodological limitations persist. The objective is not to establish a comprehensive taxonomy of circularity tools, but to identify the specific analytical gaps that motivate the development of the Building Circularity Evaluation Framework (BCEF).

2.1. Typology of circularity frameworks

Existing building circularity frameworks can be grouped into five broad methodological clusters: policy-aligned, design-centric, registry-based, certification-based, and integrated evaluation frameworks [33,34]. These categories reflect differences in assessment purpose, indicator structure, and operational depth rather than differences in ambition or relevance.

Policy-aligned frameworks, such as Level(s) [24] and CESBA [28], are primarily designed to support alignment with European sustainability policies and reporting requirements. They embed circularity within broader environmental performance assessment, often through life-cycle assessment (LCA) indicators such as Global Warming Potential (GWP). However, circularity is addressed indirectly and selectively, with limited operationalization of design strategies such as disassembly, adaptability, or service-based procurement. As a result, these frameworks provide policy consistency but limited design-stage guidance.

Design-centric frameworks, including BAMB [29], the Whole Building Circularity Indicator (WBCI) [30], and the Building Circularity Indicator (BCI) [31], place stronger emphasis on architectural and construction-related strategies such as modularity, reversibility, and reuse potential. These approaches are better aligned with early design decision-making but typically rely on qualitative or semi-quantitative scoring methods and partial life-cycle coverage. In many cases, normalization and aggregation procedures are implicit or case-specific, constraining transparency and cross-project comparability.

Registry-based systems, exemplified by Madaster [32], focus on material documentation and traceability through digital building passports. While these tools significantly improve material transparency and reuse potential, they are not performance evaluation frameworks and do not assess environmental impacts, adaptability, or service-life strategies.

Certification-based schemes, such as BREEAM [33], DGBC [34], and DGNB [35], incorporate circularity-related credits within broader sustainability assessment structures. However, circularity criteria are typically dispersed across categories and treated as optional add-ons rather than as a coherent evaluation logic. As a result, circularity performance is difficult to interpret holistically or compare across projects.

Finally, integrated evaluation frameworks aim to combine circularity-related indicators with life-cycle compatibility and early-stage applicability. BCEF is positioned within this emerging category. Its contribution is not the introduction of new indicators, but the explicit structuring, normalization, and aggregation of selected circularity-related and LCIA-based metrics into a transparent evaluation logic suitable for early design comparison. Table 1 summarizes this typology and the main limitations associated with each cluster.

2.2. Comparison of existing frameworks

Several frameworks have attempted to operationalize building circularity in a more quantitative or design-relevant manner [17,36]. Among these, BCI [28] and WBCI [27–48] are frequently cited as early-stage assessment tools. BCI emphasizes material recoverability

Table 1
Typology of building circularity frameworks.

Cluster Type	Defining Characteristics	Example Frameworks	Main Limitations
Policy-Aligned	Broad sustainability goals, use of LCIA, and limited specificity to circularity	LEVEL(s) [24], CESBA [28]	Weak in disassembly (DfD), product-service systems (PSS); not optimized for early design stages
Design-Centric	Conceptual frameworks for architects include some DfD, adaptability, and material recovery.	BAMB [29], WBCI [30], BCI [31]	Often qualitative, limited life cycle (Module D) coverage; lacks standardized KPIs
Registry-Based	Focus on material tracking and digital building passports	Madaster [32]	No performance metrics; limited adaptability and service model integration
Certification-Based	Point-based schemes for compliance; partial inclusion of circularity components	BREEAM [33], DGBC [34], DGNB [35]	Fragmented circularity aspects; lacks integrated, life cycle-based KPIs
Next-Generation Integrated	Normalized KPIs; includes DfD, PSS, and FA; life cycle compatible, digitally operable; first to combine quantitative circularity, modularity, and early-stage decision support	**BCEF** (this article)	Still in early validation phase; limited application across diverse building typologies

and reuse potential, primarily within Dutch policy and planning contexts, while WBCI proposes a building-level score based on modularity, flexibility, and demountability.

Despite their practical relevance, these frameworks exhibit recurring methodological limitations. Life-cycle coverage is often incomplete, with limited treatment of use-phase dynamics (Module B) and benefits beyond the system boundary (Module D). Moreover, indicator normalization, weighting, and aggregation are rarely formalized, which constrains analytical transparency and limits reproducibility. Similar constraints apply to design-oriented frameworks such as BAMB [25–49], which provide valuable conceptual guidance but remain difficult to apply quantitatively during early design stages.

Policy-oriented and certification-based frameworks, including Level(s) [23], CESBA [24], DGNB [31], and BREEAM [30], integrate circularity-related elements within broader sustainability assessment schemes. However, circularity indicators are typically dispersed across categories and not systematically linked to life-cycle stages or design decision workflows. Registry-based systems such as Madaster [29] offer detailed material inventories but do not address performance trade-offs between circular strategies and environmental impacts.

Table 2 provides a comparative overview of selected frameworks, highlighting differences in indicator scope, quantitative rigor, life-cycle coverage, and key limitations. Across these approaches, three persistent gaps emerge. First, early-stage applicability remains limited, despite the fact that critical circularity-related decisions are made during conceptual design [38–40]. Second, qualitative but essential aspects of circularity, such as functional adaptability and product–service systems (PSS), are rarely integrated into quantitative assessment structures. Third, inconsistencies in normalization, weighting, and aggregation reduce transparency and hinder meaningful comparison across projects [37].

2.3. Building circularity evaluation evolution frameworks

To situate the proposed framework within the broader development of circularity assessment in the built environment, Fig. 1 presents a timeline illustrating the evolution of key concepts, standards, and evaluation systems between 2000 and 2025. This evolution can be interpreted through four successive stages of increasing methodological maturity, reflecting shifts from conceptual awareness toward structured and partially standardized evaluation practices.

Stage 1: Conceptual Foundations (2000–2014).

Stage 2: Early Evaluation and Compliance-Oriented Systems (2015–2017).

Stage 3: Design-Oriented and Transitional Frameworks (2018–2020).

This phase introduced more design-oriented and digitally supported approaches. Initiatives such as BAMB (Buildings as Material Banks) [25–49] and the Whole Building Circularity Index (WBCI) [27] advanced circular design thinking by integrating concepts of reversibility, adaptability, and material passports into early-stage planning. The publication of ISO 20887:2020 [32] provided standardized guidance on design for disassembly and adaptability. Concurrent updates to EN 15804 [20] and EN 15978 [21] established a clearer foundation for life-cycle-based assessment of construction products and buildings. Despite these advances, implementation across tools and projects remained fragmented, particularly with respect to life-cycle integration and quantitative comparability.

Stage 4: Integrated and Standardization-Oriented Approaches (2021–2025).

Recent developments reflect a growing convergence between circularity assessment, digitalization, and life-cycle methodologies. Platforms such as Madaster, GRO, and certification schemes incorporating dedicated circularity credits (e.g., DGNB) enable more systematic quantification and documentation of circular strategies. Parallel standardization efforts within CEN/TC 350/SC 1, including prEN 18177 (framework and definitions) and prEN 17998 (design for circularity), indicate movement toward harmonized European approaches [52,53]. Although some draft

Table 2
Comparison of selected circularity assessment frameworks.

Framework	Category	Indicators Used	Quant/Qual	Life Cycle Stages	Key Limitation
LEVEL(s) [23]	Policy-aligned	GWP, material use, LCA	Mixed	A–C	Weak in modularity & DfD
CESBA [24]	Policy-aligned	Environmental & social KPIs	Mixed	A–C	Generic, lacks CE specificity
WBCI [27,48]	Design-phase planning	Whole-building LCA metrics	Quantitative	A–C	Lacks design flexibility and PSS
BCI [28]	Design-phase planning	Reuse potential, modularity, circular score	Mixed	C–D	Lacks normalization and early-stage integration
BAMB [25,49]	Design-phase planning	Material reuse, reversibility	Qualitative	Mostly C–D	Hard to apply at the design stage
Madaster [29]	Registry system	Circularity % by material	Quantitative	A–D	Limited to the material registry; lacks performance indicators
DGNB [31]	Certification	DfD, LCA, resource use	Mixed	A–C	PSS not included
BREEAM [30]	Certification	Material reuse, DfD, LCA	Mixed	A–C	Circularity credits vary in scope

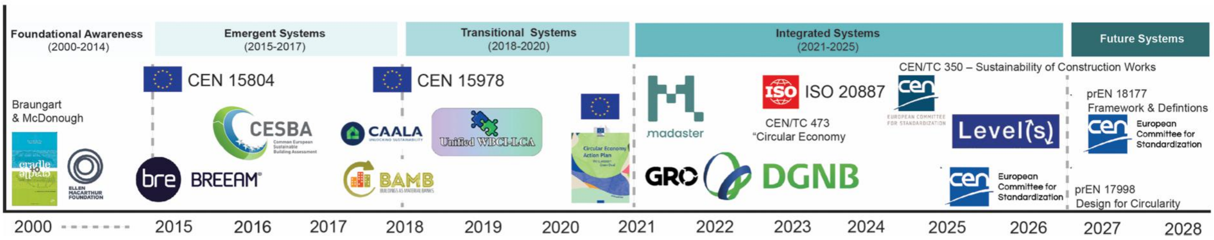


Fig. 1. illustrates the evolution of building circularity evaluation systems from 2000 to 2025 in a timeline.

standards have not yet been formally adopted, they reflect an increasing institutional effort to align circularity assessment with regulatory and life-cycle reporting requirements.

Within this context, the Building Circularity Evaluation Framework (BCEF) is positioned as a design-stage evaluation structure that builds upon, rather than replaces, existing approaches. Its contribution lies in organizing selected circularity-related and life-cycle-based indicators into a transparent, normalized framework intended for early-stage comparison, rather than in establishing a new standard or predictive model.

2.4. Review of circularity indicator development

Across the reviewed frameworks, a recurring set of indicators can be identified, addressing environmental impacts (e.g., GWP, land use), material loops (e.g., reused or recycled content), and design strategies (e.g., disassembly, adaptability). BCEF builds on this established indicator landscape rather than expanding it. Its six indicators; GWP, Land-Use Footprint (LU), Reused Content (RC), Disassembly Potential (DP), Functional Adaptation (FA), and Product–Service Systems (PSS); were selected based on their prevalence in the literature, alignment with European and international standards (EN 15804+A2 [24], EN 15978 [25], ISO 20887 [42]), and feasibility of application during early design stages [41–45].

The distinguishing feature of BCEF lies in how these indicators are structured and combined. Rather than treating circularity and environmental performance as parallel or loosely connected dimensions, BCEF explicitly maps circular design strategies to life-cycle stages and integrates selected LCIA indicators to support joint interpretation. This approach reflects emerging trends in frameworks such as Level(s) [22], DGNB [40], and BREEAM [38], while making underlying assumptions explicit and transparent.

2.4. Rationale for the BCEF framework

The literature review demonstrates that existing frameworks provide valuable but partial perspectives on building circularity. Most either prioritize policy alignment, conceptual design guidance, or material documentation, but lack a transparent evaluation structure that connects circular strategies with life-cycle impacts at the whole-building level during early design.

BCEF responds to this gap by offering a structured evaluation framework that formalizes indicator selection, life-cycle mapping, normalization, and aggregation to support quantitative comparison of design alternatives at the whole-building level. By integrating existing indicators within a coherent, standards-aligned structure, BCEF aims to support informed comparison of design alternatives and to complement, rather than replace, existing frameworks and guidelines [55–57].

The following section details the methodological development of BCEF, grounded in the critical insights derived from this review.

4. Methodology

BCEF is conceived as a structured evaluative framework for organizing, comparing, and interpreting circularity-related indicators during early design stages, when information is incomplete, and design flexibility is still high. The framework formalizes how indicators are selected, mapped to life-cycle stages, normalized, and aggregated, while explicitly acknowledging the role of expert judgment and data constraints.

3.1. Analytical approach

The development of the Building Circularity Evaluation Framework (BCEF) followed a multi-phase analytical approach grounded in literature review, regulatory alignment, and expert consultation.

In the first phase, a descriptive and comparative analysis was conducted of existing circularity frameworks and indicators. This involved extracting data from published reports, peer-reviewed case studies, and technical documents to identify key characteristics of building circularity indicators (BCIs). Each framework was examined with respect to its:

(a) underlying assumptions and limitations,
(b) theoretical foundations (e.g., circular economy definitions, scope, KPIs, and R-strategies),
(c) maturity level (emerging, in development, or fully implemented), and
(d) calculation approach (qualitative or quantitative).

To complement this analysis, a structured literature review was performed. The literature review was conducted using Scopus (for peer-reviewed journal and conference publications) and Google Scholar (to capture grey literature and emerging sources). Web of Science was not included, as preliminary testing revealed high overlap with Scopus but lower coverage of technical reports and EU project deliverables relevant to circularity in the built environment.

More than 200 peer-reviewed publications from 2010 to 2023 in English, Dutch, Danish, and German were screened using keywords such as "circularity indicators," "disassembly criteria," and "barriers to circular construction", in a previous research by the authors of this paper [16]. The timeframe 2010–2023 was selected because circular economy concepts began to be systematically applied to the building sector after 2010, following the establishment of the Ellen MacArthur Foundation and subsequent EU policy initiatives (see Fig. 1). Earlier publications (pre-2010) were primarily focused on waste minimization and recycling, without addressing building-level circularity frameworks. After title and abstract screening, 87 articles were selected for full-text analysis based on methodological relevance and contribution to indicator development. Special attention was given to disassembly-related criteria and implementation barriers, which informed both the selection and operationalization of indicators within BCEF. These barriers align with findings from international expert surveys, which highlight institutional, financial, and technical challenges to adopting the circular economy within the construction industry [13].

The final indicator set was refined through expert consultations organized within two European initiatives: the FCRBE project (2019–2023) and COST Action CA21103 (2022–2025). In total, 15 professionals from Belgium, the Netherlands, France, and Germany participated, representing academia, architectural practice, engineering, and policymaking. These consultations were conducted as structured focus group workshops intended to assess practical relevance, clarity, and early-design applicability rather than to perform formal indicator validation. The process followed four steps: (1) presentation of candidate indicators identified from the literature, (2) moderated discussion on measurability and policy alignment, (3) qualitative scoring against predefined criteria, and (4) iterative discussion leading to consensus. This process does not constitute a Delphi study or a statistical validation exercise; instead, it serves to ensure that the indicator set reflects practitioner-informed operational relevance. Summaries of these consultations are provided in Appendix 1.

The selection of six KPIs, Global Warming Potential (GWP), Reused Content (RC), Land-Use Footprint (LU), Disassembly Potential (DP), Functional Adaptability (FA), and Product-Service Systems (PSS), was based on a triangulated method combining (i) frequency in academic literature, (ii) alignment with European regulatory frameworks

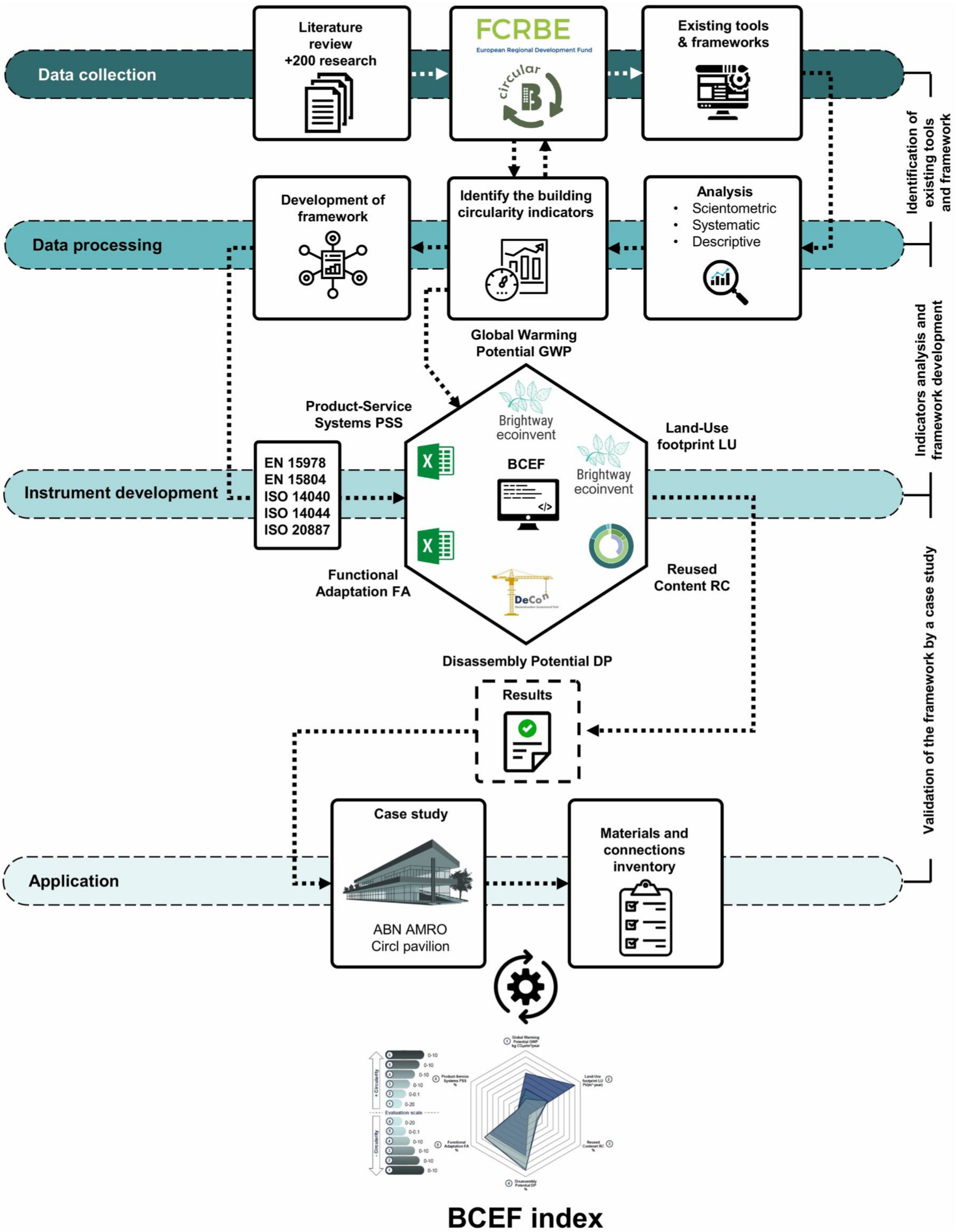


Fig. 2. Methodology framework of the research.

including LEVEL(s), ISO 20887, EN 15978, and the EU Circular Economy Action Plan [46–74], and (iii) expert consensus building through the initiatives above. These sessions enabled the refinement, ranking, and validation of candidate indicators based on their clarity, feasibility, transferability, and utility for decision-making. The inclusion of GWP and LU, while not direct measures of circularity, was justified to capture the environmental consequences of circular strategies and avoid burden shifting. The final indicator set represents a consensus-based operationalization informed by stakeholder input and builds on the authors' prior work in the field [16,59]. The resulting KPI set should therefore be interpreted as a consensus-based operational selection, not as an exhaustive or statistically optimized representation of building circularity.

Each indicator was critically assessed to determine appropriate data sources, calculation techniques, and integration within the life-cycle-based framework. Indicator weights were derived through structured expert elicitation involving six experts from academia and industry, including representatives from Colruyt Group. The process consisted of two focus group rounds aimed at achieving convergence rather than statistical consistency. Experts discussed indicator relevance based on measurability, regulatory alignment, and design-stage usefulness. No formal analytic hierarchy process (AHP), best–worst method (BWM), or consistency testing was applied. Weighting outcomes should therefore be interpreted as context-sensitive prioritizations reflecting current European circular building practice, rather than as universally optimal values.

To validate the framework, the ABN AMRO Circl Pavilion in Amsterdam was selected as a case study. The building exemplifies circular economy principles through its design for disassembly (DfD), use of reused materials, and service-based product models. The application of BCEF to this real-world case demonstrated the framework's feasibility and relevance. In addition, preliminary usability testing with professionals helped inform the framework's presentation and functionality, though no formal user experience study was conducted [75]. Finally, the indicator results were synthesized into a visual radar chart (Fig. 2), providing a holistic view of the building's circularity performance. This graphical representation supports early-stage design decision-making by clearly illustrating strengths and trade-offs across the six KPIs.

3.2. Development of the framework

Building on the analytical approach and indicator definitions established in Sections 3.1 and 3.2, this section outlines how the Building Circularity Evaluation Framework (BCEF) synthesizes diverse circularity metrics into a structured and actionable assessment framework. The framework was created with the explicit goal of supporting early design decision-making in circular building projects. This structured scoring approach was subsequently applied to a real-world case study to validate the framework's performance.

The six indicators, Global Warming Potential (GWP), Land-Use Footprint (LU), Reused Content (RC), Disassembly Potential (DP), Functional Adaptation (FA), and Product-Service Systems (PSS), were operationalized based on international standards (e.g., EN 15804+A2, EN 15978, ISO 20887), validated with experts, and tested on a real-world office building case. Each indicator captures a distinct dimension of building circularity across the full life cycle and is linked to specific life cycle stages as defined by EN 15804+A2:

- GWP and LU: assess Modules A, B, and C (product, use, and end-of-life stages [76])
- DP: focuses on Module C (deconstruction and waste processing)
- RC, FA, and PSS: emphasize Module D (potential benefits and reuse)

Each indicator is normalized to a 0–1 scale using min-max normalization, ensuring comparability across different units and value ranges. The direction of normalization depends on whether a higher raw value corresponds to better or worse circular performance. Min–max normalization was selected due to its transparency, low data requirements, and compatibility with early-stage design information, rather than to imply statistical optimality or uncertainty minimization.

3.2.1. Indicator normalization formulas

Negative Indicators (e.g., GWP, LU):

$$S_i = 1 - \frac{X_i - X_{min}}{X_{max} - X_{min}} \quad (1)$$

Positive Indicators (e.g., RC, DP, FA, PSS):

$$S_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \quad (2)$$

where:

X_i = actual value of the indicator.

X_{min} and X_{max} = empirical bounds for normalization.

3.2.2. Composite circularity index

To produce a single composite score for circularity, a weighted sum of the normalized indicator scores is computed. The composite BCEF index is intended as an interpretive aggregation to support comparison between design options, not as a predictive or decision-optimizing metric:

$$BCEF_{index} = \left(\sum_{i=1}^{n} W_i \, . \, S_i \right) X\ 100 \quad (3)$$

W_i = weight of the i indicator.

S_i = Normalized score of the i indicator.

n = Total number of indicators.

The weights used in this article were determined through a combination of expert consultation and literature review:

- GWP = 0.25
- LU = 0.15
- RC = 0.20
- DP = 0.15
- FA = 0.15
- PSS = 0.10

These weights ensure that the relative contribution of each indicator to the final score reflects its practical and environmental importance. The final weights reflect the consensus outcomes of this expert-based consensus building, with sustainability experts from academia and industry aligning with circularity priorities defined in European building sustainability research. Indicator weights were assigned through a two-step process. First, a literature review was conducted to identify weighting approaches in existing frameworks, including BCI [Kibert, 2016], WBCI [Khadim et al., 2023], DGNB Circularity Indicators (2021), and CE-LCA [17]. Second, expert workshops were held with 15 participants from academia, practice, and policymaking. Experts scored each candidate indicator against three predefined criteria: measurability, policy relevance, and design applicability. Scores (1–5) were aggregated, and results were refined through iterative group discussion and consensus voting. This ensured that final weights reflected both scientific grounding and practical utility.

To test the robustness of the Building Circularity Evaluation Framework (BCEF) and explore the influence of design scope on circularity outcomes, three distinct calculation options were defined for the case study [77]. These options represent different levels of circular integration and disassembly potential, based on the components included in the assessment:

- **Calculation Option 1**: Full-building baseline scenario. This option includes all building elements, including the basement and foundation components. It represents the actual constructed state of the building and serves as the baseline for comparison.
- **Calculation Option 2**: Above-ground scenario. This option excludes the basement and focuses only on components that are more readily recoverable or dismantlable, such as the timber superstructure and enveloping systems.
- **Calculation Option 3**: Optimized circularity scenario. This option includes only those elements that were explicitly designed for disassembly, reuse, or integration through product-service systems. It reflects a best-practice approach based on intentional circular design choices.

These scenarios facilitate a comparative evaluation of circularity indicators under varying design and construction assumptions, offering insights into how design intent and scope impact overall circularity performance.

3.3. Visual representation and application

The results are synthesized using a radar chart, offering a clear graphical summary of the building's performance across all six indicators. This visual format aids communication with design teams, clients, and policymakers by highlighting strengths and areas for improvement. Finally, the framework's flexibility and transparency allow for future adaptation. Additional indicators can be integrated, and weighting schemes can be modified to fit different project contexts or stakeholder priorities. A sensitivity analysis was conducted to assess the robustness of the BCEF Index under various assumptions.

3.4. Sensitivity analysis

A sensitivity analysis was conducted to test the robustness of the BCEF results against parameter variation. We applied a one-at-a-time (OAT) approach, varying indicator weights by ± 20 % and normalization bounds (Xmax, Xmin) by ± 10 %. The BCEF scores were recalculated under these variations. Results indicated that while absolute scores shifted, the relative ranking of design scenarios was unaffected, confirming the stability of the framework.

4. Validation

4.1. Case research

The ABN AMRO Circle Pavilion [78] is a 3350 m^2 project developed by the investment bank ABN AMRO [79] adjacent to its headquarters in Amsterdam. It is one of the earliest examples of buildings designed in accordance with circular economy principles. The pavilion is located at Gustav Mahlerplein in Zuidas, near Zuid station, and in front of the main building of ABN AMRO. The building was designed by de Architekten Cie [80] and constructed by the Royal BAM Group [81], with completion scheduled for 2017. The project prioritized the use of recycled materials and significantly reduced the embodied carbon (GHG emissions) of its construction. Notably, Circl deviated from traditional bank architecture by omitting materials commonly found in similar buildings, such as marble floors and elaborate glass and steel components. This approach resulted in a reduction in material use by approximately one-third, or 2425 tons, compared to the original plans.

All materials, components, and parts that make up the building have been recorded in a 'digital twin'; the building passport is named LLMNT. Moreover, renewable energy comes from solar panels on the building's roof to reduce GHG emissions during the use stage (Module B6). However, the emphasis on recycled materials posed a unique challenge. Obtaining a building permit was delayed because the project relied on the availability of materials, which influenced the final design. This approach, in which materials dictate design rather than conform to a predetermined architectural plan, is uncommon in contemporary commercial real estate but reflects traditional building practices seen in historical structures (see Fig. 3).

4.2. Inventory and inspection campaign

4.2.1. Building materials

To quantify the building materials, a hybrid approach was employed. Primary data were derived from the architectural plans, technical documentation, and detailed material specifications provided by the design team (de Architekten Cie) [80]. Where complete quantity data were unavailable, additional estimates were generated using reliable open-source databases and platforms, including the de Architekten Cie project repository, Bouwkosten.nl, NIBE Milieu Classificaties, and manufacturer product datasheets. Quantities were calculated through scaled take-offs from architectural drawings and cross-checked using material density benchmarks to enhance accuracy.

Additionally, the project utilized the LLMNT digital twin and material passport, which documents all components and materials present in the building. The LLMNT database was consulted to validate and supplement the inventory data, particularly in identifying reused, recycled, and service-based components. By combining drawing-based estimation with digital asset information, the final material inventory achieved both precision and transparency. This integrated methodology ensures a robust and reproducible foundation for subsequent circularity assessment.

Table 3 provides a breakdown of the primary material groups by weight. The structure used Dutch timber from DERIX [82] as a substitute for concrete, and incorporated locally sourced materials. Approximately 850 m^3 of pine CLT was used for the building structure. Simultaneously, some partition walls were repurposed from the façade of a previous building. The hardwood flooring on the ground floor was salvaged from a former monastery and a Dutch football club, and the insulation was created by recycling 16,000 pairs of jeans. Fig. 4 illustrates the weight share of each material in the building.

PV panels were excluded from the circularity index calculation due to their negligible disassembly potential and the reuse of content in the current design. They remain accounted for in environmental modeling (GWP) but were removed from material-mass-based circularity indicators to avoid inflating the index with functionally irrelevant mass. Their inclusion allows for the evaluation of embodied carbon and potential reuse. Furthermore, PV panels can be subject to product-service system contracts, in which ownership and responsibility remain with the manufacturer. Although they do not significantly contribute to the reuse of content or disassembly potential indicators unless specifically reused or leased, their relevance lies in their potential to reduce operational emissions and support long-term circular strategies, especially in the context of modular renewable energy systems.

As shown in Fig. 5, other circular inputs [83] were observed during the inventory and inspection process in this project: the plastered walls and felt on the stands contained old work clothing, second-hand fire hose reel cabinets were used, and the wall finishing was made of residual wood. The ventilation ducts are constructed using sustainable textiles. Interior and exterior claddings heavily utilize FSC-certified wood and reused wood from other construction sites. More than 2500 kg of old ABN AMRO corporate clothing was recycled to create acoustic walls. The lifts in Circl have not been purchased but have been leased and will return to the manufacturer after 10 years. Moreover, renewable energy can be generated from solar panels on the roofs of buildings, thereby reducing GHG emissions during use.

4.2.2. DfD and building connections

The building is designed for disassembly and reuse [79]. Building design facilitates future reuse and recycling, ensuring that many of these components can be repurposed at the end of a building's lifespan. This

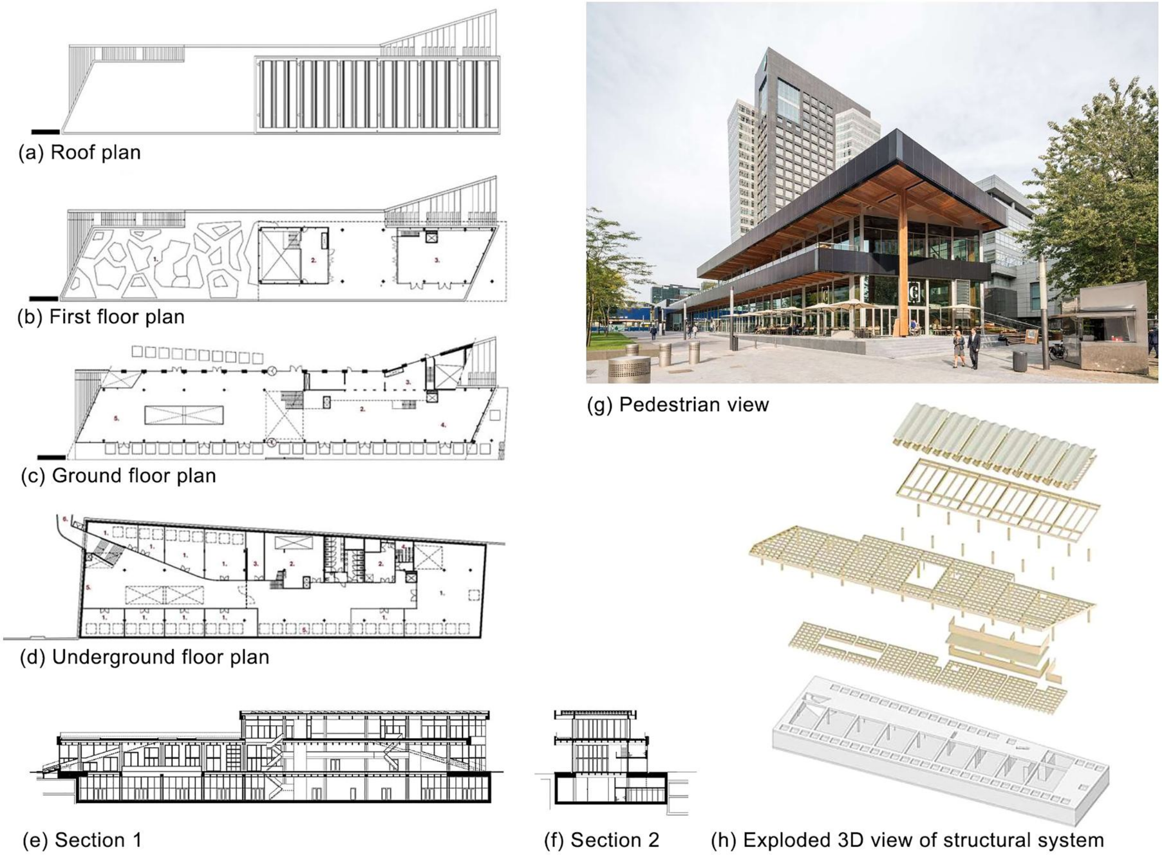


Fig. 3. Case study building visualizations. (a) Roof plan; (b) First floor plan; (c) Ground floor plan; (d) Underground floor plan; (e) Section 1; (f) Section 2; (g) Pedestrian view; (h) Exploded 3D view of structural system [80].

Table 3
Breakdown of primary material groups based on their weight.

Building material groups	ABN AMRO Circl pavilion	
	Amount [kg]	Share [%]
Concrete	5245,440	81.41
Timber	912,458	14.16
Steel	173,741	2.70
Glass (windows & doors)	72,000	1.12
Galvanized steel	7679	0.12
Solar panels	7540	0.12
Roof insulation	7400	0.11
Glass (partitions)	5500	0.09
Aluminum	3900	0.06
Air handling unit	3900	0.06
Services and cables (copper, plastic, etc.)	3800	0.06

was achieved through the use of modular construction techniques. Bolted rather than welded connections were used to facilitate disassembly. The wooden structure is detailed in such a way that hardly any holes need to be drilled, which means that the beams will be easy to reuse should the construction need to be disassembled. The façade consists of demountable glass panels that can be separated and reused. The floors are composed of modular raised units that can be easily removed and repurposed.

To evaluate the disassembly potential of a building, it is essential to inventory its products, components, and connection types, as well as any disassembly barriers that may be present. This article categorizes the building elements into seven primary groups: structure, foundation and basement, envelope, roof, interior, finishing, and technical systems. In the Circl case study, a detailed analysis was conducted to identify the key products, component assemblies, and connection methods used within each category. The structural components include columns, beams, joists, and slabs. Two components were identified for the foundations: concrete rafts and concrete walls. The following components were considered for the roof: beams, insulation, wood-fiber panels, and solar panels. Roof gravel was excluded from this research. Furthermore, four main types of façades were identified: glazed sections, recycled aluminum curtain wall frames, green walls, and photovoltaic panel cladding. All the interior and finishing components were also considered.

The connection types and their scores were considered, assuming that the same type of connection was used for each connection. Therefore, the result is the same using the expert system (DeCon tool) unless there are defects or barriers in specific connections, as observed in the foundation connections and some structural connections by the authors during the building dismantling process, as will be mentioned in the discussion section. The DP of the building, according to the second beta version of the expert system (DeCon tool) [2], is addressed in the Results section. Table 4 lists the main connection types in the building, along with their IDs, as classified in a previous article by the authors [2].

4.2.3. Product-service systems (PSS)

Circl, a notable example of sustainable architecture, incorporates innovative circular economy principles through collaboration with PSS companies [84,85]. This approach demonstrates the potential of service-based economic models for advancing circularity.

ABN AMRO Bank owns the *Circl* pavilion, but it does not own everything in the building. For example, Mitsubishi owns a lift. This implies that the lift supplier sells a service (vertical mobility) rather than a product. Mitsubishi provides the lift design and maintenance, and is paid for the proper operation of the lift based on a pay-per-use model. *Circl* receives a discount on annual costs if it uses less than what was

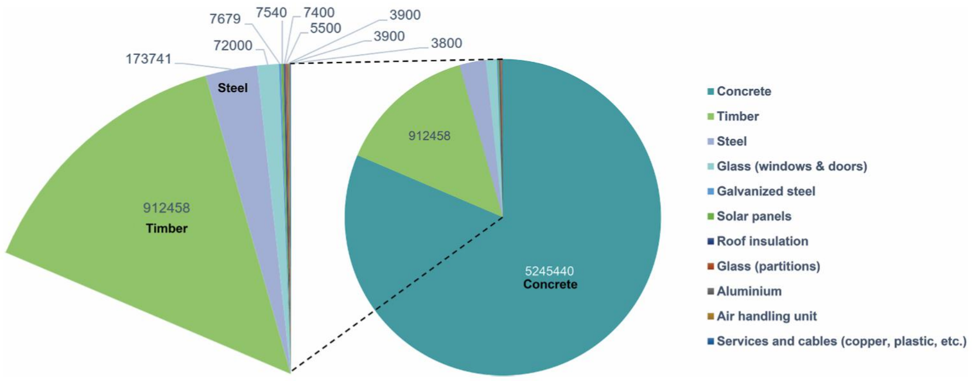


Fig. 4. Material composition of the Circular Pavilion expressed as the percentage share of each material category by total building mass (kg).

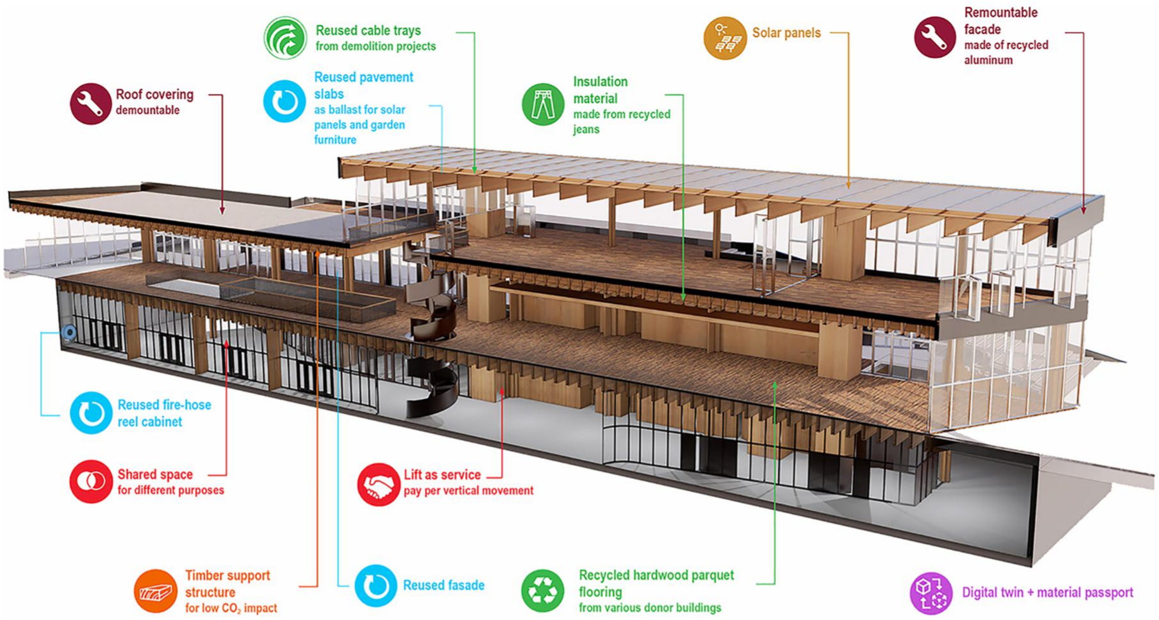


Fig. 5. The circular inputs in the building (*Architect: Hans Hammink, Pi de Bruijn, de Architekten Cie*) [80].

agreed upon in the contract. This model breaks the traditional vertical construction. While the traditional model focuses on short-term building costs, this model emphasizes long-term life cycle costs and value creation. While a long service life reduces the asset turnover ratio, this business model enables companies with high-quality products to compete with traditional, yet lower-quality, products that are cheaper. This is the essence of the change. In addition to the lift, *Circl* Pavilion buys services for audiovisual equipment. There are pay-per-use contracts for more services being tested. The Circl pavilion also has vintage furniture in the form of services. In return, the Circl pavilion serves as a storage area and showroom.

5. Results

To assess the implications of varying levels of circular integration, three calculation options were developed based on the existing Circl pavilion. Although Circl is a real and already constructed building, its disassembly and planned relocation created a unique opportunity to simulate different scenarios for material reuse and system integration. Calculation Option 1 achieved 53 %, reflecting limited disassembly and heavy material use in the basement. While this quantitative outcome is illustrative, the primary purpose of this comparison is to assess the consistency and realism of the BCEF framework's output in relation to the known ground-truth conditions observed during the building's actual deconstruction. This scenario represents the full baseline condition. Calculation Option 2 excludes the basement, focusing only on above-ground, easily recoverable components, thus simulating a realistic partial reuse scenario. Calculation Option 3 further narrows the scope to include only elements that were explicitly designed for disassembly, reuse, or integration through service-based procurement models. This last option represents an optimal case, aligned with best practices in circular construction. The three options allow for a comparative analysis of how circularity indicators respond to variations in building scope and design intent.

A comparative breakdown of the materials and components included in each calculation option is provided in Appendix 2. This additional documentation supports transparency and allows replication of the calculation logic applied in the BCEF framework.

5.1. Global warming potential (GWP)

Based on the life cycle impact assessment (LCIA) results for the Circl pavilion, as shown in Fig. 6, the global warming potential varied significantly for each calculation option. Calculation Option 1 produced a GWP of 12.84 kg CO_2e/m^2/year. In comparison, calculation Option 2 achieved a reduction of approximately 39.6 %, with a footprint of 7.75 kg CO_2e/m^2/year. Calculation Option 3 exhibited the lowest impact, achieving a 63.3 % reduction relative to Calculation Option 1, with a

Table 4
Main building connections, their IDs, and scores according to the expert system (DeCon tool) classification. Scores (0.0 g connections, their IDs, and scores according to the expert system (DeCon tool) classification *s*, as will be mentioned in the discussion section in *t material loss or damage* (e.g., dry or mechanical fixings such as insulation layers, bolted joints), score highest (1.0). Partially reversible connections, such as typical concrete structural joints (e.g., column–beam, slab–wall), receive intermediate scores (≈0.8). Fully cast-in-place or destructive connections (e.g., concrete raft–wall joints) are considered non-reversible and score lowest (0.1).

Category	Connection	Connection ID	Score
Structure	Column & beam	C.e1	0.8
	Column & slab	C.e1	0.8
	Column & bearing wall	C.e5	0.8
	Column & foundation	C.e5	0.8
	Beam & slab	C.e5	0.8
	Beam & conc. slab	C.e3	0.8
	Beam & secondary beams	C.e1	0.8
	Slab & bearing wall	C.e4	0.8
	Bearing wall components	C.e4	0.8
Foundation & Basement	Conc. raft & conc. wall	H.c6	0.1
	Conc. wall & conc. slab	H.c6	0.1
	Conc. column & conc. beam	C.e3	0.8
Envelope	Façade element. & column	C.e4	0.8
	Façade element. & beam	C.e4	0.8
	Façade element. & slab	C.e4	0.8
	Façade element. & floor	C.e4	0.8
Roof	Roof & column	C.e4	0.8
	Roof & beam	C.e4	0.8
	Roof & insulation	D.c1	1.0
Interior	Partition wall & slab	C.e4	0.8
	Partition wall & column	C.e4	0.8
	Glass wall & column	C.e4	0.8
	Glass wall & slab	C.e4	0.8
	Stair & slab	C.e1	0.8
	Railing & slab	C.e1	0.8
Finishing	Floor layers	D.c1	1.0
	Cladding	C.e4	0.8
Technical systems	PV system	C.e5	0.8
	Lighting system element.	C.e4	0.8
	Cables/cable trays	C.e4	0.8
	HVAC system element.	C.e5	0.8
	Firefighting system element.	C.e5	0.8

footprint of only 4.71 kg CO_2e/m^2/year. These different results were attributed to the different quantities of materials used in the three calculation options, which, in turn, affected the resulting GHG emissions.

Although operational energy use (Module B6) appears proportionally small in Fig. 6, this is due to the annualization of results over reference service life. When cumulative values are considered over a typical 50–60-year building lifespan, operational energy remains a dominant contributor to total GWP, often exceeding embodied impacts in most conventional buildings. The BCEF framework reports annualized values to enable comparability across design scenarios, while also acknowledging the long-term significance of operational energy. Future applications of BCEF could incorporate dynamic energy scenarios that account for grid decarbonization pathways and renewable integration, providing a more nuanced picture of B6 contributions over time.

5.2. Land-use footprint

For the land-use footprint, as illustrated in Fig. 7, calculation Option 1 generated a footprint of 0.09 Pt/(m^2·year). In comparison, calculation options 2 and 3 demonstrated a 55 % reduction, achieving a footprint of 0.04 Pt/(m^2·year). This analysis underscores the substantial differences among the calculation options, highlighting the progressive reduction in land-use impacts achieved by lowering material quantities.

5.3. Disassembly potential

Following a comprehensive audit of the building, an inventory detailing the number and types of connections was compiled using an audit sheet (see Appendix 3). These data were then processed using an expert system (DeCon), which the authors developed to evaluate a building's disassembly potential [2]. According to Fig. 8, Calculation Option 1 reveals an overall disassembly potential of 68 % for all connections. However, the disassembly potential in the foundation and basement areas showed a reduction of up to 10 % owing to the use of non-prefabricated underground concrete, which cannot be retrieved without demolition. Furthermore, an additional 10 % decrease was observed after factoring in the disassembly barriers. This highlights the limitations associated with this foundation type, which is a recognized design flaw when aiming for building disassembly. The disassembly assessment of each connection was based on the feasibility of detaching and isolating individual components from the surrounding structures.

Calculation Option 2 achieved an overall disassembly potential of 88 % when the basement was excluded, thus avoiding the related disassembly barriers. The calculations focused on assessing the connections between building products, components, technologies, electrical systems, and other components with high disassembly potential. Buildings must incorporate modular and replaceable components to achieve adaptability, futureproofing, and circularity. For instance, because building services typically have shorter lifespans than structural components, their design should facilitate straightforward disassembly and replacement. This approach can significantly extend the overall service life of buildings.

In contrast, Calculation Option 3 achieved the highest disassembly potential of 90 %, compared to Calculation Options 1 and 2. This calculation option concentrated exclusively on above-ground building products and components, which were specifically designed for disassembly. The disassembly potential reports are provided in Appendices 3, 4, and 5.

5.4. Reused content

As shown in Fig. 9, following a comprehensive inventory of the building materials, the results indicate that Calculation Option 1 had the lowest percentage of reused content at 5 %. This was primarily due to the significant quantities of concrete used in the basement, which significantly contributed to the share of virgin materials in the building. Although the building structure was constructed using sustainably sourced timber, which significantly enhanced the renewable materials indicator after accounting for the neutralization of the basement concrete, the primary construction components were emphasized to be recycled and reused materials. Under Calculation Option 2, the percentage of reused content reached 22 %, which is attributed to the high inclusion of reused components, such as flooring, insulation, and certain components of the HVAC systems. In addition, cables and cable trays from the RES contribute to this percentage. For calculation option 3, the reused content indicator was 20 %. This calculation exclusively considered construction components and materials that were either recycled or reused, including flooring, insulation, aluminum panels used in the façade, and some interior glass partitions.

5.5. Functional adaptation

Functional adaptation was evaluated in accordance with the principles and guidelines outlined in ISO 20887:2020 [86]. Although the building is generally designed with DfA principles, Calculation Option 1 exhibited a lower adaptability score than the other calculation options, reaching only 65 %, as shown in Fig. 10. This was attributed to the use of massive concrete structures during the construction of the basements. The absence of plans to dismantle internal concrete walls renders adaptation or modification neither technically feasible nor economically

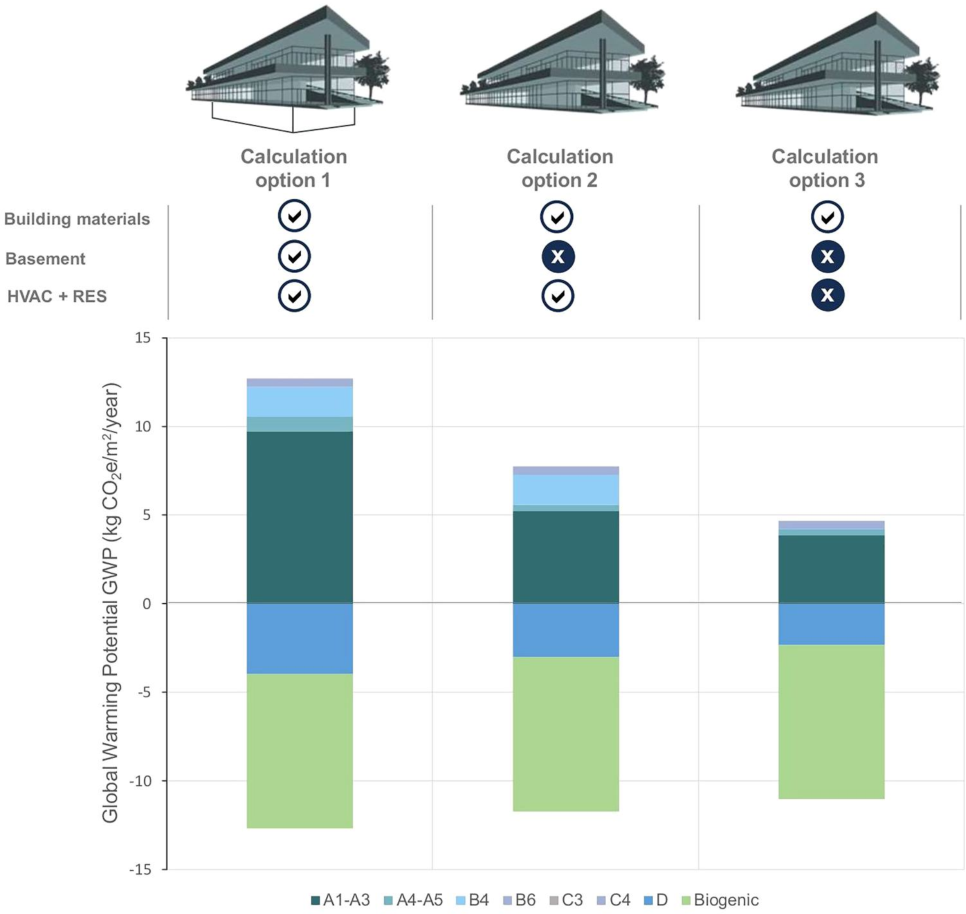


Fig. 6. Contribution of life cycle modules to building GWP (annualized values). Colors have been differentiated for clarity. Negative contributions correspond to Module D substitution credits and biogenic carbon storage, as defined in EN 15804+A2. While operational energy use (B6) appears proportionally small due to annualization, cumulative lifetime impacts remain significant and are discussed in Section 5.

viable. This section of the building serves as an example of a construction practice misaligned with the principles of a circular economy.

In contrast, Calculation Options 2 and 3 achieved identical overall adaptability scores of 75 %, which were higher than Calculation Option 1. This improvement is due to the dismantling nature of all products and components used, which enhances the building's functional adaptation and capacity for expansion. Calculation options 2 and 3 also recorded diversity and transformation scores of 80 % each, owing to the presence of open, flexible spaces that support functional adaptation.

Calculation Option 1 scored 60 % for these same indicators due to the presence of non-removable internal concrete walls at the basement level. Calculation Option 1 demonstrated a vertical expansion potential of 70 %, allowing for the addition of an extra floor or two without requiring substantial modifications to the building's foundation. Calculation Options 2 and 3 recorded the same results if the basement was dispensed. Adopting traditional foundations, such as concrete blocks and rafting, will help increase the possibility of vertical expansion owing to the lightweight nature of the building. Regarding horizontal expansion, none of the three calculation options achieved significant results. It was recorded as 0 %, owing to the absence of any additional areas that could be used or repurposed for future expansion. The building was constructed within the entire plot limit (see Appendix 6).

5.6. Product-service systems (PSS)

After inventorying the services implemented in the building as PSS and evaluating them against the optimal reference case, as detailed in Section 3.2.6, the variance was calculated as 7/50, as listed in Table 5. This placed the building at a score of 14 % on BCEF radar across all evaluated calculation options. This modest result reflects both the nascent state of the PSS metric and inherent challenges in assessing circularity within complex systems. It should be noted that the PSS indicator remains exploratory in nature: the current scoring logic (7/50 reference scale) was developed for this study and requires broader validation across diverse building typologies and procurement contexts before it can be considered a standardized metric. Future refinements may incorporate contractual value retention metrics–such as lease duration, residual value agreements, and manufacturer take-back obligations–to provide a more robust and reproducible basis for PSS assessment within building circularity frameworks.

5.7. Implementation of BCEF

The BCEF index scores from the three scenarios are normalized composite values across six weighted indicators. A score of 65 % or 68 % does not imply that the building is 65–68 % circular in absolute terms, but rather that, relative to the benchmarked best- and worst-case assumptions, the design achieves a moderately high level of circular integration. This includes high disassembly potential, reused content, and minimized environmental impact. These values are intended as comparative decision-support frameworks, not absolute metrics of circularity.

In this case, Calculation Option 1 achieved 57 %, reflecting limited disassembly and heavy material use in the basement. Options 2 and 3, with scores of 67 % and 69 % respectively, approach the threshold of high circularity, primarily due to reduced material intensity and better

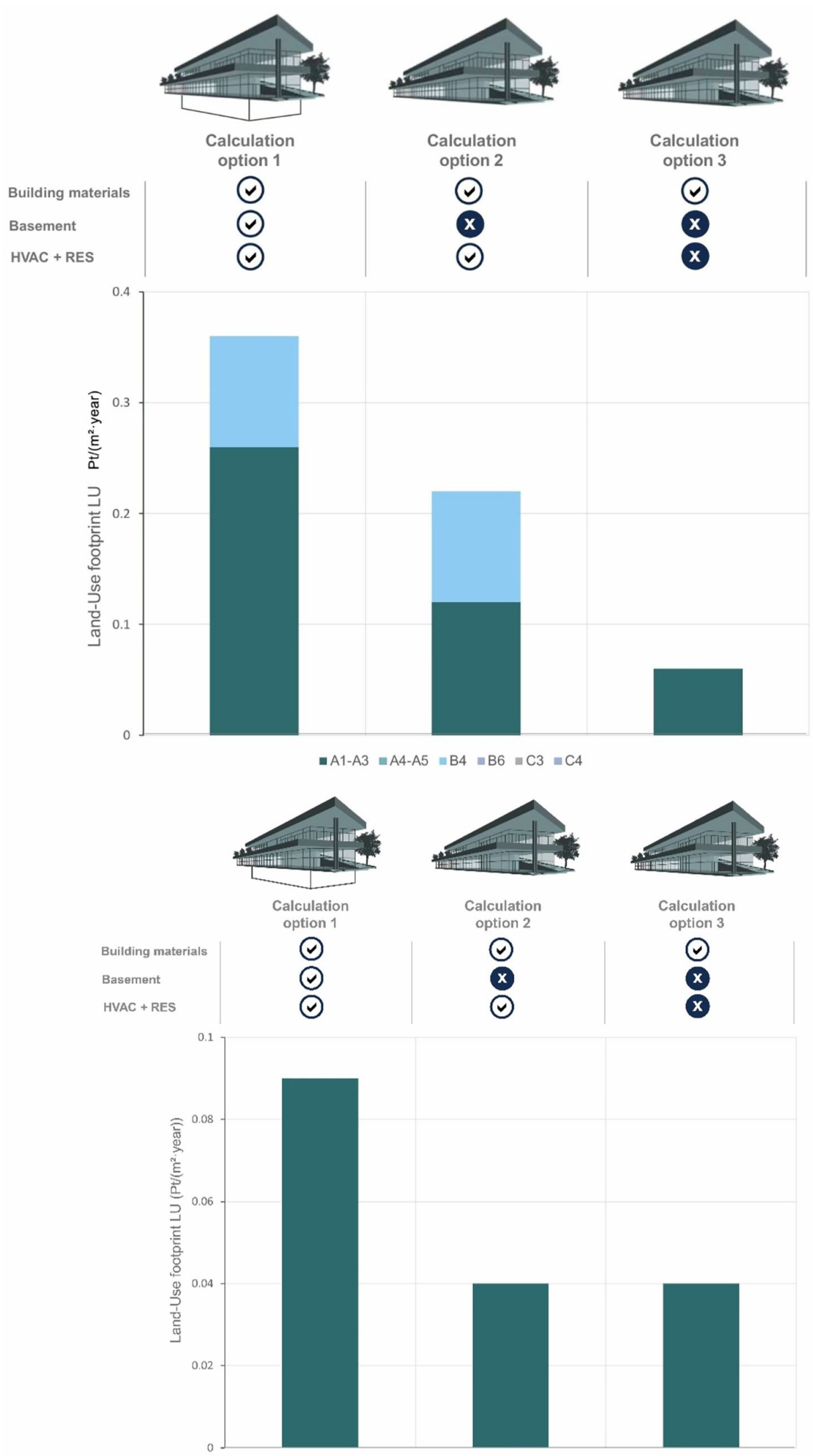


Fig. 7. Land-use (LU) footprint of the Circular Pavilion expressed in Pt/(m^2·year), calculated using the EF 3.1 (LANCA) Soil Quality Index for built-up land occupation in the Netherlands.

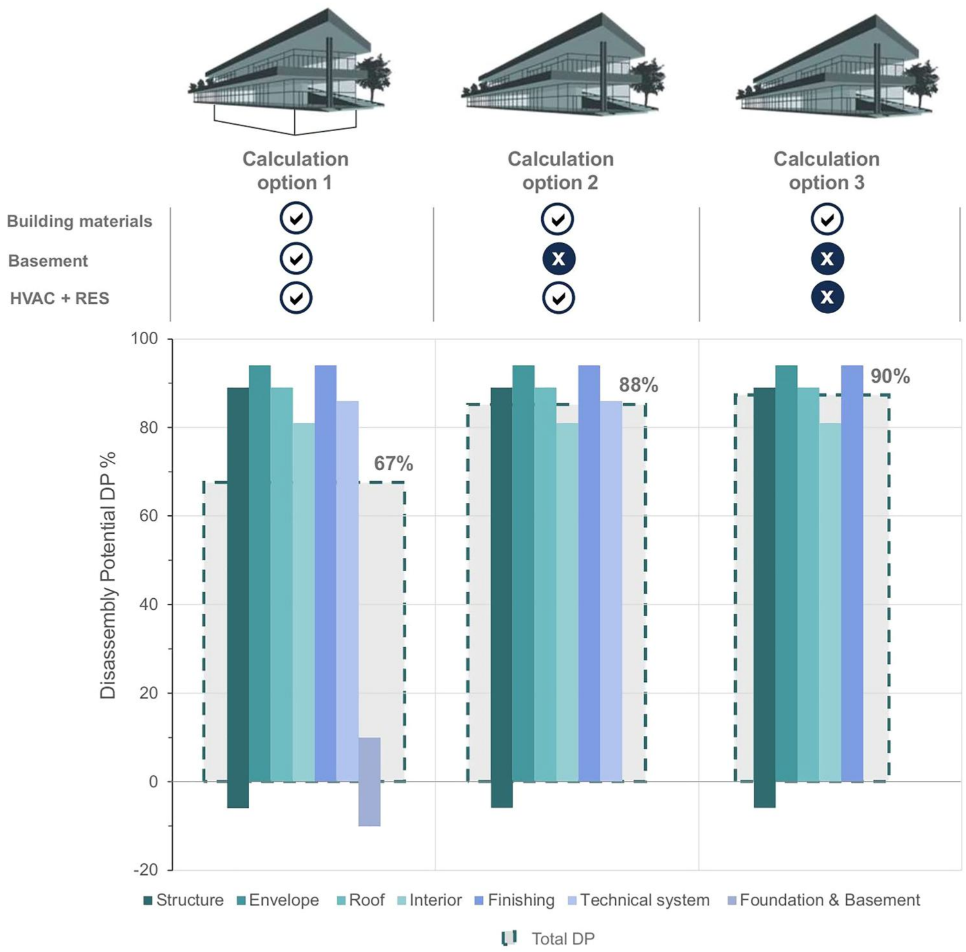


Fig. 8. Disassembly potential scores for case study components. Negative values result from the penalty system applied in the DeCon tool, indicating that irreversible or destructive connections (e.g., adhesives, cast-in-place joints) outweigh reversible connections. Values below zero should be interpreted as negligible disassembly potential.

integration of reused components.

Fig. 11 presents a visual representation of BCEF, illustrating a comprehensive comparison between the three calculation options in radar format based on the framework's KPIs. This radar chart summarizes the relative behavior of the six BCEF indicators across the three calculation options under the study's stated scope and normalization assumptions. The visualization is intended to support comparative interpretation between internally consistent design scopes rather than to claim an absolute "percent circularity." Higher DP, RC, FA, and PSS scores combined with lower GWP and LU values indicate stronger circular-design integration within BCEF's indicator set, but these patterns remain conditional on the selected system boundaries, the availability of project-specific data, and the chosen normalization bounds [16–22]. To improve interpretability, the radar is accompanied by an explicit reading scale that distinguishes between (i) quantitative LCIA-based indicators (GWP, LU), aligned with EN 15804+A2 and EN 15978 [20,21], and (ii) percentage-based circularity indicators (RC, DP, FA, PSS), informed by ISO 20887 and prior circularity frameworks [27–42]. The purpose of the figure is therefore to make trade-offs and hotspots visible at early design stage, not to establish a benchmark against "typical practice" or against other circularity tools in this single-case demonstration.

Based on the radar scores, Options 2 and 3 yield higher BCEF index values than Option 1 because they intentionally exclude or de-emphasize low-recoverability, high-mass elements (notably basement concrete) and focus on above-ground assemblies and components with clearer pathways for disassembly and reuse. Importantly, these results should be interpreted as a within-case scope comparison rather than a comparison against a "conventional office baseline," since no external counterfactual building was modeled in this study [16,30]. Option 1 therefore functions as the internal baseline (full-building scope) against which the two design scopes (above-ground and optimized circularity scope) are compared. In this case, the main driver of the difference is the basement and foundation system, which increases GWP and LU while reducing DP and FA due to the practical irreversibility of heavy concrete substructures, as also observed in circular deconstruction literature [25, 87]. The result demonstrates BCEF's sensitivity to design scope and recoverability assumptions, which is precisely the type of early-stage insight the framework is designed to surface [17].

5.8. Sensitivity analysis

A quantitative sensitivity analysis was conducted to evaluate the robustness of BCEF to weight perturbations under the current aggregation model (min–max normalization and weighted sum), consistent with practices reported in prior circularity assessment studies [16,37]. Each of the six KPI weights was perturbed by ±10 % while preserving a total sum of 1.0 via compensatory adjustments, and the recalculation was performed for all three options. This analysis tests parametric sensitivity of the composite score to weight choices, but it does not quantify (i) uncertainty in the underlying inventory data, (ii) uncertainty in normalization bounds, or (iii) structural uncertainty associated with

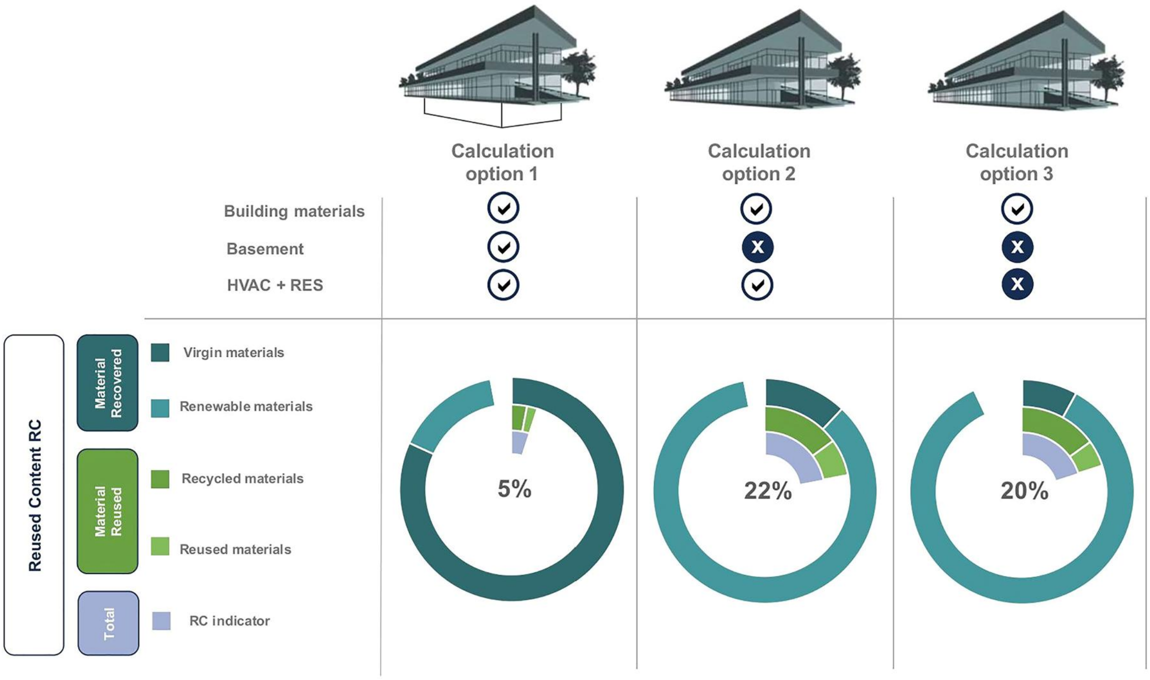


Fig. 9. Reused content results of the Circl pavilion.

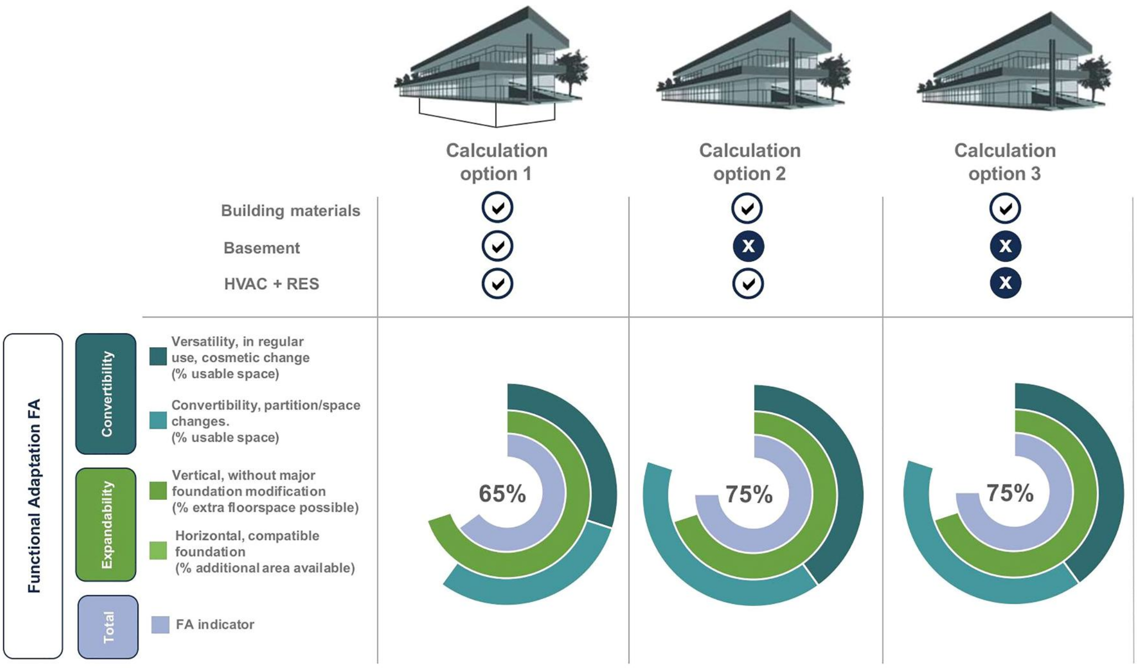


Fig. 10. Functional adaptation results of the Circl pavilion.

alternative aggregation models, as discussed in CE-LCA and multi-criteria assessment literature [17,22]. The resulting BCEF ranges, therefore, indicate how strongly the index depends on stakeholder preference encoded as weights, not the probabilistic uncertainty of the building's "true" circularity. The observed spreads across the three options confirm that results are weight-sensitive, especially where GWP is traded against RC and PSS, which supports the methodological recommendation that BCEF be used with transparent weight reporting and, where needed, scenario-specific or stakeholder-specific weight sets [37, 88].

The results, summarized in Appendix 7, indicate varying degrees of sensitivity across the three options. Calculation Option 1 (full-building baseline) exhibited BCEF values ranging from 45.35 % to 61.75 %, a spread of 16.4 percentage points. Option 2 (above-ground scenario) demonstrated greater fluctuation, with BCEF values spanning from 57.15 % to 72.75 % (a range of 15.6 points). Calculation Option 3 (optimized circularity scenario) demonstrated the highest sensitivity, with BCEF values ranging from 59.9 % to 76.1 %, representing a 16.2-point range.

The most impactful shifts occurred under the following

Table 5
PSS in the Circl pavilion compared with the optimal reference case.

Category	Weight	Product-Service Systems PSS					
		Optimal reference case			ABN AMRO Circl pavilion		
		Incl/ Discl	Number	Score	Incl/ Discl	Number	Score
Furniture	1	✓	2	2	✓	1	1
System	2	✓	5	10	✓	3	6
Partition & Finish	3	✓	1	3	×	0	0
Shell	4	✓	5	20	×	0	0
Core	5	✓	3	15	×	0	0
			Total score	**50**		**Total score**	**7**
				Overall total / 50			**7**
				Overall total %			**14**

perturbations:

- +10 % GWP, −10 % RC, and +10 % GWP, −10 % PSS led to the highest BCEF scores across all options, indicating GWP's strong positive influence on the composite score when prioritized.
- Conversely, +10 % RC, −10 % GWP, and +10 % PSS, −10 % GWP resulted in lower composite scores, suggesting a comparatively weaker influence of RC and PSS when increased at the expense of GWP.

These results reveal that Calculation Option 3 is the most responsive to changes in weight distribution, reflecting its reliance on design-optimized circular features that interact more directly with dynamic weighting. Option 2 shows similar sensitivity, while Option 1, representing a less optimized baseline, demonstrates comparatively reduced responsiveness, likely due to the dominant impact of its foundational mass.

Overall, the analysis confirms that BCEF is sensitive to weight assumptions, particularly for GWP, RC, and PSS. This highlights the need for transparent weighting protocols and potentially context-specific

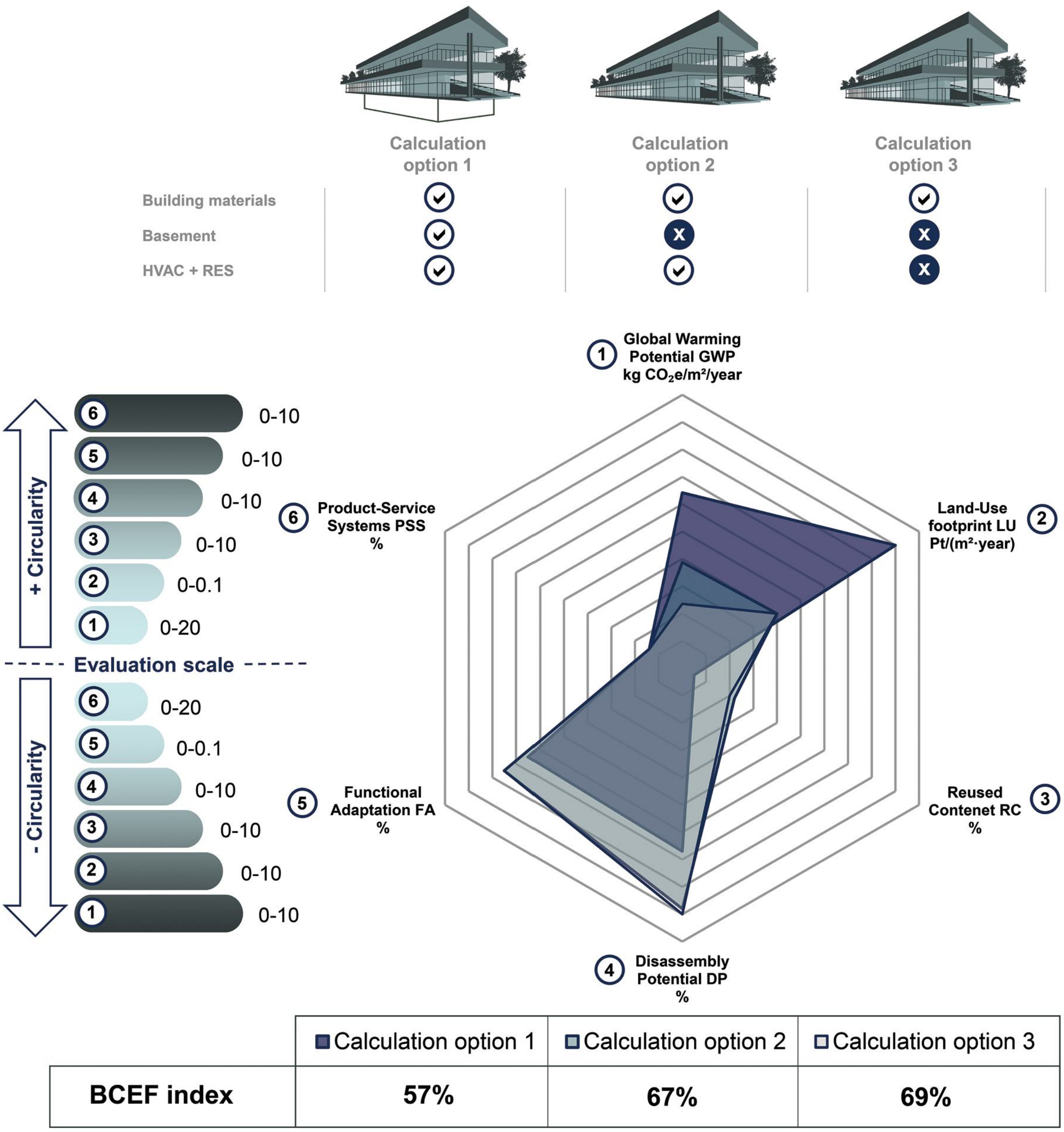


Fig. 11. Radar chart illustrating the Building Circularity Evaluation Framework (BCEF) results across six key performance indicators (KPIs) for the three calculation options of the Circular Pavilion.

adjustments depending on project goals or regulatory priorities. Future refinements could include stakeholder-based weight elicitation or probabilistic weighting schemes to further enhance framework reliability and applicability across diverse building typologies.

6. Discussion

6.1. Summary and main findings

The Circl Pavilion is an information-rich and deliberately circular showcase project, and its selection was intentional to test BCEF under conditions where disassembly and reuse strategies are explicit and documented [78,79]. This choice strengthens internal coherence testing (indicator behavior, module mapping, and scoring transparency), but it limits external validity: the resulting BCEF values should not be interpreted as representative of typical office buildings or general practice [16,30]. Accordingly, the contribution of this paper is methodological demonstration and internal stress-testing of BCEF, not statistical generalization. The three calculation options were defined to expose how scope decisions (full-building vs above-ground vs disassembly-optimized components) influence indicator outcomes and the composite score, thereby highlighting where circularity performance is most affected by design choices and recoverability assumptions, consistent with observations in whole-building circularity research [27,31].

Application of BCEF to the three options shows that the composite score is driven by a small number of dominant mechanisms: (i) mass-intensive, low-reversibility substructure elements that penalize GWP and LU and constrain DP and FA, and (ii) recoverable above-ground assemblies and reused components that raise DP and RC. This aligns with broader findings in whole-building circularity assessment, which emphasize the critical role of system boundaries and recoverability assumptions [16–87]. In contrast to circularity-only scoring approaches such as WBCI or BCI, BCEF intentionally couples circular design proxies (DP, RC, FA, PSS) with LCIA-based pressures (GWP, LU) in a single, transparent structure, enabling early-stage visualization of trade-offs rather than isolated optimization [17,22]. At the same time, the present study does not claim superiority over other frameworks through comparative experiments; instead, it demonstrates that BCEF can be executed with explicit module mapping, normalized indicator scoring, and clear scope options, producing interpretable differences that are actionable for early design discussion [30,37]. The early disassembly of the project after seven years further underscores the importance of evaluating adaptability, reversibility, and scope-dependent reuse potential rather than assuming planned service life translates into realized circular outcomes [79].

1. Difficulty in Removing Bolts from Structural Connections. The first issue arises from the difficulty in unscrewing the bolts used in the building's structural connections. In some cases, bolts and even portions of wooden connections had to be cut because of their resistance to disassembly.
2. Challenges with the Concrete Basement Structure. The second issue pertains to reinforced concrete basements. Before the deconstruction, a 3D scanning system was used to survey the entire basement. Subsequently, a specialized demolition company was hired to cut the reinforced concrete into specific dimensions because full dismantling was deemed unfeasible, as mentioned in Section 5.3.
3. Groundwater Pressure on the Basement. The third challenge involves groundwater pressure acting on the basement. As the aboveground components were dismantled, the load on the basement structure decreased, causing the buoyant force of the groundwater to lift the concrete basement upward. Many concrete blocks were placed to counteract buoyancy, allowing all above-ground components to be fully dismantled and mitigating this issue during the deconstruction process.

These challenges significantly delay the deconstruction process. Fig. 12 shows a part of the disassembly process during a site visit.

Regarding functional adaptation, the results were similar across all calculation options due to the use of open and adaptable spaces, except for certain internal concrete walls in the basement, which had a significant impact on the building's circularity indicator. The application of PSS in BCEF highlights the feasibility of service-oriented models, which shift the focus from product ownership to service provision. However, introducing the PSS indicator into BCEF is a step toward refining the assessment frameworks for the circular economy. While its current performance may be limited, its significance lies in its potential to catalyze the broader adoption of circular economic practices. By fostering transparency and accountability, a PSS model can significantly influence the evolution of sustainable business practices and ultimately drive systemic changes in the near future. The Circl pavilion demonstrates that even modest advancements in PSS metrics can offer valuable insights and inspire greater commitment to circularity. As such, this initiative represents a practical implementation and foundational experiment that can inform the global trajectory of circular economy strategies.

Therefore, we recommend standardization efforts in the construction industry. The case study demonstrates the need for standardized circular product information to enhance industry-wide adoption and ensure consistency in circularity assessments. Additionally, circularity indicators should be designed to support and integrate into future European and international standards, fostering greater comparability and reliability across projects. By refining the Building Circularity Evaluation Framework (BCEF) to align with these evolving standards, the construction sector can adopt a more unified and effective approach to measuring and enhancing circularity.

6.2. Strengths and limitations of this research

The BCEF significantly aids decision-making during the early stages of the design process. Its strength lies in its ability to inform designers about the feasibility of a design before finalizing decisions and to facilitate comparisons across different calculation options. A key advantage is its use of KPIs derived from a comprehensive literature review, enabling scalable application across varying levels of input detail and frameworks. The integration of Building Circularity Indicators (BCIs) with life cycle impact assessment (LCIA) distinguishes BCEF by encompassing the full life cycle, from material production to end-of-life.

BCEF further consolidates existing knowledge, incorporates standardized indicators, and aligns with regulatory requirements such as those from CEN/TC 350. Among existing frameworks, DGNB, BREEAM, Level(s), and Madaster each address circularity partially: they lack early-stage engineering applicability, integrated cross-indicator weighting, or explicit connection-level disassembly assessment. BCEF is the first framework to combine all three within a single, digitally operable, standards-aligned structure. The application of the DeCon expert system for semi-automated disassembly scoring, validated against a real building deconstruction, provides an engineering-grade evidence base not present in prior circularity frameworks. This positions BCEF as a reproducible, quantitative engineering tool adaptable to future policy and design environments.

The observation that Option 1 received the lowest circularity score (53 %) is not merely a numerical outcome but a validation checkpoint for the BCEF framework. This design option featured a basement-intensive layout with irreversible connections and heavy material use, which in practice led to significant challenges in material recovery during deconstruction. The BCEF accurately captured this limitation through low disassembly and reuse scores, confirming its capacity to reflect real-world circularity constraints. This alignment supports the construct validity of the method and underscores its utility as a predictive tool during early design stages. Rather than highlighting the

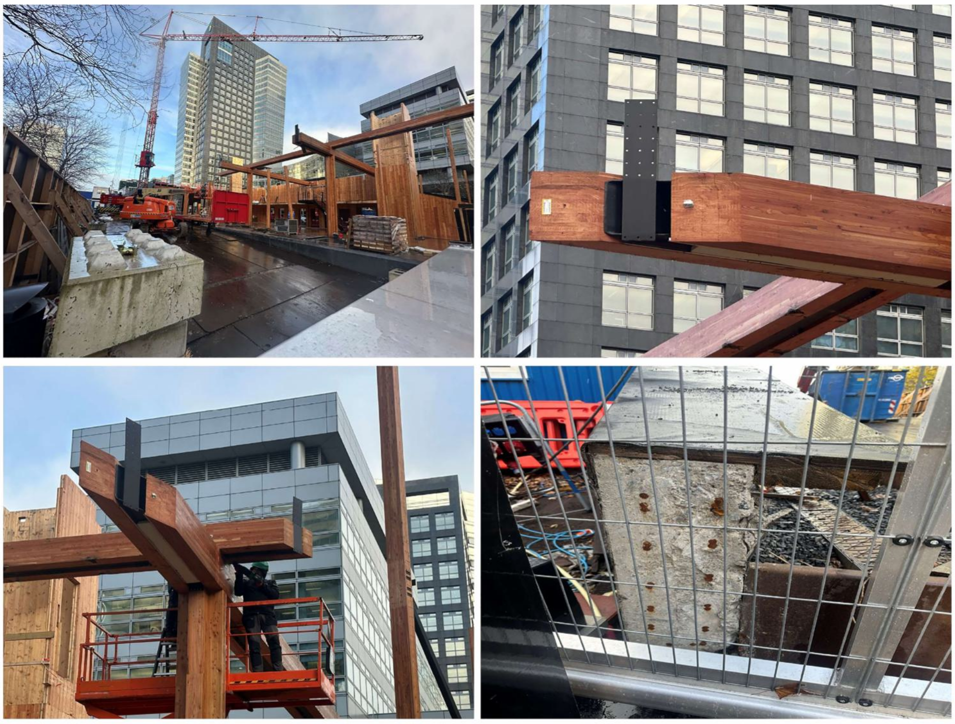


Fig. 12. The Circl pavilion during the disassembly process.

result in isolation, this case illustrates the framework's broader diagnostic value in identifying structural and material features that compromise circular performance.

Similarly, Option 3 received high disassembly and reuse scores, reflecting its modular design and efficient separation of the service layer. These scores aligned with empirical observations, reinforcing the reliability of the framework's disassembly and reuse indicators. The stability of scenario rankings under ±10 % changes in indicator weights demonstrates internal consistency and robustness.

Therefore, BCEF provides predictive potential by allowing early-stage comparisons of design options and estimating likely performance trends across circularity and life cycle impact indicators. Existing frameworks and rating systems such as LEVEL(s), Madaster, and DGNB tend to focus narrowly on either operational impacts or digital inventory management, often excluding system-oriented indicators like Functional Adaptation (FA) and Product-Service Systems (PSS). BCEF's integration of these underrepresented indicators offers a more holistic perspective, particularly valuable in early-stage design. The radar-based visualization format facilitates intuitive multi-criteria decision-making, improving usability compared to score-heavy systems.

Nonetheless, limitations persist. BCEF currently emphasizes material mass for assessing reused content, which may skew results toward heavier materials (e.g., concrete) and undervalue lighter but high-impact systems (e.g., HVAC, PV). While material mass was used as the primary quantification basis due to data availability and compatibility with LCA tools, it may overrepresent components that are heavy but not functionally dominant, such as PV panels. These panels contribute minimally to functional circularity (e.g., adaptability or reuse potential), and their inclusion was maintained solely to ensure consistency across indicators (e.g., the impact of energy systems under PSS or operational GWP) [89]. Future iterations of the BCEF should consider alternative normalization strategies, such as economic value, embodied energy, or functional utility, to address this bias. Future iterations could incorporate composite weighting schemes reflecting mass, embodied carbon, and service life.

Furthermore, while BCEF aligns with EN 15804+A2 and ISO 20887, broader validation across diverse building typologies, project scales, and climatic contexts is essential to assess the external generalizability of the findings. Benchmarking against established frameworks and applying BCEF across longitudinal case studies could further enhance its reliability and acceptance.

6.3. *Future work and possible applications*

The Building Circularity Evaluation Framework (BCEF) represents a significant step toward operationalizing circularity assessment during the early design stages of buildings. While the current version of the framework integrates six key performance indicators (KPIs), it intentionally excludes certain dimensions, such as water use, toxicity, and social sustainability, which remain underdeveloped or contested within the scope of circular economy (CE) definitions. Future research may incorporate these aspects as data availability and consensus on their quantification improve.

BCEF complements ongoing European standardization efforts, notably the emerging CEN/TC 350 framework on Circular Economy in the Construction Sector – Framework, Principles, and Definitions [7]. Annex B of this standard proposes new circularity indicators, including Resource Flow Analysis (RFA), the Material Circularity Indicator (MCI), and Construction Waste Diversion Rates (CWDR). These indicators enrich the understanding of material efficiency and waste dynamics across the building life cycle. However, their integration at early design stages remains methodologically and practically challenging due to limited predictive capability. BCEF addresses this gap by focusing on operational, design-phase-compatible metrics that can directly support early decision-making and stakeholder engagement.

To enhance its relevance and future applicability, BCEF is well-positioned to align with upcoming EU policy instruments, most notably:

- The EU Digital Product Passport (DPP), mandated under the revised EcoDesign for Sustainable Products Regulation (ESPR), will require construction products to disclose key sustainability and circularity data, including information on material composition, recyclability,

repairability, and reusability. BCEF's structure, particularly its Disassembly Potential (DP), Reused Content (RC), and Product-Service Systems (PSS) indicators, could be adapted to inform DPP data layers, especially those relating to end-of-life value retention and component traceability. Integration with DPP would also enhance the transferability of BCEF outputs into digital building logbooks, BIM object libraries, and procurement platforms.
- The Energy Performance of Buildings Directive (EPBD) Recast (2024/1275): For the first time, the EPBD requires Member States to assess and report whole life cycle Global Warming Potential (GWP) of buildings. BCEF already incorporates GWP as a core KPI, aligned with EN 15978 and EN 15804+A2. By extending BCEF to include Module D impacts and aligning its GWP indicator with national LCA databases (e.g., TOTEM, ÖKOBAUDAT), the framework could contribute directly to EPBD reporting and compliance monitoring.

Moreover, BCEF supports convergence with other instruments such as the LEVEL(s) framework, the Construction Products Regulation (CPR), and upcoming EU Taxonomy Delegated Acts on circularity. Integration of these frameworks would enable BCEF to serve not only as a design support framework but also as a compliance and certification mechanism.

To maintain scientific robustness and practical relevance, future development of BCEF should consider:

- Incorporating dynamic weighting systems based on stakeholder priorities or project typologies.
- Testing with probabilistic or Monte Carlo methods for uncertainty quantification.
- Adding support for automated data extraction from BIM and material passports.
- Refining indicators to better reflect circular procurement strategies and contractual models (e.g., leasing or take-back schemes).

The practical utility of BCEF depends on its broad validation across building types and stakeholder profiles. While the Circl Pavilion provides a unique case of disassembly and reuse, future case studies should target additional typologies, such as residential, educational, and healthcare, to stress-test the framework's flexibility. This could be supported by usability testing with architects, engineers, and contractors to assess its integration into typical workflows and procurement stages [40].

The framework's alignment with CEN/TC 350′s new SC1/WG5 working group, focused on developing technical guidance for circularity assessment, provides a platform for institutionalizing BCEF principles into future European norms. Active participation in this working group will enable the authors to contribute to the development of standardized approaches for indicator selection, data reporting, and aggregation methodologies.

Ultimately, BCEF has the potential to support a new generation of digital and regulatory tools for circular construction. Its application to the Circl Pavilion sets a benchmark by demonstrating how post-disassembly data, service-based procurement models, and modular design can be jointly assessed within a unified framework. Compared to existing frameworks such as LEVEL(s), BCI, or TOTEM, BCEF bridges the gap between theoretical modeling and actionable circular design.

The growing portfolio of built examples, such as the Lister Building (Brussels) and CBCI Living Lab (Ghent), reflects increasing readiness to adopt performance-based circularity indicators. BCEF can serve as a harmonizing instrument to guide these practices across design stages, stakeholder groups, and regulatory contexts, enabling early-stage trade-off analysis between circularity, carbon, and adaptability.

Through broader validation, policy alignment, and digital integration, BCEF can evolve into a mainstream assessment and benchmarking framework that not only reflects the state of the art but actively shapes the future of circular construction in Europe and beyond.

7. Conclusion

The Building Circularity Evaluation Framework (BCEF) provides a structured and transparent whole-building evaluation approach that operationalizes six indicators, Global Warming Potential, Land-Use Footprint, Reused Content, Disassembly Potential, Functional Adaptation, and Product-Service Systems, in a single early-stage assessment workflow. The contribution is not the invention of new indicators, but the explicit integration of indicator scope definition, life-cycle module mapping, normalization, weighting, and aggregation into a reproducible evaluation structure aligned with EN 15804+A2, EN 15978, and ISO 20887 [20–42].

Demonstration on the dismantled Circl Pavilion shows that BCEF can be applied to a real project with documented circular features and can differentiate outcomes across three scope definitions (full-building, above-ground, and disassembly-optimized component scope) [78,79]. However, this single-case demonstration does not establish generalizable benchmarks or external validity, and it does not replace comparative testing against conventional baselines or other assessment tools [16,30]. The results should therefore be interpreted as evidence of feasibility, transparency, and internal consistency, with clear limitations regarding representativeness.

Future work should focus on (i) expanding testing to additional building typologies and to at least one explicit counterfactual baseline per typology, (ii) formalizing indicator selection and weighting protocols (for example, structured elicitation and consistency checks), and (iii) extending sensitivity treatment beyond weights to include uncertainty in inventory data, normalization bounds, and alternative aggregation models, as recommended in recent reviews of circularity metrics and CE-LCA methods [17–88]. These steps are required before BCEF can be used for benchmarking claims; they are also necessary to make BCEF robust for policy-facing use cases and for integration into digital workflows such as BIM-linked material passports, Digital Product Passports, and procurement decision support [31,52].

Dear Sir,

I am sending here with a copy of the manuscript, which I would like to submit to the Journal of Results in Engineering. The paper is entitled:

BCEF: A Multi-Criteria Framework for Assessing Circularity and Life Cycle Impacts in Early-Stage Building Design

I hereby certify that this paper consists of original, unpublished work which is not under consideration for publication elsewhere.

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author and which has been configured to accept email from your journal.

Signed by all authors as follows:

Corresponding Author
Muheeb Al-Obaidy
16.07.2025
Sustainable Building Design Laboratory, Department. Urban And

Environmental Engineering, School of Engineering, Université de Liège, 4000 Liège, Belgium

Sustainable Building Materials, Construction Department, Colruyt Group, 1500 Halle, Belgium

Address : Univeristé de Liège, Sustainable Buildings Design Lab, Office +0/542, Quartier Polytech 1, Allée de la Découverte 9, 4000 Liège, Belgium

Tel: +32 43.66.91.55 - Fax: +32 43.66.29.09, E-mail: muheeb.al-obaidy@uliege.be

CRediT authorship contribution statement

Muheeb Al-Obaidy: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luc Courard:** Writing – review & editing, Supervision. **Rafael Passarelli:** Writing – review & editing, Supervision. **Enola Giannasi:** Software, Investigation, Formal analysis, Data curation. **Shady Attia:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

None.

Acknowledgments

This research is part of the Ph.D. research project DeConstruct: A circularity evaluation framework for office building design, supported by the University of Liège and Colruyt Group [90,91]. We would like to acknowledge the Sustainable Building Design Lab for providing us with data processing software for this research and their valuable support during focus group discussions and data content analysis. This research was supported by the EU COST Action 21103 – Implementation of Circular Economy in the Built Environment (Circular B), EU COST Action 20139 – Holistic Design of Tall Timber Buildings HELEN, and CEN/TC 350: Sustainability of Construction Works, SC1, and SC5, for circularity assessment. We thank our colleagues from the COST Action Workgroups and CEN 350 committees, under the leadership of Prof. Lisbeth M. Ottosen from the Technical University of Denmark, who provided valuable insights and expertise that greatly assisted in the screening and review of papers. The authors would also like to gratefully acknowledge de Architekten Cie, the designer of the Circl pavilion, for sharing information regarding the case research.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rineng.2026.110824.

Appendices

The full list of technical appendices, detailed tables, and consultation reports referenced in this paper is available in the companion report: Al-Obaidy, M., & Attia, S. (2025). Development of the BCEF and DeCon Tools. Université de Liège. ISBN 978-2-930909-25-7. Retrieved from https://orbi.uliege.be/handle/2268/334554

Data availability

https://orbi.uliege.be/handle/2268/334554

References

[1] ecoinvent, Ecoinvent: life cycle inventory database, Accessed: Jun. 30, https://ecoinvent.org/, 2024.
[2] EEA, Construction and Demolition Waste: Challenges and Opportunities in a Circular Economy, EEA Briefing 13/2020, Luxembourg, 2020.
[3] M. Al-Obaidy, et al., Expert system for building disassembly potential evaluation and inspection, J. Build. Eng. 103 (2025) 112148.
[4] IEA and UNEP, Global Status Report For Buildings and Construction 2021: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector, International Energy Agency, Paris, France, 2021.
[5] M. Al-Obaidy, L. Courard, S. Attia, A parametric approach to optimizing building construction systems and carbon footprint: a case study inspired by circularity principles, Sustainability 14 (6) (2022) 3370.
[6] L. Braakman, S. Bhochhibhoya, R. de Graaf, Exploring the relationship between the level of circularity and the life cycle costs of a one-family house, Resour. Conserv. Recycl. 164 (2021) 105149.
[7] E. Durmisevic, Transformable building structures: design for disassembly as a way to introduce sustainable engineering to building design and construction, Accessed: Jun. 29, 2025. [Online]. Available, https://elibrary.ru/item.asp?id=9358959, 2005.
[8] M.J. Thaheem, A.J. Baber, B. Bakhtawar, Cumulative sustainability performance index of contractors and consultants: toward a prequalification system, J. Leg. Aff. Dispute Resolut. Eng. Constr. 14 (1) (2022) 05021007, https://doi.org/10.1061/(ASCE)LA.1943-4170.0000515. Feb.
[9] J.F. Azcarate-Aguerre, T. Klein, T. Konstantinou, M. Veerman, Facades-as-a-service: the role of technology in the circular servitisation of the building envelope, Appl. Sci. 12 (3) (2022) 1267.
[10] prEN 18177: Framework and Definitions For Circularity in Buildings (Under Development), CEN, Brussels, Belgium, 2026.
[11] S. Cristiano, et al., Construction and demolition waste in the Metropolitan City of Naples, Italy: state of the art, circular design, and sustainable planning opportunities, J. Clean. Prod. 293 (2021) 125856.
[12] I.Y. Wuni, Burden of proof beyond the triple bottom line: mapping the benefits of circular construction, Sustain. Prod. Consum. 34 (2022) 528–540.
[13] G. Finch, G. Marriage, A. Pelosi, M. Gjerde, Building envelope systems for the circular economy; evaluation parameters, current performance and key challenges, Sustain. Cities Soc. 64 (2021) 102561.
[14] B.I. Oluleye, D.W. Chan, T.O. Olawumi, A.B. Saka, Assessment of symmetries and asymmetries on barriers to circular economy adoption in the construction industry towards zero waste: a survey of international experts, Build. Environ. 228 (2023) 109885.
[15] S.H. Ghaffar, M. Burman, N. Braimah, Pathways to circular construction: an integrated management of construction and demolition waste for resource recovery, J. Clean. Prod. 244 (2020) 118710.
[16] N. Khadim, R. Agliata, M.J. Thaheem, L. Mollo, Whole building circularity indicator: a circular economy assessment framework for promoting circularity and sustainability in buildings and construction, Build. Environ. 241 (2023) 110498.
[17] A. van Stijn, L.M. Eberhardt, B.W. Jansen, A. Meijer, A circular economy life cycle assessment (CE-LCA) model for building components, Resour. Conserv. Recycl. 174 (2021) 105683.
[18] N. Khadim, R. Agliata, A. Marino, M.J. Thaheem, L. Mollo, Critical review of nano and micro-level building circularity indicators and frameworks, J. Clean. Prod. 357 (2022) 131859.
[19] S. Attia, Regenerative and positive impact architecture. SpringerBriefs in Energy, Cham: Springer International Publishing, London, UK, 2018, https://doi.org/10.1007/978-3-319-66718-8.
[20] L.A. Akanbi, et al., Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy, J. Clean. Prod. 223 (2019) 386–396, https://doi.org/10.1016/j.jclepro.2019.03.172. Jun.
[21] S. Attia, et al., Disassembly calculation criteria and methods for circular construction, Autom. Constr. 165 (2024) 105521.
[22] M. Buyle, W. Galle, W. Debacker, A. Audenaert, Sustainability assessment of circular building alternatives: consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context, J. Clean. Prod. 218 (2019) 141–156.
[23] L. Jiang, S. Bhochhibhoya, N. Slot, R. de Graaf, Measuring product-level circularity performance: an economic value-based metric with the indicator of residual value, Resour. Conserv. Recycl. 186 (2022) 106541.
[24] European Commission, A Common EU Framework of Core Sustainability Indicators For Office and Residential Buildings, European Commission, Brussels, Belgium, 2024 [Online]. Available, https://ec.europa.eu/environment/topics/circular-economy/levels_en.
[25] M. Henrysson, A. Papageorgiou, A. Björklund, F. Vanhuyse, R. Sinha, Monitoring progress towards a circular economy in urban areas: an application of the European Union circular economy monitoring framework in Umeå municipality, Sustain. Cities Soc. 87 (2022) 104245.
[26] CEN, 15804:2019+A2 sustainability of construction works - environmental product declaration - core rules for the product category of construction products, 2019.
[27] CEN, 15978:2025 Sustainability assessment of construction works – assessment of the environmental performance of buildings – calculation method, 2025.
[28] CESBA, Common European sustainable built environment assessment, Accessed: Jan. 05, http://www.cesba.eu, 2025.
[29] BAMB, Buildings As Material Banks: Integrating Materials Passports with Reversible Building Design to Optimise Circular Industrial Value Chains, Bruxelles Environnement, Brussels Belgium, 2019.
[30] N. Khadim, R. Agliata, Q. Han, L. Mollo, From circularity to sustainability: advancing the whole building circularity indicator with Life Cycle assessment (WBCI-LCA), Build. Environ. 269 (2025) 112413.

[31] J.J.H. Verberne, Building Circularity Indicators: An Approach For Measuring Circularity of a Building, Eindhoven University of Technology, Eindhoven, 2016. Master Thesis[Online]. Available, https://pure.tue.nl/ws/portalfiles/portal/46934924/846733-1.pdf.
[32] Madaster, Madaster Circularity Indicator Explained, Madaster, Amsterdam, Netherlands, 2021.
[33] BRE, BREEAM | Sustainable Building Certification, Building Research Establishment, London, UK, 2025.
[34] DGBC, Circular Buildings: Disassembly potential Measurement Method Version 2.0, Pays-Bas, 2021. [Online]. Available: https://www.dgbc.nl/publicaties/circular-buildings-een-meetmethodiek-voor-losmaakbaarheid-v20-41.
[35] DGNB, Deutsche Gesellschaft für Nachhaltiges Bauen, German Sustainable Building Council, Berlin, Germany, 2025.
[36] I. Amarasinghe, Y. Hong, R.A. Stewart, Development of a material circularity evaluation framework for building construction projects, J. Clean. Prod. 436 (2024) 140562.
[37] E. Roos Lindgreen, R. Salomone, T. Reyes, A critical review of academic approaches, methods and tools to assess circular economy at the micro level, Sustainability 12 (12) (2020) 4973.
[38] H.S. Kristensen, M.A. Mosgaard, A review of micro level indicators for a circular economy–moving away from the three dimensions of sustainability? J. Clean. Prod. 243 (2020) 118531.
[39] J. Fernandes, P. Ferrão, A new framework for circular refurbishment of buildings to operationalize circular economy policies, Environments 10 (3) (2023) 51.
[40] C.T. De Oliveira, T.E.T. Dantas, S.R. Soares, Nano and micro level circular economy indicators: assisting decision-makers in circularity assessments, Sustain. Prod. Consum. 26 (2021) 455–468.
[41] W. McDonough, M. Braungart, Cradle to Cradle: Remaking the Way We Make Things, North Point Press, New York, USA, 2022.
[42] ISO, 14040:2006 Environmental Management: Life Cycle Assessment, Principles and Framework, Geneva, Switzerland, 2006.
[43] M. Finkbeiner, A. Inaba, R. Tan, K. Christiansen, H.-J. Klüppel, The new international standards for life cycle assessment: ISO 14040 and ISO 14044, Int. J. Life Cycle Assess. 11 (2006) 80–85.
[44] C. Mutel, Brightway: an open source framework for Life cycle assessment, J. Open Source Softw. 2 (12) (2017) 236, https://doi.org/10.21105/joss.00236. Apr.
[45] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, The ecoinvent database version 3 (part I): overview and methodology, Int. J. Life Cycle Assess. 21 (2016) 1218–1230.
[46] V. Cascione, et al., Integration of life cycle assessments (LCA) in circular bio-based wall panel design, J. Clean. Prod. 344 (2022) 130938.
[47] A. Luthin, R.H. Crawford, M. Traverso, Demonstrating circular life cycle sustainability assessment–a case study of recycled carbon concrete, J. Clean. Prod. 433 (2023) 139853.
[48] O. Nuri Cihat, M. Kucukvar, Carbon footprint of construction industry: a global review and supply chain analysis, Accessed: Jun. 29, 2025. [Online]. Available, http://qspace.qu.edu.qa/handle/10576/14086, 2020.
[49] B. Sizirici, Y. Fseha, C.-S. Cho, I. Yildiz, Y.-J. Byon, A review of carbon footprint reduction in construction industry, from design to operation, Materials 14 (20) (2021) 6094.
[50] M.Q. Huang, X.L. Chen, J. Ninić, Y. Bai, Q.B. Zhang, A framework for integrating embodied carbon assessment and construction feasibility in prefabricated stations, Tunn. Undergr. Space Technol. 132 (2023) 104920.
[51] Y.H. Labaran, V.S. Mathur, S.U. Muhammad, A.A. Musa, Carbon footprint management: a review of construction industry, Clean. Eng. Technol. 9 (2022) 100531.
[52] Nordic Sustainable Construction, Metrics For Circularity, Nordic Council of Ministers, Copenhagen, Denmark, 2024.
[53] S. Attia, M.C. Santos, M. Al-Obaidy, M. Baskar, Leadership of EU member states in building carbon footprint regulations and their role in promoting circular building design, in: IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2021, p. 012023. Accessed: Aug. 17, 2024. [Online]. Available, https://iopscience.iop.org/article/10.1088/1755-1315/855/1/012023/meta.
[54] R. Grover, "Towards Zero Carbon Buildings Reducing the Embodied Carbon Footprint of a Construction", PhD Thesis, Delft University of Technology Delft, The Netherlands, 2020.
[55] EN 15978:2011, Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation method, iTeh Standards Store, 2021. Accessed: Jul. 19[Online]. Available, https://standards.iteh.ai/catalog/standards/cen/62c22cef-5666-4719-91f9-c21cb6aa0ab3/en-15978-2011.
[56] D. Trigaux, K. Allacker, F. De Troyer, Life cycle assessment of land use in neighborhoods, Procedia Environ. Sci. 38 (2017) 595–602.
[57] K. Allacker, D.M.D. Souza, S. Sala, Land use impact assessment in the construction sector: an analysis of LCIA models and case study application, Int. J. Life Cycle Assess. 19 (11) (2014) 1799–1809, https://doi.org/10.1007/s11367-014-0781-7. Nov.
[58] T. Mattila, T. Helin, R. Antikainen, S. Soimakallio, K. Pingoud, H. Wessman, Land use in life cycle assessment, Finn. Environ. 24 (2011) 2011.
[59] European Commission and Joint Research Centre, Land-use Related Environmental Indicators For Life Cycle assessment: Analysis of Key Aspects in Land Use Modelling, European Commission, Brussels, Belgium, 2016 [Online]. Available, https://ec.europa.eu/environment/topics/circular-economy/levels_en.
[60] T. Perminova, N. Sirina, B. Laratte, N. Baranovskaya, L. Rikhvanov, Methods for land use impact assessment: a review, Environ. Impact Assess. Rev. 60 (2016) 64–74.
[61] G. Pristerà, D. Tonini, M.L. Tornaghi, D. Caro, S. Sala, Taxonomy of design for deconstruction options to enable circular economy in buildings, Resour. Environ. Sustain. (2024) 100153.
[62] A. Antunes, et al., Environmental impacts and benefits of the end-of-life of building materials: database to support decision making and contribute to circularity, Sustainability 13 (22) (2021) 12659.
[63] Science mapping approach to assisting the review of construction and demolition waste management research published between 2009 and 2018 - ScienceDirect, Accessed: Sep. 29, https://www.sciencedirect.com/science/article/pii/S0921344918303628, 2023. ?via%3Dihub.
[64] European Commission, Construction and demolition waste (CDW), Accessed: May 20, ttps://environment.ec.europa.eu/topics/waste-and-recycling/construction-and-demolition-waste_en, 2025.
[65] B. Guy, S. Shell, H. Esherick, Design for deconstruction and materials reuse, Proc. CIB Task Group 39 (4) (2006) 189–209.
[66] K. Knoth, S.M. Fufa, E. Seilskjær, Barriers, success factors, and perspectives for the reuse of construction products in Norway, J. Clean. Prod. 337 (2022) 130494.
[67] É. Gobbo, E.M. Nia, A. Straub, A. Stephan, Exploring the effective reuse rate of materials and elements in the construction sector, J. Build. Eng. 98 (2024) 111344.
[68] E. Durmisevic, \.H.O. Ciftcioglu, C.J. Anumba, Knowledge model for assessing disassembly potential of structures, in: Deconstruction and Materials Reuse Proceedings of the 11th Rinker International Conference, 2003. Accessed: Jun. 29, 2025. [Online]. Available, https://4darchitects.nl/download/TG39_2003_2.pdf.
[69] W. Debacker, S. Manshoven, M. Peters, A. Ribeiro, Y. De Weerdt, Circular economy and design for change within the built environment: preparing the transition, in: International HISER Conference on Advances in Recycling and Management of Construction and Demolition Waste, Delft University of Technology Delft, The Netherlands, 2017, pp. 114–117. Accessed: Jun. 29, 2025. [Online]. Available: https://www.researchgate.net/profile/Ali-Vahidi-2/publication/323829991_Advances_in_Recycling_and_Management_of_Construction_and_Demolition_Waste_HISER_International_Conference/links/66ed594c750edb3bea5ef569/Advances-in-Recycling-and-Management-of-Construction-and-Demolition-Waste-HISER-International-Conference. pdf#page=135.
[70] D.J. Joustra, E. de Jong, F. Engelaer, Guided Choices: Towards a Circular Business Model, C2C BIZZ, 2013.
[71] A.T. Rosário, P. Lopes, F.S. Rosário, Sustainability and the circular economy business development, Sustainability 16 (14) (2024) 6092.
[72] Vlaanderen Circulair, CESCGO! preparing the playing field for circular economy service companies (CESCo), Accessed: May 20, https://vlaanderen-circulair.be/en/cases/detail/cescgo, 2025.
[73] J. Dsilva, S. Zarmukhambetova, J. Locke, Assessment of building materials in the construction sector: a case study using life cycle assessment approach to achieve the circular economy, Heliyon 9 (10) (2023). Accessed: Jun. 29, 2025. [Online]. Available, https://www.cell.com/heliyon/fulltext/S2405-8440(23)07612-0.
[74] European Commission, Circular Economy Action Plan: The EU's New Circular Action Plan Paves the Way For a Cleaner and More Competitive Europe, European Commission, Energy, 2023. Climate change, Environment, Brussels Belgium [Online]. Available, https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en.
[75] S. Attia, A. El-Degwy, M. Attia, Usability and fitness testing for building performance simulation tools, J. Build. Perform. Simul. 17 (4) (2024) 460–479, https://doi.org/10.1080/19401493.2024.2341089. Jul.
[76] S. Attia, S. Petersen, A. Stephan, and E. Gobbo, "Framework to model building carbon emissions", 2024.
[77] P. Antwi-Afari, S.T. Ng, J. Chen, X.M. Zheng, Determining the impacts and recovery potentials of a modular designed residential building using the novel LCA-C2C–PBSCI method, J. Clean. Prod. 378 (2022) 134575.
[78] ABN AMRO Ban, Bank homepage, Accessed: Jan. 05, https://www.abnamro.nl/nl/prive/index.html, 2025.
[79] The making of Circl, Accessed: May 20, https://circl.nl/themakingof/en/, 2025.
[80] de Architekten Cie, Accessed: Sep. 14, https://www.cie.nl, 2024.
[81] Material District, Circl: a completely circular and innovative pavilion, MaterialDistrict. Accessed: Nov. 21, https://materialdistrict.com/article/circl-circular-pavilion/, 2023.
[82] DERIX, The experts in engineered timber construction, Accessed: May 20, https://derix.de/en/, 2025.
[83] Circle Economy, A Future-Proof Built Environment - Insights, ABN AMRO, Amsterdam, Netherlands, 2024 [Online]. Available, https://www.circle-economy.com/resources/a-future-proof-built-environment.
[84] Vlaanderen Circulair, Product-service systems – Vlaanderen Circulair, Accessed: May 20, https://vlaanderen-circulair.be/en/knowledge/what-is-it/product-service-systems, 2025.
[85] C. Henrotay, BAMB - buildings As material banks (BAMB2020) - BAMB, Accessed: Mar. 05, https://www.bamb2020.eu/library/overview-reports-and-publications/, 2025.
[86] ISO 20887:2020, Sustainability in Buildings and Civil Engineering Works Design for Disassembly and Adaptability Principles, Requirements and Guidance, ISO, Geneva, Switzerland, 2020.
[87] K. Ostapska, P. Rüther, A. Loli, K. Gradeci, Design for disassembly: a systematic scoping review and analysis of built structures designed for disassembly, Sustain. Prod. Consum. 48 (2024) 377–395.
[88] S. Mani, M.R. Hosseini, G. Karunsena, T. Kocaturk, Inconsistencies revealed: a critical analysis of circular economy assessment methods for buildings, Resour. Conserv. Recycl. 218 (2025) 108203.
[89] J. Zhang, Y. Zhang, Y. Chen, J. Wang, L. Zhao, M. Chen, Evaluation of carbon emission efficiency in the construction industry based on the super-efficient slacks-

based measure model: a case study at the provincial level in China, Buildings 13 (9) (2023) 2207.
[90] M. Al-Obaidy, S. Attia, DeConstruct: a circularity evaluation framework for office buildings design, Accessed: Jan. 10, https://www.sbd.uliege.be/cms/c_11206193/en/sbdlab-project-deconstruct, 2025.
[91] M. Al-Obaidy, "A circularity evaluation framework for newly constructed office building design", PhD dissertation, Liege, Belgium, 2025. [Online]. Available: https://orbi.uliege.be/handle/2268/326928.

Chapter 06. *Implementation of Building Circularity Evaluation Framework (BCEF) – Unpublished*

1. BCEF evaluation indicators and tools

As detailed in Chapter 05, the Building Circularity Evaluation Framework (BCEF) integrates multiple indicators to assess the circularity and sustainability of buildings. These indicators have been identified based on a comprehensive review of existing literature, their prevalence in established rating systems, and insights gained through expert consultations conducted as part of this Ph.D. research. Drawing upon these sources, six key evaluation indicators have been established which will be addressed again for further clarification below with their calculation methods:

1. **Global Warming Potential (GWP) Indicator:** The Global Warming Potential indicator applies the Life Cycle Impact Assessment (LCIA) methodology to evaluate the environmental impact of a building throughout its entire life cycle. This approach is in accordance with the European Standard EN 15978 [26] and the International Standards ISO 14040 [23] and ISO 14044 [24]. LCIA is a widely recognized tool for assessing the environmental implications of materials, their Global Warming Potential (GWP) [105], and the sustainability of entire construction systems [73]. Furthermore, Environmental Product Declarations (EPDs), which are derived from LCIA, provide quantifiable environmental data for specific products in compliance with relevant standards such as EN 15804 [27] for construction materials [106]. As shown in Figure 3.1., the LCIA process in this study was conducted in accordance with the most recent draft requirements of the EU Taxonomy [107] and the European standard CEN/TC 350 [108]. The calculation methodology aligns with the International Energy Agency's Energy in Buildings and Communities Programme (IEA EBC) - Annex 89, which outlines strategies for achieving net-zero whole-life carbon buildings [109]. Additionally, it is noteworthy that Denmark revised its building regulations in June 2024, stipulating that from 2025, new office buildings must comply with a carbon footprint limit of 7.5 kg CO_2e/m^2/year, along with an additional 1.5 kg CO_2e/m^2/year for life cycle modules A4 and A5 [110]. These revised thresholds serve as a benchmark for evaluating case studies within this Ph.D. research. To ensure compliance with EN 15978 [26] and alignment with sustainability frameworks such as Level(s) [29] and the EU Taxonomy [107], the software tool One Click LCA [111] was employed to conduct the carbon footprint assessment.

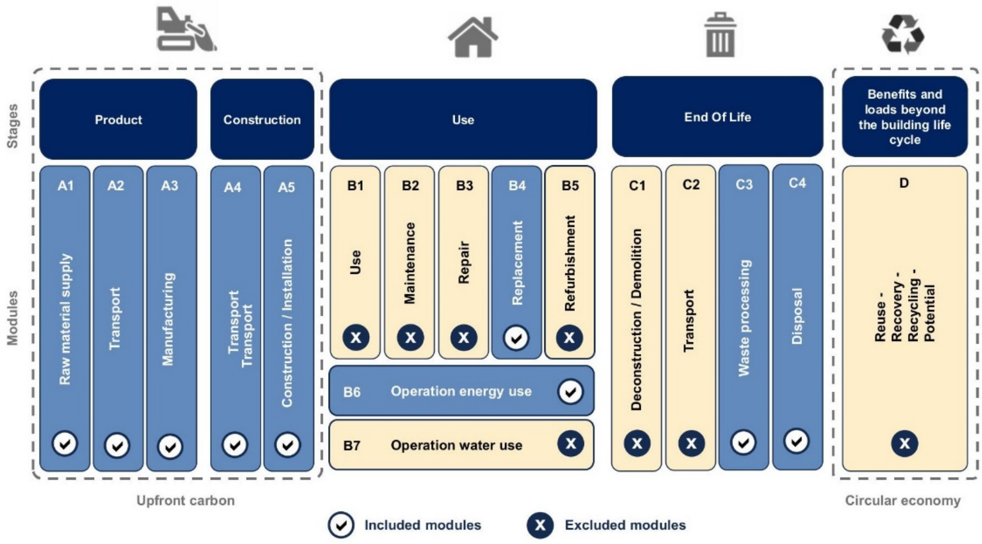


Figure 3.1. LCIA modules included in this research according to the Danish requirements [110], as defined by EN 15978 [26]

2. **Land-use footprint (LU) indicator:** This indicator assesses the potential environmental impacts of land occupation and transformation over the building's entire life cycle [112]. It captures effects on soil quality and ecosystem functions, such as biotic production, erosion resistance, mechanical filtration, and groundwater recharge [113], [114], [115]. In line with EN 15804+A2 [27] and the Environmental Footprint (EF 3.1) method, the LU assessment is based on the LANCA® soil quality model [116], which characterizes land-use impacts in terms of changes to ecosystem services rather than greenhouse-gas emissions. Land-use related carbon fluxes (e.g., deforestation and soil carbon losses) are addressed separately under the Climate change – land-use and land-use change (LULUC) subcategory [117], [118]. LU values were calculated using the ecoinvent 3.10 database within the LCIA workflow implemented in One Click LCA, ensuring consistency with EN 15804+A2 requirements. The LU score is expressed as a Soil Quality Index in points (Pt) per functional unit, here reported as Pt/(m^2·year) of gross floor area [117].
3. **Reused content (RC) indicator:** The latest draft of the EU Taxonomy for circularity stipulates that at least 90% (by weight) of non-hazardous construction and demolition waste (CDW) must be either prepared for reuse or recycled [107], [119]. This indicator is designed to assess the extent to which recycled or repurposed materials are incorporated into construction projects. Enhancing a building's circularity involves increasing the proportion of reused materials, thereby promoting resource efficiency and reducing reliance on virgin raw materials. In this Ph.D. research, reused content was assessed through a systematic inventory of materials, distinguishing between virgin, recycled, and reused components based on project-specific data. A dedicated equation has been formulated to facilitate a quantitative evaluation of this indicator, which is elaborated in Chapter 05.
4. **Disassembly potential (DP)indicator:** This indicator assesses the disassembly potential of the building at the end of its life cycle to optimize

material recovery and reuse. The ability to design buildings for disassembly plays a crucial role in advancing circular economy objectives by facilitating efficient recycling and repurposing of construction materials. As part of this Ph.D. research, the second beta version of the expert system, referred to as the DeCon tool [120], was employed to evaluate the disassembly potential of buildings. The DeCon tool, developed by the Ph.D. candidate, serves as an analytical framework for assessing the extent to which buildings can be efficiently deconstructed to support sustainable material management.

5. **Functional Adaptation (FA; Design for Flexibility DfF) indicator:** This indicator evaluates a building's capacity to accommodate functional changes over time, supporting long-term utility and minimizing the need for demolition. Despite growing interest in adaptability, its quantitative assessment remains an emerging field, with limited empirical data available for validation [121]. Adaptability models focus on existing buildings, although some frameworks extend to early design stages. In the context of the circular economy (CE), adaptability is increasingly recognized as a key strategy for sustainable construction, facilitating Design for Adaptability (DfA), which underpins various circular design approaches such as Design for Disassembly (DfD), multifunctionality, spatial transformability, and design reversibility [122], [123]. Structures that enable modification or expansion without significant reconstruction contribute to circular building concepts. The BCEF framework adopts the guidelines outlined in ISO 20887:2020 [124] to assess building adaptability. The evaluation considers the extent to which spaces can accommodate regular and cosmetic modifications, the flexibility of walls and partitions, and the feasibility of vertical and horizontal expansion. Vertical adaptability is assessed based on the potential for additional floors, while horizontal expansion is determined by the availability of adjacent areas for future use. The calculation method of this indicator has been detailed in Chapter 05.
6. **Product-service systems (PSS) indicator:** Although the concept of Product-Service Systems (PSS) is still in its early stages, it is recognized as a critical indicator for assessing building circularity within this research. The incorporation of PSS components and services in the case study underscores the necessity of including this indicator in the evaluation framework. To quantify the extent of PSS implementation, this indicator was measured as a percentage of the total PSS components and services utilized in the building. This study establishes an optimal reference case for the quantitative application of PSS, identified as the 't Centrum office building [125], a pioneering circular construction project in Belgium. To assess the circularity of this building, discussions were conducted with the owning company to inventory the PSS elements integrated into the structure, as well as additional systems intended for future implementation during the building's deconstruction and reconstruction phases. The methodology for calculating this indicator is comprehensively detailed in Chapter 5 of this Ph.D. research.

To ensure a balanced evaluation, weights (Wi) were assigned to each indicator based on insights derived from expert consultations and an extensive literature review. The total sum of these weights is standardized to 1 (or 100%) to reflect the relative significance of each indicator within the framework. The assigned weights are as follows:

GWP = 0.25, LU = 0.15, RC = 0.20, DP = 0.15, FA = 0.15, PSS = 0.10.

To quantify the circularity index, the following equation was developed by the doctoral candidate and applied within this research.

$$BCEF_{index} = \left(\sum_{i=1}^{n} W_i \, . S_i \right) X100$$

W_i = weight of the i indicator.
S_i = Normalized score of the i indicator.
n = Total number of indicators.

As shown in the results (Section 4., Figure 3.6.), to enhance clarity and ensure consistency in data presentation, a reading scale was added alongside the radar chart. Specific ranges were defined for the indicators of Global Warming Potential (GWP), extending from zero to 20 (kg CO_2e/m^2/year), and Land-Use footprint (LU), extending from zero to 0.5 (kg CO_2e/m^2). This distinction was necessary due to the quantitative nature of these two indicators, which rely on carbon impact and land use metrics, thereby requiring a dedicated numerical scale for accurate assessment. For the remaining indicators, a standardized percentage-based unit was adopted, ranging from zero to 10, which corresponds to a scale of 0-100%. This unified range was applied across both the radar chart and the evaluation reading scale, facilitating visual comparison between indicators and improving interpretability for users and researchers alike.

2. Case Studies

In this Ph.D. research, three case studies were employed to implement and validate the proposed framework. These case studies were previously assessed individually to evaluate and test distinct phases of the framework's development. These case studies were specifically chosen because they embody circular building principles, aligning with the objectives of this Ph.D. research. Each case study demonstrates a commitment to circular economy principles and achieves its intended design objectives. In this research, the circularity of each building was assessed holistically to enable a comprehensive comparison across the three projects.

2.1. **Case Study 1:** \`t Centrum Building

The first case study is \`t Centrum Building, which was utilized to validate and test the first three indicators of the framework: Global Warming Potential (GWP), land-use footprint (LU), and reused content (RC). This case study was documented in a published article, corresponding to Chapter 02 of this Ph.D. research.

\`t Centrum is an office building located in Kamp C, Westerlo, Belgium [125]. It was designed by [126] and constructed by Beneens [127]. The three-story building spans 2,200 square meters and is classified as carbon-neutral while adhering to circular economy principles. Moreover, it serves as a catalyst for modular and circular buildings in the region. Construction was completed in March 2022, with the building designed to be dismantled after five years and reassembled in the same location with a different configuration to assess its deconstruction capabilities [128]. It is an experimental project; therefore, the planned service life of this project is 20 years. The building features a modular office arrangement with adaptable workspaces, enabling full disassembly at the end of its lifecycle. Constructed using Cross-Laminated Timber (CLT), it employs dry-assembly fastening mechanisms for connections. The roof, floors, and internal walls are primarily wooden, with partitions and flooring tiles installed using dry joints to enhance disassembly potential. Project data was collected through technical meetings with the project consortium from the early design stages, supplemented by necessary drawings, datasets, and 3D scanning analysis. Regular weekly site visits were conducted to monitor and evaluate the construction and assembly process (see Figure 3.2.).

Figure 3.2. First case study building, 't Centrum [125].

2.2. Case Study 2: Green Office Building

The second case study examines the Green Office Building, which was analyzed alongside `t Centrum to validate the disassembly potential indicator using the expert system (DeCon) a tool developed as part of this Ph.D. research within the multi-indicator framework. This case study was presented in a published article, corresponding to Chapter 04.

Green Office is an office building located in Givisiez, Switzerland. Designed by Lutz Architects [129] as an environmentally optimal building with a net-positive impact, it was constructed in 2005 by Vonlanthen Holzbau AG [130]. As a sustainable office building, it provides commercial spaces for companies specializing in sustainable development. The three-story structure covers a total area of 5,391 square meters and holds the distinction of being the first MINERGIE-P-ECO-certified building in Switzerland [131]. The building was designed with minimal energy consumption in mind, not only during its operational phase but also throughout construction by selecting materials with low embodied energy. Each construction material was analyzed and chosen based on its environmental impact. In principle, only ecologically friendly materials were used, including untreated wood for the facade, natural interior coatings, thermal insulation made from waste paper, and entirely natural wood frames. The overall environmental budget of the building is highly positive (see Figure 3.3.).

Figure 3.3. Second case study, the Green Office building [129]

2.3. Case Study 3: ABN AMRO Circl Pavilion

The third case study is ABN AMRO Circl Pavilion, located in Amsterdam, the Netherlands, which was used to validate the comprehensive building circularity evauation framework (BCEF). This case study was documented in a published article, corresponding to Chapter 05 of this Ph.D. research.

The ABN AMRO Circl Pavilion [132] is a 3,350 m^2 project developed by ABN AMRO Investment Bank [133], adjacent to its headquarters in Amsterdam. As one of the earliest examples of circular economy-inspired buildings, the pavilion is situated at Gustav Mahlerplein in Zuidas, near Zuid Station, directly opposite the main ABN AMRO building. Designed by de Architekten Cie [134] and constructed by Royal BAM Group [135], the building was completed in 2017. The project prioritized the use of recycled materials and significantly reduced embodied carbon emissions during construction. Notably, Circl Pavilion deviated from conventional banking architecture by eliminating typical materials such as marble flooring and complex glass and steel components. This strategy reduced material consumption by approximately one-third (2,425 tons) compared to initial plans [136]. Furthermore, all building materials, components, and elements were digitally recorded in a “Digital Twin” known as LLMNT [137]. The building also integrates renewable energy sources, including solar panels installed on its roof, to minimize greenhouse gas emissions during the operational phase (Module B6). This case study is of particular significance in this Ph.D. research, as it underwent practical evaluation through close monitoring of the deconstruction process. Initially, the building was designed with a minimum lifespan of 20 years. However, due to the sale of the land by ABN AMRO bank to a new investor, the building was dismantled after just seven years to allow for the construction of a 20-story wooden building on the same site. The deconstruction process was originally scheduled to take eight months, but on-site monitoring revealed three major challenges that extended the process to 14 months. These challenges, discussed in Chapter 05, included difficulty in removing bolts from structural joints, issues related to the concrete basement structure, and hydrostatic pressure from groundwater during deconstruction (see Figure 3.4.).

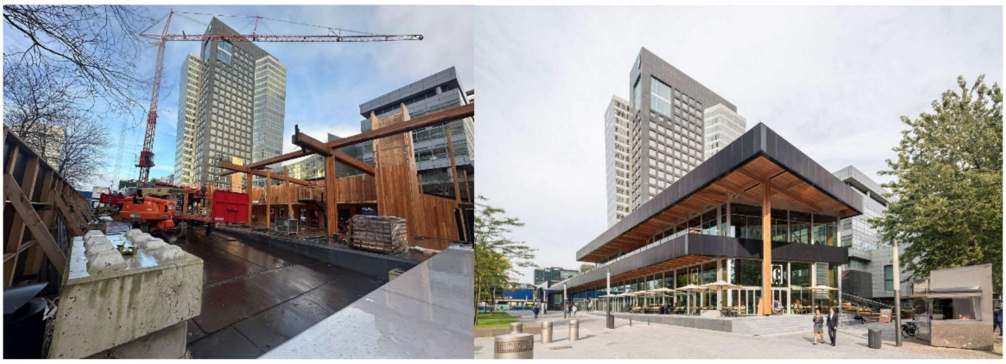


Figure 3.4. Third case study, ABN AMRO Circl pavilion [134]

3. Inventory and inspection campaign

Table 4.1. lists the breakdown of the primary material groups based on their weights for each building. These quantities of material were used in the evaluation process for each indicator. Figure 3.5. illustrates the weight share of each material in the building.

Table 4.1. Breakdown of primary material groups based on their weight for each building.

Building Material Category	`t Centrum		Green Office		Circl Pavilion	
	Amount [kg]	Share [%]	Amount [kg]	Share [%]	Amount [kg]	Share [%]
Timber	216,585	49.08	144,241	13.50	912,458	14.13
Steel	4,800	1.09	13,458	1.26	173,741	2.69
Galvanized steel	2,210	0.50	×	×	7,679	0.12
Concrete	135,000	30.59	788,650	73.84	5,245,440	81.23
Gypsum	5,352	1.21	31,545	2.95	×	×
Carton grey boards	8,500	1.93	×	×	×	×
Aluminium	2,000	0.45	×	×	3,900	0.06
Glass (partitions)	4,500	1.02	5,670	0.53	5,500	0.09
Glass (windows & doors)	31,352	7.10	3,247	0.30	72,000	1.12
Wall insulation	5,700	1.29	50,895	4.76	×	×
Floor insulation	3,000	0.68	13,896	1.30	7,400	0.11
Roof insulation (Pavatex)	820	0.19	×	×	×	×
Roof insulation (Steico)	6,200	1.41	4200	0.39	9,000	0.14
Services and cables (copper, plastic, etc.)	9500	2.15	6500	0.61	13,200	0.20
Solar panels	5,800	1.31	5,916	0.55	7,540	0.12

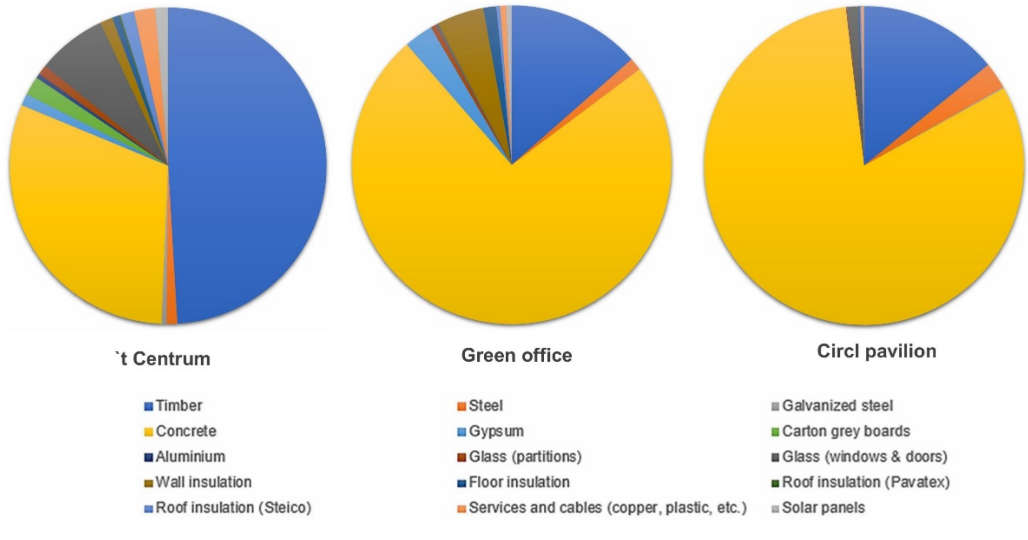
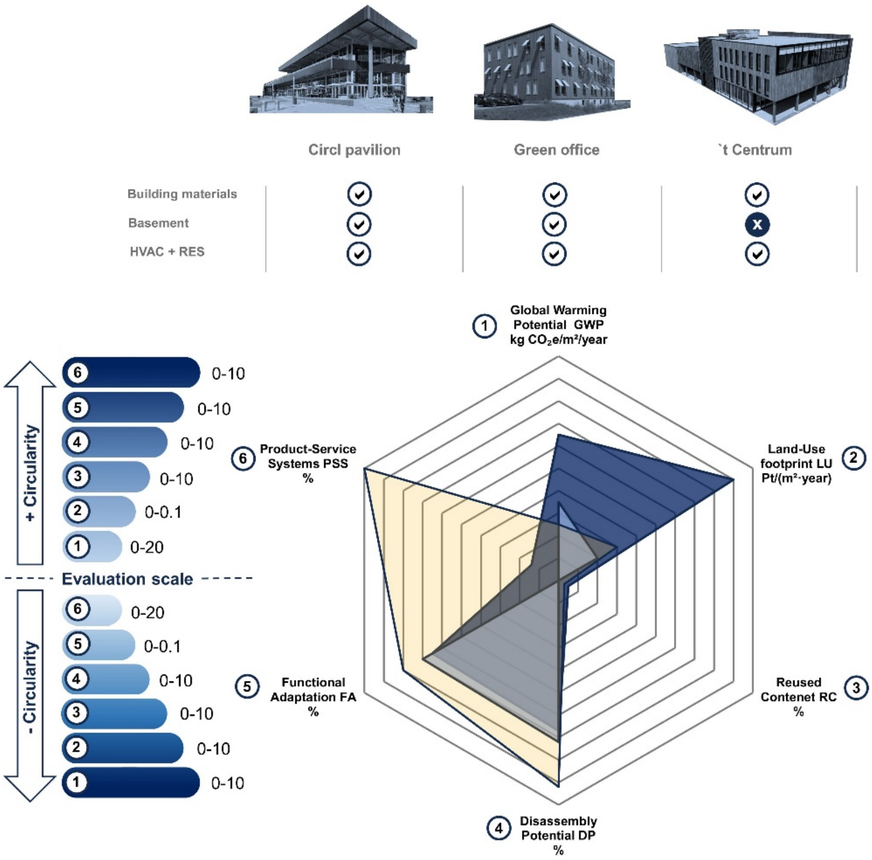


Figure 3.5. Weight share of materials in each building.

4. Results

Through a comprehensive evaluation process, Figure 3.6. visually represents the Building Circularity Evaluation Framework (BCEF), offering a radar chart comparison of three buildings based on key performance indicators. This radar chart elucidates the varying outcomes influenced by project size, material quantities, and construction techniques employed across the three buildings. Notably, higher values in indicators such as disassembly potential, reused content, functional adaptability, and Product-Service Systems (PSS), coupled with lower Global Warming Potential (GWP) and land-use footprint (LU), correspond to a higher degree of building circularity, and vice versa. The evaluation scale further facilitates the interpretation of the radar chart.



	Circl pavilion	Green office	`t Centrum
BCEF index	**57%**	**59%**	**76%**

Figure 3.6. BCEFs radar shows the circularity of the three case studies.

The analysis indicates that the `t Centrum building outperforms the Green Office and ABN AMRO Circl Pavilion, respectively. This superiority is attributed to material quantities, environmental impact, and construction techniques. Specifically, the `t Centrum building achieved up to 76% on the BCEF index, while the Green Office and ABN AMRO Circl Pavilion scored 59% and 57%, respectively, as detailed below:

- **Global Warming Potential (GWP):** A significant factor influencing these results is the quantity of concrete and the type of foundation technique employed in each building. The `t Centrum building utilized innovative separate concrete blocks with the URBCON foundation technique, producing concrete foundations from slag provided by ResourceFull [138]. In total, 22,500 kg of secondary raw materials were used, resulting in a reduction of 13,000 kg of CO_2 emissions compared to traditional foundations. In contrast, the Green Office incorporated a substantial amount of concrete in the ground floor construction, with a significant portion situated underground due to the land slope. This concrete is inaccessible or irretrievable without complete demolition, constituting a design flaw when aiming for disassemblable buildings. Similarly, the ABN AMRO Circl Pavilion's foundation type significantly impacted its circularity outcome, according to the BCEF index. Extensive concrete use in the basement increased greenhouse gas emissions.

- **Land-Use footprint (LU):** ABN AMRO Circl Pavilion scored a footprint of 0.09 Pt/(m²·year). In comparison, `t Centrum and Green Office scored a footprint of 0.03 and 0.02 Pt/(m²·year), respectively. This analysis underscores the substantial differences among the three buildings, highlighting the progressive reduction in land-use impacts achieved by lowering material quantities relative to the building area used.
- **Reused Content:** Both the `t Centrum and Green Office buildings were constructed from virgin materials that are reusable, except for some wooden elements in the `t Centrum's facade, sourced from Hangar 26 in the Port of Antwerp post-dismantling, constituting 3% of the reused content. The ABN AMRO Circl Pavilion features reused materials such as insulation, glass partitions, cable trays, and others detailed in Chapter 05.
- **Disassemblability:** According to results obtained using the expert system (DeCon) [120] developed in Chapter 04, the `t Centrum building achieved a disassembly potential of up to 92%, including the disassembly of concrete foundation blocks. In contrast, the Green Office and ABN AMRO Circl Pavilion achieved disassembly potentials of 72% and 67%, respectively. This disparity stems from the non-disassemblable concrete in the Green Office and Circl Pavilion, necessitating destruction at the end of the building's life. Additionally, disassembly barriers in some Green Office connections were addressed in Chapter 4, and similar issues in the ABN AMRO Circl Pavilion were observed during disassembly monitoring, as detailed in Chapter 05.
- **Functional Adaptability:** This indicator was assessed per the principles and guidelines outlined in ISO 20887:2020 [124]. Although all three buildings are generally designed according to Design for Adaptability (DfA) principles, the Green Office and ABN AMRO Circl Pavilion exhibited lower adaptability scores of 70% and 65%, respectively. This is attributed to the use of massive concrete structures in basement construction. The absence of plans to dismantle internal concrete walls renders adaptation or modification technically unfeasible and economically impractical. This section of the building exemplifies construction practices misaligned with circular economy principles. Conversely, the `t Centrum building achieved an overall adaptability score of 75%, higher than that of the Green Office and Circl Pavilion. This improvement is due to the disassemblable nature of all utilized products and components, enhancing the building's functional adaptability and expansion capacity. The `t Centrum building recorded versatility and convertibility scores of 80%, owing to open and flexible spaces supporting functional adaptability. The Green Office and ABN AMRO Circl Pavilion scored 70% and 65%, respectively, in these indicators, due to non-disassemblable internal concrete walls at the basement level. The `t Centrum building demonstrated a vertical expansion potential of 80%, allowing for the addition of one or two extra floors without substantial modifications to the building's foundations. The Green Office and ABN AMRO Circl

Pavilion scored 60% and 70%, respectively, on the vertical expansion index. Neither the Green Office nor the ABN AMRO Circl Pavilion achieved significant horizontal expansion results, both recording 0%. This is due to the absence of additional spaces available for future expansion, as the buildings were constructed within the plot's boundary. In contrast, the `t Centrum building achieved an 80% horizontal expansion rate, owing to additional spaces available for future expansion as planned.

- **Product-Service Systems (PSS):** The implemented services in the building as a Product-Service System (PSS) were inventoried and evaluated according to the optimal reference case adopted in this Ph.D. research, the `t Centrum building, which includes all categories of building service systems (PSS) as detailed in Chapter 05. According to the results, the `t Centrum building scored full marks for utilizing all categories of Product-Service System (PSS) (Furniture, System, Partition & Finish, Shell, and Core), regardless of their number and quantities. The ABN AMRO Circl Pavilion was rated at 14% on the BCEF radar. The Green Office did not score any notable points due to the absence of a Product-Service System (PSS). This modest result reflects both the emerging state of the PSS scale and the inherent challenges in evaluating circularity within complex systems.

5. Conclusion

Through the application of the Building Circularity Evaluation Framework (BCEF) and the analysis of six key performance indicators across the three evaluated buildings, as illustrated in Figure 3.6., it was determined that the Green Office and ABN AMRO Circl Pavilion exhibited the lowest circularity scores compared to `t Centrum. This discrepancy is primarily attributed to the extensive use of concrete in the basement levels of these buildings, which significantly contributes to high greenhouse gas emissions and negatively impacts the land-use footprint index.

Furthermore, the Green Office and ABN AMRO Circl Pavilion demonstrated lower scores in both disassembly potential and functional adaptability compared to `t Centrum. These results highlight the influence of material selection and construction techniques on building circularity. The reduced material consumption and the integration of prefabricated components designed for disassembly substantially enhanced the circularity index, as evidenced by the superior performance of the `t Centrum building.

The findings further confirmed that the utilization of materials and components with extended lifespans in building services and energy systems positively impacts circularity. This is achieved by minimizing the frequency of component replacements throughout the building’s lifecycle and increasing the potential for reuse.

Additionally, the evaluation of three building design and material selection strategies indicated that prioritizing the design and use of easily disassembled and reusable materials leads to a higher circularity index. These insights emphasize the importance of integrating circular economy principles into architectural design to enhance sustainability and reduce environmental impact.

Discussion

4. Discussion

The findings of Chapters 01 to 06 have been detailed in each publication. This section further discusses the findings, the connections between the chapters, and their implications. Figure 4.1. illustrates the connections between the various chapters, highlighting the interrelatedness of the topics covered.

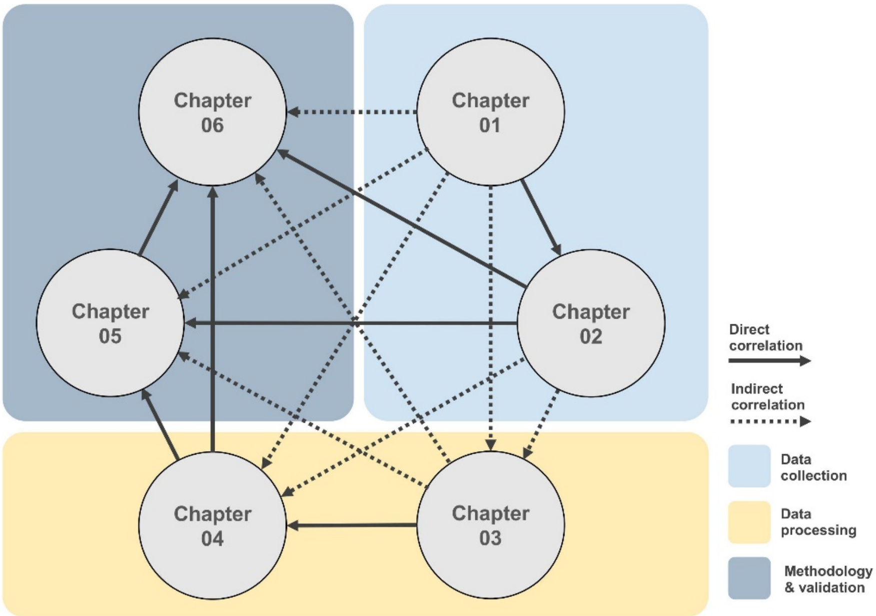


Figure 4.1. Connections among the chapters of the thesis.

Chapter 01 establishes the policy and regulatory foundations for circular construction by analyzing how five leading EU member states; Denmark, Finland, France, the Netherlands, and Sweden; integrate carbon footprint reduction and circular economy principles into their building policies. The systematic review highlights how progressive regulatory frameworks, such as mandatory life-cycle carbon assessments and circularity requirements, create incentives for sustainable building practices. The key takeaway from this chapter is that policy-driven interventions have a significant influence on material choices, construction practices, and waste reduction strategies. By establishing key performance indicators (KPIs) based on existing EU policies, the chapter provides a crucial reference for developing the BCEF framework in subsequent chapters. The alignment between carbon neutrality and building circularity forms a critical foundation for assessing disassembly potential, material reuse, and design flexibility, which are explored in subsequent chapters. The policy analysis supports circularity targets; however, if set prematurely or designed too rigidly, they may lead to the lock-in of sub-optimal technologies, the narrowing of indicator sets, or the displacement of impacts across geographies or life-cycle stages. To mitigate these risks, outcome-based and technology-neutral targets should be adopted, periodic reviews or sunset clauses should be incorporated, and ex ante and ex post impact assessments should be mandated. In this way, unintended consequences can be identified and policy coherence across waste and energy domains can be maintained. This approach is consistent with EU Better Regulation guidance and OECD recommendations on circular-economy policy design [139], [140]. This chapter is directly connected to the evaluation framework BCEF through:

- Identifies regulatory benchmarks for circularity assessment.
- Links carbon neutrality goals to circular building strategies.
- Establishes KPIs that inform the development of the BCEF framework.

Chapter 02 builds on Chapter 1 by providing an empirical analysis of how material selection and structural design impact carbon footprint and circularity potential. Through a parametric life cycle impact assessment (LCIA), various structural systems; namely, timber, steel, concrete, and hybrid; are evaluated for their environmental impact and adaptability. The calculations in this chapter are based on a 20-year calculation period, which is the planned service life of the building. In addition to performing calculations according to the European standard EN 15978 [26], which excludes biogenic carbon and module D from the results and considers them beyond the building LCIA, the results in this chapter are presented with and without biogenic and module for comparison purposes. This comprehensive analytical approach was adopted because the timber used in construction is sourced from sustainably managed forests, and the majority of building components are expected to undergo reuse at regular five-year intervals throughout the 20-year experimental period. A major finding of this chapter is that timber and hybrid systems demonstrate superior carbon reduction potential, supporting circular construction goals. The parametric methodology enables real-time performance optimization, allowing for a data-driven approach to selecting materials that align with both sustainability and disassembly potential. This chapter is integral to the BCEF framework as it introduces quantitative methods for evaluating material circularity. It bridges the gap between policy-driven circularity goals (Chapter 1) and technical assessment methods (Chapters 3 and 4), ensuring that regulatory mandates translate into practical design solutions. This chapter is directly connected to the evaluation framework BCEF through:

- Establishes material performance metrics for BCEF.
- Demonstrates how parametric modeling can optimize circularity indicators.
- Provides empirical support for the disassembly and reuse strategies discussed in later chapters.

Chapter 03 introduces the concept of Design for Disassembly (DfD) as a core principle of circular construction. It systematically reviews existing disassembly assessment methods, identifying key metrics such as connection reversibility, modularity, and ease of component separation. The study finds that current disassembly evaluation tools lack standardization, making it difficult to quantify and compare circularity potential across different buildings. To address this gap, the chapter proposes a set of disassembly criteria, which later serve as core indicators in the BCEF framework. By linking disassembly potential to material selection and construction methods (as explored in Chapter 02), this chapter provides a scientific basis for assessing end-of-life material recovery. It also lays the groundwork for decision-support tools, which are further developed in Chapter 04. This chapter is directly connected to the evaluation framework BCEF through:

- Defines standardized disassembly metrics for BCEF.
- Establishes quantitative methods for evaluating the feasibility of building deconstruction.
- Bridges material selection (Chapter 2) with disassembly optimization (Chapter 4).

Chapter 04 takes the disassembly concepts from Chapter 3 and operationalizes them into a decision-support system for evaluating building disassembly potential. The expert system classifies over 2,500 structural connections, assessing dismantling feasibility through standardized inspections. A key contribution of this chapter is the integration of statistical analysis to categorize disassembly barriers. The study identifies the most critical factors that influence reusability and material recovery, providing practical guidelines for architects, engineers, and demolition teams. This chapter enhances the BCEF framework by offering a practical tool for quantifying circularity in real-world applications. By integrating expert-driven assessments, the BCEF framework ensures its applicability beyond theoretical models, thereby supporting its industry adoption. This chapter is directly connected to the evaluation framework BCEF through:

- Translates disassembly theory (Chapter 3) into practical evaluation tools.
- Establishes connection classification systems to enhance BCEF's assessment accuracy.
- Provides decision-support mechanisms for optimizing material recovery.

Chapter 05 consolidates insights from the previous chapters into the Building Circularity Evaluation Framework (BCEF). BCEF is a multi-indicator tool that evaluates building circularity using six core metrics:

- Global Warming Potential (GWP) – Tracks embodied and operational carbon emissions.
- Reused Content (RC) – Measures the percentage of reclaimed materials.
- Land-use footprint (LU) – Assesses the impact on ecosystems.
- Disassembly Potential (DP) – Quantifies the feasibility of component reuse.
- Functional Adaptability (FA) – Evaluates long-term building flexibility.
- Product-Service Systems (PSS) – Assesses integration of service-based construction models.

The framework was validated through a case study of the ABN AMRO Circl Pavilion in Amsterdam, demonstrating its applicability for industry professionals. The sensitivity analysis further refines BCEF, ensuring reliability and robustness. BCEF is the culmination of the thesis, integrating policy analysis (Chapter 1), material optimization (Chapter 2), disassembly criteria (Chapter 3), and expert system evaluation (Chapter 4) into a comprehensive assessment tool. This chapter is directly connected to the evaluation framework BCEF through:

- Synthesizes insights from all previous chapters into a unified framework.
- Provides a standardized approach for measuring building circularity.
- Demonstrates practical applicability through case studies.

Chapter 6 plays a crucial role in this Ph.D. research by translating the theoretical and methodological foundation established in previous chapters into practical application. This chapter focuses on the implementation and validation of the BCEF framework through three carefully selected case studies: ’t Centrum Building (Belgium), Green Office Building (Switzerland), and ABN AMRO Circl Pavilion (Netherlands). By applying the BCEF indicators; Global Warming Potential (GWP), Land-Use footprint (LU), Reused Content (RC), Disassembly Potential (DP), Functional Adaptation (FA), and Product-Service Systems (PSS); this chapter provides empirical evidence of the framework’s applicability and reliability in assessing building circularity. The chapter's main contribution lies in its ability to demonstrate the practical relevance of BCEF by quantitatively evaluating circularity performance across different construction methodologies, material choices, and design principles. The calculations in this chapter were made in accordance with the EU Taxonomy [112], and the service life of the buildings was assumed to be 50 years. Findings indicate that ’t Centrum outperforms the other case studies in terms of disassembly potential, material reuse, and adaptability, due to its modular construction and reliance on dry assembly techniques. In contrast, the extensive use of concrete in the Green Office and ABN AMRO Circl Pavilion negatively impacts their circularity scores, particularly regarding carbon footprint and land-use impact.

This chapter is a critical extension of Chapter 5, where BCEF was formulated, and it serves as the practical validation of the entire research framework. It directly builds upon Chapter 1’s policy analysis by assessing compliance with emerging circular economy standards, and it integrates insights from Chapter 2’s parametric analysis by evaluating the impact of material choices on life-cycle sustainability. Moreover, the contributions of Chapter 3 and Chapter 4 to disassembly criteria and expert evaluation systems are applied here to measure disassembly potential and functional adaptability, ensuring that BCEF is robust and adaptable across different building types. This chapter is directly connected to the evaluation framework BCEF and the overall Ph.D. research through:

- Empirical validation of BCEF through real-world case studies.
- Reinforces policy insights (Chapter 1) by aligning BCEF with EU circular economy regulations.
- Applies parametric analysis (Chapter 2) to assess material impacts on circularity.
- Uses disassembly criteria and expert systems (Chapters 3 and 4) to evaluate building adaptability.
- Finalizes BCEF’s development by demonstrating its effectiveness in practical applications.

Thus, Chapter 6 completes the thesis by confirming the feasibility and industry applicability of BCEF, ensuring that it can serve as a decision-support tool for architects, engineers, and policymakers aiming to implement circular construction principles.

Finally, the six chapters of this thesis are deeply interconnected, each contributing a specific dimension to the development of BCEF.

- Chapter 01 provides the regulatory context.
- Chapter 02 introduces parametric optimization for circular materials.
- Chapter 03 defines quantitative disassembly criteria.
- Chapter 04 develops an expert system for practical evaluation.
- Chapter 05 integrates these elements into a holistic assessment tool.
- Chapter 06 implements the BCEF on three case studies.

Here, it is necessary to point out that the HVAC calculation and integration refer to "passive energy storage capacity," which denotes passive thermal storage within the building fabric (thermal mass). In ISO 52016-1 [141], areal heat capacity is an explicit input, so high-mass assemblies (e.g., concrete) are modeled with greater effective heat capacity than light assemblies (e.g., timber); thermal mass mainly shifts loads and can modestly reduce annual heating/cooling while lowering peaks, depending on climate, internal gains, and control (e.g., night ventilation/precooling). Accordingly, our modelling (i) assigns mass-consistent heat-capacity values in the ISO 52016-1 setup, (ii) holds envelope U-values constant across variants to isolate mass effects, and (iii) reports any change in B6 (operational energy) and peak loads [142].

HVAC replacements beyond 50 years (sensitivity). Replacements are counted in B4 using reference service lives from ISO 15686-8 and the ASHRAE Service Life Database. If the reference study period (RSP) is extended from 50 to 75 years, equipment with RSL = 20 years increases from 2 to 3 replacements (≈ +50% B4 for that item), while B6 scales with the longer RSP; results are normalized back to per m^2·year for comparability. Conclusions remain unchanged, but the embodied share from HVAC replacements rises in proportion to RSP [143], [144].

Together, these contributions bridge policy, technical assessment, and practical implementation, making BCEF a scientifically rigorous and industry-applicable framework. This research significantly advances the field of circular construction by providing a standardized, multi-criteria framework for evaluating and enhancing the circularity of buildings.

As shown in Table 4.1, BCEF is a design-stage evaluation framework. It preserves Level(s)/EN 15978-consistent GWP reporting while adding operational circularity indicators; reused content (RC), disassembly potential (DP), functional adaptability (FA), and product–service systems (PSS); to support rapid, evidence-based option ranking in concept and schematic design. BCEF can (i) plug into GRO as a quantification layer at decision gates, (ii) use or cross-check with TOTEM when detailed LCA comparisons are required, (iii) generate evidence that later supports BREEAM/LEED credits, and (iv) exchange BoM/passport fields with Madaster when projects maintain a materials registry. and (v) complement CAALA by enriching its real-time LCA outputs with standardized circularity KPIs.

Table 4.1. Comparison of the principal European references, along with the position and the complementary role of BCEF in the early design stage.

Framework, Tool, Platform	Core purpose & scope	Treatment of LCA / circularity	How BCEF adds
EU Level(s) v1.2, 2020 EU	Common EU reporting framework with macro-objectives and indicators for building sustainability.	Indicator 1.2 requires whole-life GWP aligned to EN 15978/EN 15804 across A–C (+D as applicable).	Retains Level(s)-consistent GWP, and adds early-design circularity KPIs (RC, DP, FA, PSS) for rapid option ranking.
GRO v2025 Belgium	Public guide with project-phase criteria (Analysis–Concept–Design) including a Circular Building theme.	Actionable guidance and checklists for circular practice; not a quantitative early-design method.	Serves as a quantification layer at GRO decision gates (BCEF KPIs + quick LCA feedback).
TOTEM v2021 Belgium	National building LCA tool to compare design options using a Belgian dataset.	Computes life-cycle impacts for elements and whole buildings; supports option comparison in design.	BCEF keeps EN 15978-consistent GWP and can be cross-checked in detail with TOTEM; BCEF adds unified circularity KPIs at concept stage.
BREEAM v6.0, 2019 UK	Third-party certification with credit structure.	Mat 01 – Building LCA using recognised tools and EPDs; evidence for scoring.	BCEF generates early evidence and extends beyond Mat 01 by explicitly scoring reuse, disassembly, adaptability, PSS alongside GWP.
LEED v4/4.1, 2019/2020 USA	Third-party certification (MR credits).	MR: Building Life-Cycle Impact Reduction (incl. whole-building LCA option; EU ACP available).	BCEF provides an architect-friendly dashboard to compare concepts and track RC/DP/FA/PSS that complement LEED documentation.
Madaster v2023 Netherlands	Materials cadastre / material passports from BIM/BoQ with circularity & residual-value fields.	Digital passports and inventories to enable reuse and data compliance; not an evaluation method.	BCEF can consume/export passport fields (BoM, RC) while supplying the early-design evaluation Madaster lacks.
CAALA v2022 **Germany**	Early-stage building LCA tool providing real-time feedback on energy, carbon, and costs through simplified parametric modelling.	Uses generalized datasets to estimate life-cycle impacts during preliminary design; supports option comparison but lacks detailed circularity indicators.	BCEF complements CAALA by adding standardized circularity KPIs (RC, DP, FA, PSS) and project-specific scoring. It strengthens CAALA's exploratory use with quantifiable circularity evidence and compatibility with certification/reporting systems.

Conclusions

5. Conclusions

This Ph.D. thesis has systematically explored the evaluation of building circularity through a comprehensive framework, addressing a critical gap in sustainable construction practices. By integrating established sustainability metrics, life cycle assessment methodologies, and emerging principles of the circular economy, this thesis has developed a robust Building Circularity Evaluation Framework (BCEF). This framework offers a structured approach for evaluating the circularity potential of newly constructed office buildings, ensuring alignment with international standards, such as CEN/TC 350 [145] and ISO 20887 [124]. Through an extensive review of existing literature, empirical validation using case studies, and a systematic application of key performance indicators (KPIs), this research advances the knowledge necessary for transitioning to circular construction practices.

The findings demonstrate that integrating circularity principles at the early design stage significantly enhances resource efficiency, minimizes embodied carbon emissions, and extends the functional lifespan of buildings. Key evaluation indicators; such as global warming potential, land-use footprint, disassembly potential, and reused content; have been systematically quantified, providing measurable insights into circular construction performance. The research highlights that adaptable design, dry reversible connections, and modular construction techniques contribute to higher circularity scores, reinforcing the necessity for policy interventions to standardize and incentivize these practices.

In conclusion, this Ph.D. underscores the urgent need for a paradigm shift in the construction industry toward circularity-driven design and evaluation methodologies. The BCEF framework serves as a foundational tool for policymakers, designers, and sustainability practitioners, offering a scientifically validated approach to measuring and enhancing circularity in building projects. By fostering interdisciplinary collaboration and advancing regulatory frameworks, the insights from this research can contribute to a more sustainable and resilient built environment, aligning with global climate goals and resource conservation strategies.

5.1. Revisiting the research sub-questions

This Ph.D. thesis is structured into six chapters, each corresponding to a peer-reviewed journal article or conference paper, with the exception of Chapter 6, which remains unpublished and focuses on applying the developed framework to various case studies. Each chapter is designed to address a specific research sub-question, contributing to the overarching research inquiry. Collectively, these chapters provide a comprehensive and systematic response to the main research question, ensuring a structured progression of findings. The organization of the dissertation into six distinct chapters enables a coherent presentation of the research while also allowing readers to engage with individual studies in a targeted manner. This structure not only enhances clarity but also facilitates accessibility for researchers interested in specific aspects of the research.

SQ1: *How do carbon neutrality and circularity principles integrate into the building regulations of leading Northwestern European states, and what policy measures are most effective in promoting sustainable construction practices?* ***(Chapter 01)***

The findings derived from Chapter 01 provide a comprehensive analysis of how carbon neutrality and circularity principles are embedded within the regulatory frameworks of leading Northwestern European states. This investigation was conducted through a systematic literature review and expert interviews, focusing on five key nations; Denmark, Finland, France, the Netherlands, and Sweden; recognized for their leadership in sustainable building policies. The study highlights the role of legislative measures, performance metrics, and target thresholds in shaping the transition towards a more circular and low-carbon built environment.

The results indicate that while carbon neutrality is increasingly incorporated into building regulations across the EU, the integration of circularity principles remains fragmented. Denmark and Finland emerge as frontrunners in this domain, implementing stringent life cycle impact assessment (LCIA) requirements and promoting environmental product declarations (EPDs) as a prerequisite for building permits. France's RE2020 regulation sets ambitious operational and embodied carbon thresholds, whereas the Netherlands mandates the use of a Building Environmental Performance Declaration (DBED) for new constructions. Sweden, while emphasizing carbon neutrality, also integrates circularity principles through regulatory incentives for material reuse and deconstruction strategies.

Key policy measures identified as effective in fostering sustainable construction practices include mandatory LCIA-based assessments, carbon emission thresholds for building materials, and public procurement policies that prioritize circular and bio-based materials. However, the study reveals a critical gap in harmonizing carbon reduction strategies with circularity objectives. While some nations have successfully coupled these agendas, others maintain separate regulatory pathways, thereby limiting the potential for a fully integrated sustainability framework.

In conclusion, the answer to SQ1 underscores the importance of aligning carbon neutrality and circularity within regulatory frameworks to achieve a truly sustainable construction sector. Future research should focus on developing standardized metrics that bridge these two paradigms, facilitating their widespread adoption across the EU. Additionally, increasing the enforcement of circular economy principles in building codes, alongside carbon reduction mandates, will be essential in ensuring long-term environmental and economic benefits.

SQ2: *How can parametric approaches help to evaluate the environmental impact and the building circularity?* ***(Chapter 02)***

The findings presented in Chapter 02 provide a detailed exploration of how parametric modeling can be utilized to assess the environmental impact of buildings while incorporating circularity principles. Through the application of a parametric approach, this research systematically evaluates different construction materials and design configurations to optimize sustainability performance in the built environment.

The study demonstrates that parametric methods enable rapid assessment of multiple design alternatives by automating life cycle impact assessment (LCIA) calculations. Using tools such as One Click LCA and BIM-integrated workflows, the research tested 21 design variations across 630 iterations to identify the most environmentally efficient solutions. The analysis focused on key performance indicators, including global warming potential, material reuse potential, and adaptability of the construction system. Results indicate that parametric modeling can effectively quantify the environmental trade-offs between various building materials, including timber, steel, concrete, and hybrid construction systems. Timber-based designs emerged as the most sustainable option due to their capacity for biogenic carbon storage and high reuse potential.

Moreover, the study highlights that integrating parametric tools with LCIA methodologies facilitates informed decision-making at the early design stage, allowing architects and engineers to optimize material selection and structural configurations. The findings also emphasize the importance of developing standardized parametric evaluation frameworks to enhance the comparability and reliability of sustainability assessments across different projects.

In conclusion, the response to SQ2 underscores the transformative potential of parametric approaches in advancing environmental impact assessments and circularity evaluations. By enabling a data-driven design process, these methods provide a scalable and adaptable approach to achieving more resource-efficient and sustainable construction practices. Future research should focus on refining parametric models to incorporate real-time data on material flows, demolition scenarios, and reuse pathways, further aligning building design with circular economy objectives.

SQ3: *What are the most effective criteria and methods for evaluating the disassembly potential of buildings to enhance circular construction practices?* ***(Chapter 03)***

The findings from Chapter 03 provide a detailed investigation into the assessment methods and criteria essential for evaluating the disassembly potential of buildings within the framework of circular construction. The study addresses a key gap in current research by systematically reviewing and categorizing existing methodologies that measure the ease of disassembly and the potential for material recovery in building deconstruction.

The analysis highlights that multiple factors, including connection type, component accessibility, structural dependencies, and material composition influence disassembly potential. The research identifies that dry, reversible connections, such as bolted or screwed joints, significantly enhance a building's disassembly potential compared to glued or welded connections, which hinder material reuse. Additionally, modular construction and prefabricated elements demonstrate a higher potential for disassembly due to their standardized design and predictable dismantling sequences.

To provide a robust assessment framework, the study synthesizes existing methodologies, including the Building Circularity Indicator (BCI) and Deconstructability Assessment Score (DAS), as well as emerging parametric modeling techniques. The evaluation criteria are categorized into technical, economic, and environmental dimensions, enabling a holistic assessment of disassembly potential at various levels; component, product, and system. The research also underscores the importance of integrating life cycle impact assessment (LCIA) tools to quantify the environmental benefits of disassembly-based design strategies.

In conclusion, the response to SQ3 establishes that an effective evaluation of disassembly potential must incorporate a combination of qualitative and quantitative criteria, supported by standardized assessment methodologies. The findings advocate for the adoption of policy measures that incentivize design for disassembly (DfD) principles, ensuring that buildings are constructed with future adaptability and resource efficiency in mind. Future research should focus on refining digital tools, such as BIM-integrated assessment models, to enhance the accuracy and scalability of disassembly evaluations, ultimately fostering a more circular built environment.

SQ4: *How can the evaluation of building disassembly potential be enhanced to support circularity and decision-making in the early design and deconstruction stages?* ***(Chapter 04)***

The findings from Chapter 04 present a structured approach to enhancing the evaluation of building disassembly potential, thereby reinforcing circular construction practices and informed decision-making in both early design and deconstruction phases. The study introduces an expert system [120] tailored to assess disassembly potential through standardized inspection methodologies, ensuring that structural components are designed and constructed with future deconstruction and reuse in mind.

A key contribution of this research is the development of a comprehensive framework that integrates technical, environmental, and economic factors into disassembly evaluations. The study identifies critical parameters influencing disassembly, including connection types, accessibility, material composition, and modularity. Through fieldwork and empirical analysis of over 2500 construction connections, the research systematically categorizes disassembly barriers and evaluates their impact on circular construction potential.

The implementation of this expert system in real-world case studies demonstrates its effectiveness in quantifying disassembly potential and guiding stakeholders in selecting design strategies that maximize material recovery. The system employs a decision-support mechanism that utilizes predefined criteria and statistical modeling to assess disassembly feasibility at multiple levels; component, assembly, and structural systems. The research underscores that adopting design-for-disassembly (DfD) principles from the outset significantly enhances the ease of material retrieval at end-of-life, minimizing demolition waste and contributing to a circular economy.

In conclusion, the response to SQ4 establishes that integrating systematic disassembly evaluation tools into the early design stage and pre-demolition assessments is essential for optimizing circularity in the built environment. Future research should focus on refining these assessment methodologies by integrating digital modeling technologies, such as Building Information Modeling (BIM) and Artificial Intelligence (AI)-driven predictive analytics, to further enhance accuracy and scalability in disassembly potential evaluations.

SQ5: *How can a building circularity evaluation framework be utilized to assess and optimize circularity and sustainability in the building sector?* ***(Chapter 05 & Chapter 06)***

The findings presented in Chapters 05 and 06 provide a detailed investigation into the development, validation, and implementation of the Building Circularity Evaluation Framework (BCEF), a comprehensive framework designed to assess and enhance circularity in the construction sector. The framework integrates multiple key performance indicators (KPIs) to evaluate a building's environmental footprint, disassembly potential, material reuse, and adaptability, contributing to the optimization of circular economy principles in the built environment. Chapters 05 and 06 answer to SQ5 as follows:

- Chapter 05 outlines the conceptual foundation of the BCEF, detailing the selection of six core indicators: Global Warming Potential (GWP), Land-Use Footprint (LU), Reused Content (RC), Disassembly Potential (DP), Functional Adaptation (FA), and Product-Service Systems (PSS). These indicators were identified through a systematic literature review, expert consultations, and alignment with established sustainability assessment methodologies such as EN 15978 [26] and ISO 20887 [124]. The framework is designed to address the fragmentation in existing circularity evaluation methods by providing a standardized and quantifiable approach applicable across different building typologies.
- Chapter 06 builds upon this foundation by implementing BCEF in real-world case studies, demonstrating its applicability in evaluating office buildings designed for circularity. The results highlight the effectiveness of the framework in identifying areas where material efficiency, adaptability, and disassembly strategies can be optimized. Case studies of circular buildings, such as the `t Centrum, Green Office, and ABN AMRO Circl Pavilion, illustrate how BCEF facilitates decision-making by quantifying circularity scores and benchmarking sustainability performance. The analysis confirms that modular construction, dry reversible connections, and increased use of reclaimed materials significantly enhance the circularity potential, thereby reducing the overall environmental impact.

In conclusion, the response to SQ5 underscores that the BCEF framework provides a systematic and scientifically validated methodology for assessing and optimizing circularity in the building sector. By integrating multi-criteria assessment tools and digital modeling techniques, BCEF enables policymakers, architects, and sustainability practitioners to make data-driven decisions at both the design and deconstruction stages. Future research should focus on refining the framework by incorporating artificial intelligence-driven analytics, expanding its application to additional building types, and enhancing regulatory integration to promote widespread adoption of circular construction principles.

5.2. Revisiting the main research question

MRQ: *How can a Building Circularity Evaluation Framework be developed and validated to guide early design stage evaluation of buildings from a life-cycle thinking approach?*

The main research question has been addressed through the systematic development of a Building Circularity Evaluation Framework (BCEF), which integrates key sustainability and circularity indicators to assess building construction in its early design stages. This research has been structured into three major parts: Part II Policy and Theoretical Foundation (Chapter 01 and Chapter 02), Part II Disassembly and Circularity Assessment Methods (Chapter 03 and Chapter 04), and Part III Development and Implementation of the BCEF (Chapter 05 and Chapter 06). Each phase contributes distinct insights and methodologies that collectively establish a robust framework for evaluating circular construction from a life cycle perspective.

- **Policy and Theoretical Foundation:** Part I (Chapters 01 and 02) focuses on the regulatory and parametric foundations for circular building construction. Chapter 01 examines the extent to which carbon neutrality and circularity principles are incorporated into the building regulations of leading Northwestern European states, highlighting the role of policy measures in promoting circularity in construction. This analysis confirms that while carbon-focused regulations are well-integrated, circularity remains inconsistently applied, necessitating further policy alignment to ensure consistent application.
  Chapter 02 explores parametric modeling approaches to assess building circularity and environmental impacts. The findings demonstrate that parametric design tools, when integrated with Life Cycle Impact Assessment (LCIA) methodologies, enable the optimization of material selection and building configurations for enhanced circular performance. The study also establishes that key variables, such as material reuse potential, construction typology, and adaptability, play a decisive role in determining a building's environmental footprint.
- **Disassembly and Circularity Assessment Methods:** Part II (Chapters 03 and 04) provides methodological advancements for evaluating a building's disassembly potential; a critical component of circular design. Chapter 03 identifies the most effective criteria and methods for assessing disassembly potential, emphasizing connection types, accessibility, modularity, and material composition. This research introduces a structured methodology for quantifying disassembly feasibility, ensuring that circularity metrics are integrated into early design decision-making.
  Building on these findings, Chapter 04 presents an expert system for evaluating disassembly potential. This system classifies building connections based on their reversibility and ease of deconstruction, offering a structured inspection framework for architects and engineers. The expert system is validated through an extensive dataset of construction connections, providing practical insights into optimizing building designs for material reuse and adaptation.
- **Development and Implementation of the BCEF:** Part III (Chapters 05 and 06) introduces and applies the Building Circularity Evaluation Framework (BCEF) as a comprehensive framework for assessing circular construction. Chapter 05 details the development of the BCEF, identifying six key performance indicators: Global Warming Potential (GWP), Land-Use footprint (LU), Reused Content (RC), Disassembly Potential (DP), Functional Adaptation (FA), and Product-

Service Systems (PSS). These indicators provide a standardized means of quantifying a building's circular performance.
Chapter 06 extends the BCEF by implementing it in real-world case studies. The analysis confirms that modular construction, reversible connections, and adaptable spaces significantly enhance circularity potential. The results validate the BCEF's applicability in guiding design teams towards data-driven decisions that optimize material efficiency, reduce environmental impact, and align with circular economy principles.

The response to the main research question establishes that circular building construction can be effectively evaluated in early design stages through a life cycle thinking approach that integrates policy, parametric modeling, disassembly assessments, and circularity evaluation frameworks. The BCEF serves as a comprehensive and scientifically validated framework for assessing circularity across different building typologies, providing valuable insights for architects, policymakers, and sustainability practitioners.

5.3. Thesis contribution

This thesis aims to fill specific knowledge gaps between academic knowledge, industry application, and policy formulation. The BCEF provides a scientifically validated framework for evaluating circular construction, enabling architects, policymakers, construction professionals, and sustainability consultants to make data-driven decisions that enhance resource efficiency and environmental performance. This thesis makes significant contributions to the field of circular building construction by developing a comprehensive Building Circularity Evaluation Framework (BCEF) that enables the assessment and optimization of circularity in the early design stages. Significantly contributes. By integrating life cycle thinking, parametric modeling, disassembly assessment, and sustainability metrics, this Ph.D. The thesis provides a structured and scientifically validated approach for evaluating circular construction practices. This thesis solves the three problems faced by architects in the early design stage that were mentioned previously in the introduction: (i) Material quantities; Chapter 02 operationalizes a parametric approach that yields repeatable, rule-based quantity take-offs for construction systems, replacing ad-hoc manual take-offs and enabling rapid scenario testing. This workflow is demonstrated again in the case-study implementation. (ii) Cumbersome LCA at concept stage; Chapters 05–06 consolidate a light-touch early-design LCA within the BCEF; centered on a GWP indicator using EPD-based data structures; so designers can compare options without full specialist software modelling. (iii) Complicated evaluation workflow; The BCEF unifies six KPIs (GWP, land-use footprint, reused content, disassembly potential, functional adaptability, and PSS) and integrates the disassembly expert system from Chapters 03–04 into a single decision-support workflow, which the three case studies validate as usable for option ranking and design feedback in early phases. The key contributions of this thesis are summarized as follows:

- **Advancing Policy and Regulatory Frameworks for Circular Construction:** The thesis provides a comparative analysis of building regulations in leading Northwestern European states, focusing on the integration of carbon neutrality and circularity principles (Chapter 01).

By systematically reviewing policy frameworks in Denmark, Finland, France, the Netherlands, and Sweden, the study identifies best practices and regulatory gaps, offering policy recommendations to align circularity and carbon reduction goals. These findings contribute to a deeper understanding of how regulatory interventions shape the adoption of circular economy principles in the built environment.

- **Development of a Parametric Evaluation Approach for Circularity Assessment:** This thesis introduces an innovative parametric modeling approach to evaluate the environmental impact and circularity potential of buildings (Chapter 02). By integrating Life Cycle Impact Assessment (LCIA) with parametric design tools, the study quantifies key sustainability metrics, including global warming potential, material reuse potential, and construction system adaptability. The study demonstrates how parametric analysis enables rapid optimization of material selection and structural configurations, ensuring early-stage decision-making that supports circularity objectives.
- **Establishing Criteria and Methods for Evaluating Disassembly Potential:** A key contribution of this thesis is the systematic identification and quantification of disassembly potential, a critical factor in circular construction (Chapter 03). Through a hybrid systematic review, the study consolidates disassembly assessment criteria, emphasizing connection types, accessibility, modularity, and material composition. The research develops a standardized methodology for evaluating the ease of deconstruction, providing a foundation for future European standards on design-for-disassembly (DfD) principles.
- **Expert System for Disassembly Potential Evaluation:** Building upon the findings of Chapter 03, this thesis develops an expert system for assessing building disassembly potential (Chapter 04). The system classifies structural connections and evaluates their dismantling feasibility through standardized inspections of over 2,500 construction connections. By employing statistical analysis and decision-support mechanisms, the expert system enhances circular construction practices by facilitating material recovery and reuse strategies. This research provides architects, engineers, and demolition professionals with a decision-support tool for optimizing disassembly-friendly building designs.
- **Formulation and Validation of the Building Circularity Evaluation Framework (BCEF):** The central contribution of this thesis is the development of the BCEF, a robust multi-indicator framework for evaluating circularity in building design (Chapter 05). The framework integrates six key performance indicators (Global Warming Potential (GWP), Land-Use footprint (LU), Reused Content (RC), Disassembly Potential (DP), Functional Adaptation (FA), and Product-Service Systems (PSS)), ensuring a comprehensive and standardized methodology for assessing circular construction. BCEF bridges the gap between theoretical circularity concepts and practical implementation strategies, offering valuable insights for policymakers, sustainability consultants, and design professionals. Where BCEF can (i) plug into GRO as a quantification layer at decision gates, (ii) use or cross-check with TOTEM when detailed LCA comparisons are

required, (iii) generate evidence that later supports BREEAM/LEED credits, and (iv) exchange BoM/passport fields with Madaster when projects maintain a materials registry.

- **Implementation and Validation of BCEF in Real-World Case Studies:** This thesis applies and validates BCEF in real-world building projects, demonstrating its effectiveness in quantifying circularity performance and optimizing sustainability outcomes. Case studies include the 't Centrum Building, Green Office, and ABN AMRO Circl Pavilion, providing empirical evidence of the framework's applicability. Findings confirm that modular construction, reversible connections, and adaptable spaces significantly enhance circularity potential. This thesis establishes BCEF as a standardized framework for benchmarking and improving circular building practices, facilitating its adoption across industry and policy landscapes.

This thesis lays the foundation for a paradigm shift in circular construction assessment, providing a holistic, scalable, and practical evaluation framework for enhancing circular economy principles in the built environment. By integrating policy insights, parametric evaluation, disassembly assessment, and circularity optimization, the findings contribute to academic scholarship, industry practice, and regulatory frameworks, facilitating a transition towards a sustainable and low-carbon built environment.

5.4. Limitations

While this Ph.D. research presents a comprehensive framework for evaluating circular building construction, it is important to acknowledge certain limitations that may have influenced the findings and their broader applicability. The key limitations of this Ph.D. thesis can be summarized as follows:

- **Scope of Regulatory Analysis:** The policy analysis in Chapter 01 focused on five leading Northwestern European states; Denmark, Finland, France, the Netherlands, and Sweden; to evaluate the integration of carbon neutrality and circularity principles in building regulations. While this selection provided valuable insights, it may not fully represent the diversity of regulatory approaches across all EU nations or international contexts. Future studies should expand the geographic scope to include other EU countries, North America, and Asia to ensure a more globally comprehensive regulatory analysis.
- **Parametric Modeling Constraints:** The parametric modeling approach in Chapter 02 enabled quantitative assessment of material choices and design strategies for enhancing circularity. However, several constraints exist:
  - The study relied on predefined parametric rules, which may not fully capture the complexity of real-world construction scenarios.
  - Material reuse and end-of-life strategies were modeled using assumed recovery rates, rather than real-world deconstruction case studies.
  - The framework does not yet integrate real-time data from digital twin technologies or AI-driven optimizations, which could improve model accuracy in future research.

- **Generalizability of Disassembly Assessment Methods:** Chapters 3 and 4 focused on evaluating disassembly potential using standardized criteria, such as connection types, material compositions, and modularity. However, the developed expert system was tested on a limited dataset of 2500 construction connections, primarily from office buildings. While these results provide a strong foundation, they may not be directly transferable to other building typologies, such as high-rise buildings, residential complexes, or industrial facilities.
- **Challenges in Standardizing Circularity Evaluation:** The Building Circularity Evaluation Framework (BCEF), proposed in Chapters 5 and 6, integrates six key performance indicators (KPIs) to assess the circularity potential. However, several limitations were identified in its application:
    - Variability in data availability: The GWP evaluation in BCEF relies on Environmental Product Declarations (EPDs) and Life Cycle Impact Assessment (LCIA) databases, which vary in coverage and accuracy across regions. In the database, certain Environmental Product Declarations (EPDs) are published in accordance with the EN 15804+A2 [27] standard, whereas others adhere to the earlier EN 15804+A1 [146] standard. This coexistence is primarily due to the substantial number of construction material manufacturers who have not yet updated their EPDs to reflect the latest standard in the database. Two significant factors contribute to this scenario. Firstly, existing EPDs have a validity period extending up to five years; thus, manufacturers often wait until the expiration of the current declarations before undertaking updates. Secondly, the financial implications and resource requirements associated with prematurely issuing an updated EPD based on the newer EN 15804+A2 standard further discourage immediate revision.
    - Additionally, the lack of data updates is influenced by limited regulatory and market pressures, as well as insufficient awareness regarding the importance of maintaining up-to-date information. Notably, One Click LCA [111] offers functionality to integrate and analyze results from both standards seamlessly. This platform automatically updates comparative assessments whenever a new or revised EPD for the same product is issued or revised in alignment with the EN 15804+A2 standard, thereby facilitating efficient transitions between EPD versions and ensuring accurate, up-to-date environmental assessments.
    - Lack of uniform benchmarking: Current circularity scoring metrics lack standardized thresholds for what constitutes "high" or "low" circularity performance. This limits comparability between projects.
    - Applicability to building renovations: The BCEF was developed for newly constructed office buildings, and its applicability to renovation projects remains untested.
- **Limited Consideration of Socioeconomic and Market Barriers:** Although this Ph.D. research primarily focuses on technical and environmental aspects, it does not thoroughly examine the economic

feasibility, market readiness, and industry adoption challenges associated with circular building practices. Factors such as cost premiums for circular materials, supply chain disruptions, and resistance to policy changes could significantly impact the scalability of circular construction, requiring further investigation.

- **Case Study Limitations:** The implementation of BCEF in Chapter 06 was tested on a limited number of office building case studies. While these case studies validated the framework's applicability, the study does not account for climatic variations, regional construction practices, or cultural differences that may influence circularity outcomes in different geographic contexts. Expanding the case studies to diverse building types and climates would strengthen the robustness of the findings.
- **Data Constraints and Uncertainty in Future Scenarios:** Certain methodological choices introduce data constraints and uncertainty:
    - Life cycle impact assessments (LCIA) are dependent on assumptions about material degradation, recycling rates, and demolition practices, which may evolve.
    - Future regulatory shifts (e.g., stricter carbon taxation, new circularity mandates) could alter the effectiveness of current circular design strategies.

Despite these limitations, this research provides a foundational framework for evaluating the circular construction of buildings. The framework follows a systematic approach to integrating circular economy principles into the early design stages. Future advancements in data availability, standardization, and regulatory integration will be essential in ensuring the widespread adoption of circular economy principles in the construction sector.

5.5. Suggestions for future work

This Ph.D. thesis presents a comprehensive evaluation framework for circular building construction, with a focus on early design assessment informed by life cycle thinking principles. This thesis introduces the Building Circularity Evaluation Framework (BCEF), validated through multiple case studies, and demonstrates its applicability in assessing the potential for building circularity and sustainability performance. However, like any research, this work has its limitations and opens up avenues for further exploration. Building upon the findings of this Ph.D. thesis, several key areas require further investigation to enhance the applicability, reliability, and scalability of circularity assessment methods, as follows:

- **Expanding the Application of BCEF to Different Building Typologies:** The current research focuses on newly constructed office buildings. Future research should extend BCEF applications to residential, industrial, and mixed-use buildings to test its adaptability across diverse construction types and urban contexts.
- **Integration of Digital Twin Technologies for Real-Time Circularity Assessment:** Digital Twin technology and Artificial Intelligence (AI)-driven analytics could enhance real-time circularity monitoring. Future studies should explore how these technologies can be integrated with

BCEF to improve predictive modeling for material flow tracking, adaptive reuse planning, and deconstruction feasibility assessments.

- **Harmonizing Regulatory Frameworks for Circular Building Design:** The research identifies gaps in regulatory alignment in the Northwestern European states. Further research should analyze policy evolution and develop harmonized regulatory frameworks that incentivize circularity-based building codes, material passports, and Extended Producer Responsibility (EPR) schemes.
- **Developing Economic Feasibility Models for Circular Construction:** One of the major barriers to circularity implementation is economic viability. Future studies should develop cost-benefit models that compare traditional and circular construction approaches, considering material costs, operational savings, and long-term sustainability benefits.
- **Refining Disassembly Assessment Methodologies:** This Ph.D. thesis introduces an expert system for evaluating disassembly potential. Future studies should refine these methodologies by incorporating real-world demolition scenarios, material traceability mechanisms, and building component reuse databases.
- **Advancing Multi-Criteria Decision Analysis for Circularity Optimization:** The BCEF framework currently assesses multiple Key Performance Indicators (KPIs). Future research should enhance its multi-criteria decision analysis capabilities, integrating weighted scoring models, stakeholder preference evaluations, and dynamic performance trade-offs.
- **Exploring the Role of User Behavior and Social Acceptance in Circular Building Adoption:** Circular construction adoption is not solely a technical or regulatory challenge; it also involves stakeholder engagement and market acceptance. Future research should investigate how architects, contractors, and occupants perceive circular design and what incentives can drive behavioral shifts toward sustainable building choices.
- **Incorporating Circular Economy Principles into Building Information Modeling (BIM):** BIM-based workflows should be further developed to embed circularity parameters, allowing for automated material tracking, circularity benchmarking, and end-of-life scenario simulations.

This Ph.D. thesis has laid the groundwork for a structured, scientifically validated approach to evaluating circular building construction. By addressing policy gaps, enhancing assessment methodologies, and integrating digital innovations, the findings contribute to bridging the gap between academic research, industry application, and regulatory frameworks. Future advancements in technology, policy harmonization, and economic modeling will be crucial in ensuring the scalability and adoption of circular economy principles in the construction sector.

References

[1] J. Dsilva, S. Zarmukhambetova, and J. Locke, “Assessment of building materials in the construction sector: A case study using life cycle assessment approach to achieve the circular economy,” *Heliyon*, vol. 9, no. 10, p. e20404, Oct. 2023, doi: 10.1016/j.heliyon.2023.e20404.

[2] “Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast),” European Union. Accessed: Jan. 11, 2025. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2010/31/oj/eng

[3] BRE *et al.*, “Resource efficient use of mixed wastes improving management of construction and demolition waste: final report,” Publications Office of the European Union, Report, Brussels, Belgium, 2017.

[4] J. Tillman Lyle, “Regenerative Design for Sustainable Development | Wiley,” Wiley.com. Accessed: Jan. 11, 2025. [Online]. Available: https://www.wiley.com/en-us/Regenerative+Design+for+Sustainable+Development-p-9780471178439

[5] R. Cole, “Transitioning from Green to Regenerative Design,” *Build. Res. Inf.*, vol. 40, pp. 39–53, Jan. 2012, doi: 10.1080/09613218.2011.610608.

[6] S. Attia, “Towards regenerative and positive impact architecture: A comparison of two net zero energy buildings,” *Sustain. Cities Soc.*, vol. 26, pp. 393–406, Oct. 2016, doi: 10.1016/j.scs.2016.04.017.

[7] W. McDonough and M. Braungart, *Cradle to Cradle: Remaking the Way We Make Things*. 2002. Accessed: Jan. 11, 2025. [Online]. Available: https://mcdonough.com/writings/cradle-cradle-remaking-way-make-things/

[8] W. McDonough and M. Braungart, *The Upcycle: Beyond Sustainability—Designing for Abundance (2013)*. 2013. Accessed: Jan. 11, 2025. [Online]. Available: https://mcdonough.com/writings/the-upcycle/

[9] J. Benyus, *Biomimicry: Innovation Inspired By Nature*. New York, NY: HarperCollins/Perennial, 2002.

[10] K. Van Acker *et al.*, “Circular economy,” 2016, Accessed: Jan. 11, 2025. [Online]. Available: https://repository.uantwerpen.be/link/irua/204192

[11] European Commission, “COM(2011)571 - Roadmap to a Resource Efficient Europe - EU monitor.” Accessed: Jan. 11, 2025. [Online]. Available: https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/visyrzh4x3gh

[12] European Commission, “Annexes to COM(2015)614 - Closing the loop - An EU action plan for the Circular Economy.” Accessed: Jan. 11, 2025. [Online]. Available: https://www.eumonitor.eu/9353000/1/j4nvirkkkr58fyw_j9vvik7m1c3gyxp/vjzpj6v9jiu8

[13] “Germany’s largest wooden hybrid office building: 100% match for Madaster,” Madaster Global. Accessed: Aug. 24, 2025. [Online]. Available: https://madaster.com/inspiration/germany/

[14] “Powerhouse Brattørkaia,” CBE Facade Map. Accessed: Aug. 24, 2025. [Online]. Available: https://facademap.cbe.berkeley.edu/building/powerhouse-brattorkaia/

[15] S. Van Dijk and I. Erbas, “Future direction for effective sustainable design,” 2012, Accessed: Jan. 11, 2025. [Online]. Available: https://repository.tudelft.nl/record/uuid:227bc1b6-4d15-4c88-bad6-4fff34a666a8

[16] K. Molenaar, N. Sobin, D. Gransberg, T. McCuen, S. Korkmaz, and M. Horman, “Sustainable, high performance projects and project delivery methods: A state-of-practice report,” *White Pap. Des.-Build Inst. Am. Charles Pankow Found.*, pp. 1–26, 2009.

[17] S. Altomonte, “Environmental education for sustainable architecture,” *Rev Eur Stud*, vol. 1, p. 12, 2009.

[18] M. Hegger, M. Fuchs, T. Stark, and M. Zeumer, *Energy manual: sustainable architecture*. Walter de Gruyter, 2012. Accessed: Jan. 11, 2025. [Online]. Available: https://books.google.be/books?hl=en&lr=&id=IWPRAAAAQBAJ&oi=fnd&pg=PA6&dq=Energy+Manual:+Sustainable+Architecture&ots=vF4c-QJ6It&sig=n0jRZBoGMZdf7rDI9_4ZmsuuoVs
[19] B. Janssens, "Design Support for Sustainable Building," University of Antwerp, 2015. Accessed: Jan. 11, 2025. [Online]. Available: https://www.researchgate.net/profile/Bart-Janssens-4/publication/311650469_Design_Support_for_Sustainable_Building_-_Guiding-into-action_tools_tailored_to_architect-designers/links/5852673008ae95fd8e1d42e0/Design-Support-for-Sustainable-Building-Guiding-into-action-tools-tailored-to-architect-designers.pdf
[20] S. Attia, E. Gratia, A. De Herde, and J. L. M. Hensen, "Simulation-based decision support tool for early stages of zero-energy building design," *Energy Build.*, vol. 49, pp. 2–15, Jun. 2012, doi: 10.1016/j.enbuild.2012.01.028.
[21] "Construction producer price and construction cost indices overview." Accessed: Aug. 24, 2025. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Construction_producer_price_and_construction_cost_indices_overview
[22] "Shortage of Labour in the Construction industry," FIEC. Accessed: Aug. 24, 2025. [Online]. Available: https://www.fiec.eu/fiec-opinions/position-papers-pl/shortage-labour-construction-industry
[23] ISO, "ISO 14040:2006: Environmental management — Life cycle assessment — Principles and framework." Accessed: Jul. 19, 2021. [Online]. Available: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/74/37456.html
[24] ISO, "ISO 14044:2006: Environmental management — Life cycle assessment — Requirements and guidelines." Accessed: Jul. 19, 2021. [Online]. Available: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/84/38498.html
[25] "ISO 21930:2017: Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services," ISO. Accessed: Oct. 19, 2025. [Online]. Available: https://www.iso.org/standard/61694.html
[26] EN 15978:2011, "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method," iTeh Standards Store. Accessed: Jul. 19, 2021. [Online]. Available: https://standards.iteh.ai/catalog/standards/cen/62c22cef-5666-4719-91f9-c21cb6aa0ab3/en-15978-2011
[27] E. Standards, "EN 15804+A2," https://www.en-standard.eu. Accessed: Aug. 18, 2021. [Online]. Available: https://www.en-standard.eu/csn-en-15804-a2-sustainability-of-construction-works-environmental-product-declarations-core-rules-for-the-product-category-of-construction-products/
[28] CEN, "prEN 18177:2025 - Circular economy in the construction sector - Framework, principles, and definitions." CEN, Brussels, Belgium, Jun. 19, 2025. Accessed: Oct. 19, 2025. [Online]. Available: https://standards.iteh.ai/catalog/standards/sist/384c53df-fced-4183-8dcd-496ee7115a35/osist-pren-18177-2025
[29] "Level(s) - European Commission." Accessed: Jan. 07, 2025. [Online]. Available: https://environment.ec.europa.eu/topics/circular-economy/levels_en
[30] "Construction Products Regulation (CPR) - Internal Market, Industry, Entrepreneurship and SMEs." Accessed: Oct. 18, 2025. [Online]. Available: https://single-market-economy.ec.europa.eu/sectors/construction/construction-products-regulation-cpr_en

[31] T. Malmqvist *et al.*, “Design and construction strategies for reducing embodied impacts from buildings – Case study analysis,” *Energy Build.*, vol. 166, pp. 35–47, May 2018, doi: 10.1016/j.enbuild.2018.01.033.
[32] M. Röck *et al.*, “Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation,” *Appl. Energy*, vol. 258, p. 114107, Jan. 2020, doi: 10.1016/j.apenergy.2019.114107.
[33] F. Pomponi and A. Moncaster, “Circular economy for the built environment: A research framework,” Dec. 2016, doi: 10.17863/CAM.7204.
[34] “Material efficiency in clean energy transitions – Analysis,” IEA. Accessed: Aug. 24, 2025. [Online]. Available: https://www.iea.org/reports/material-efficiency-in-clean-energy-transitions
[35] N. M. P. Bocken, I. de Pauw, C. Bakker, and B. van der Grinten, “Product design and business model strategies for a circular economy,” *J. Ind. Prod. Eng.*, vol. 33, no. 5, pp. 308–320, Jul. 2016, doi: 10.1080/21681015.2016.1172124.
[36] Ellen MacArthur Foundation, “Towards the circular economy Vol. 1: an economic and business rationale for an accelerated transition.” Accessed: Jan. 10, 2025. [Online]. Available: https://www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an
[37] European Commission, “Circular economy action plan - European Commission.” Accessed: Sep. 28, 2024. [Online]. Available: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en
[38] European Commission, “Circular Economy - Principles for Building Design,” Report, Brussels, Belgium, 2020.
[39] M. Cooper, “ABN AMRO’s perfect Circl,” Sustain. Accessed: Dec. 31, 2024. [Online]. Available: https://www.sustain-re.com/abn-amros-perfect-circl/
[40] M. Rehberger and M. Hiete, “Allocation of Environmental Impacts in Circular and Cascade Use of Resources—Incentive-Driven Allocation as a Prerequisite for Cascade Persistence,” *Sustainability*, vol. 12, no. 11, Art. no. 11, Jan. 2020, doi: 10.3390/su12114366.
[41] C. Koffler and M. Finkbeiner, “Are we still keeping it ‘real’? Proposing a revised paradigm for recycling credits in attributional life cycle assessment,” *Int. J. Life Cycle Assess.*, vol. 23, no. 1, pp. 181–190, Jan. 2018, doi: 10.1007/s11367-017-1404-x.
[42] M. L. French and R. L. LaForge, “Closed-loop supply chains in process industries: An empirical study of producer re-use issues,” *J. Oper. Manag.*, vol. 24, no. 3, pp. 271–286, 2006, doi: 10.1016/j.jom.2004.07.012.
[43] European Commission, “2050 long-term strategy - European Commission.” Accessed: Jan. 10, 2025. [Online]. Available: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en
[44] Directorate-General for Research and Innovation (European Commission), *Circular economy research and innovation : connecting economic & environmental gains*. Publications Office of the European Union, 2017. Accessed: Jan. 10, 2025. [Online]. Available: https://data.europa.eu/doi/10.2777/688203
[45] European Parliament and the Council of the European Union, “Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste (Text with EEA relevance),” In Official Journal of the European Union, 2018. Accessed: Jan. 10, 2025. [Online]. Available: http://data.europa.eu/eli/dir/2018/851/oj/eng
[46] EPBD, “Whole Life-Cycle Global Warming Potential reporting for buildings,” Whole Life-Cycle greenhouse gas emission reporting for buildings. Accessed: Mar. 11, 2025. [Online]. Available: https://www.wlc-epbd-guidance.eu/documents/
[47] Nordic sustainable construction, “Overview of Nordic Climate Declarations and Limit Values Integration.” Accessed: Mar. 11, 2025. [Online]. Available:

https://www.nordicsustainableconstruction.com/knowledge/2024/september/overview-of-nordic-climate-declarations
[48] Ellen MacArthur Foundation, “Growth within: a circular economy vision for a competitive Europe.” Accessed: Jan. 10, 2025. [Online]. Available: https://www.ellenmacarthurfoundation.org/growth-within-a-circular-economy-vision-for-a-competitive-europe
[49] Danish Transport and Construction Agenc, “Vejledning om den frivillige bæredygtigheds klasse,” 2020. Accessed: Jan. 10, 2025. [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.xn--bredygtighedsklasse-lxb.dk/Media/637989281458917375/Vejledning%20om%20den%20frivillige%20baeredygtighedsklasse%20maj%202020.pdf
[50] “Circle House (Lisbjerg) - Building Social Ecology.” Accessed: Jan. 10, 2025. [Online]. Available: https://www.buildingsocialecology.org/projects/circle-house-lisbjerg/
[51] “Buildings’ Life Cycle Assessments gain ground in the Nordics.” Accessed: Aug. 24, 2025. [Online]. Available: https://www.nordicsustainableconstruction.com/news/2023/january/denmark-introduces-co2-limit-for-new-constructions
[52] “Known paths and new tracks to 70 per cent reduction | Klimarådet.” Accessed: Jan. 10, 2025. [Online]. Available: https://klimaraadet.dk/en/report/known-paths-and-new-tracks-70-cent-reduction
[53] Innovation Fund Denmark, “Circular Construction - Transition of the construction sector to a circular resource economy,” 2020. Accessed: Jan. 10, 2025. [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://innovationsfonden.dk/sites/default/files/2020-03/eng_opslagstekst_byggeriets-omstilling-til-cirkulaer-ressourceokonomi_grand-solutionsdocx.pdf
[54] S. Attia, M. C. Santos, M. Al-Obaidy, and M. Baskar, “Leadership of EU member States in building carbon footprint regulations and their role in promoting circular building design,” presented at the Crossing Boundaries 2021, Parkstadt, The Netherlands: Zuyd Uninversity, Mar. 2021, p. 13. doi: 10.1088/1755-1315/855/1/012023.
[55] J. Karhu and L. Linkola, “Circular Economy in the Built Environment in Finland - A case example of collaboration,” *ResearchGate*, Oct. 2024, doi: 10.1088/1755-1315/297/1/012024.
[56] A. Sánchez Cordero, S. Gómez Melgar, and J. M. Andújar Márquez, “Green Building Rating Systems and the New Framework Level(s): A Critical Review of Sustainability Certification within Europe,” *Energies*, vol. 13, no. 1, Art. no. 1, Jan. 2020, doi: 10.3390/en13010066.
[57] “Färdplan för fossilfri konkurrenskraft,” skanska.se. Accessed: Jan. 10, 2025. [Online]. Available: https://www.skanska.se/om-skanska/hallbarhet/samverkan/fardplan-for-fossilfri-konkurrenskraft/
[58] Ministère de la Transition écologique, “RE2020 : Une nouvelle étape vers une future règlementation environnementale des bâtiments neufs plus ambitieuse contre le changement climatique,” Ministère de la Transition écologique. Accessed: Jul. 26, 2021. [Online]. Available: https://www.ecologie.gouv.fr/re2020-nouvelle-etape-vers-future-reglementation-environnementale-des-batiments-neufs-plus
[59] “MilieuPrestatie Gebouwen - MPG,” RVO.nl. Accessed: Jan. 10, 2025. [Online]. Available: https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/milieuprestatie-gebouwen-mpg
[60] “Country profiles on waste prevention,” European Environment Agency. Accessed: Mar. 08, 2025. [Online]. Available: https://www.eea.europa.eu/themes/waste/waste-prevention/countries
[61] “Le site officiel de Bruxelles Environnement,” Brussels Environment. Accessed: Mar. 08, 2025. [Online]. Available: https://environnement.brussels/

[62] Flanders Circular Economy Plan, “Retrospect - Vlaanderen Circulair.” Accessed: Mar. 08, 2025. [Online]. Available: https://vlaanderen-circulair.be/en/retrospect
[63] GRO, “GRO tool.” Accessed: Mar. 08, 2025. [Online]. Available: https://gro-tool.be/
[64] J. Kirchherr, D. Reike, and M. Hekkert, “Conceptualizing the circular economy: An analysis of 114 definitions,” *Resour. Conserv. Recycl.*, vol. 127, pp. 221–232, Dec. 2017, doi: 10.1016/j.resconrec.2017.09.005.
[65] J. Hart, K. Adams, J. Giesekam, D. D. Tingley, and F. Pomponi, “Barriers and drivers in a circular economy: the case of the built environment,” *Procedia CIRP*, vol. 80, pp. 619–624, Jan. 2019, doi: 10.1016/j.procir.2018.12.015.
[66] C. Sassanelli, P. Rosa, R. Rocca, and S. Terzi, “Circular economy performance assessment methods: A systematic literature review,” *J. Clean. Prod.*, vol. 229, pp. 440–453, Aug. 2019, doi: 10.1016/j.jclepro.2019.05.019.
[67] C. Cavalliere, G. Habert, G. R. Dell’Osso, and A. Hollberg, “Continuous BIM-based assessment of embodied environmental impacts throughout the design process,” *J. Clean. Prod.*, vol. 211, pp. 941–952, Feb. 2019, doi: 10.1016/j.jclepro.2018.11.247.
[68] P. Means and A. Guggemos, “Framework for Life Cycle Assessment (LCA) Based Environmental Decision Making During the Conceptual Design Phase for Commercial Buildings,” *Procedia Eng.*, vol. 118, pp. 802–812, Jan. 2015, doi: 10.1016/j.proeng.2015.08.517.
[69] F. Blomsma, L. Kjaer, D. Pigosso, T. McAloone, and S. Lloyd, “Exploring Circular Strategy Combinations - towards Understanding the Role of PSS,” *Procedia CIRP*, vol. 69, pp. 752–757, Jan. 2018, doi: 10.1016/j.procir.2017.11.129.
[70] K. Allacker *et al.*, “Allocation solutions for secondary material production and end of life recovery: Proposals for product policy initiatives,” *Resour. Conserv. Recycl.*, vol. 88, pp. 1–12, Jul. 2014, doi: 10.1016/j.resconrec.2014.03.016.
[71] P. Ghisellini, M. Ripa, and S. Ulgiati, “Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review,” *J. Clean. Prod.*, vol. 178, pp. 618–643, Mar. 2018, doi: 10.1016/j.jclepro.2017.11.207.
[72] M. H. A. Nasir, A. Genovese, A. A. Acquaye, S. C. L. Koh, and F. Yamoah, “Comparing linear and circular supply chains: A case study from the construction industry,” *Int. J. Prod. Econ.*, vol. 183, pp. 443–457, Jan. 2017, doi: 10.1016/j.ijpe.2016.06.008.
[73] Md. U. Hossain and S. T. Ng, “Critical consideration of buildings’ environmental impact assessment towards adoption of circular economy: An analytical review,” *J. Clean. Prod.*, vol. 205, pp. 763–780, Dec. 2018, doi: 10.1016/j.jclepro.2018.09.120.
[74] A. Gallego-Schmid, H.-M. Chen, M. Sharmina, and J. M. F. Mendoza, “Links between circular economy and climate change mitigation in the built environment,” *J. Clean. Prod.*, vol. 260, p. 121115, Jul. 2020, doi: 10.1016/j.jclepro.2020.121115.
[75] C. E. Andersen *et al.*, “Assessment of absolute environmental sustainability in the built environment,” *Build. Environ.*, vol. 171, p. 106633, Mar. 2020, doi: 10.1016/j.buildenv.2019.106633.
[76] “GRO - Heading Towards Future-Oriented Buildings.” Accessed: Aug. 29, 2025. [Online]. Available: https://ecosysteme-economiecirculaire.wallonie.be/en/publication/gro-heading-towards-future-oriented-buildings/?utm_source=chatgpt.com
[77] “GRO 2025 – A Common Tool for Sustainable Building and Renovation.” Accessed: Aug. 29, 2025. [Online]. Available: https://ecosysteme-economiecirculaire.wallonie.be/en/publication/gro-2025-a-common-tool-for-sustainable-building-and-renovation/?utm_source=chatgpt.com
[78] “GRO support,” Bureau Bouwtechniek. Accessed: Aug. 29, 2025. [Online]. Available: https://b-b.be/en/portfolio/gro-support

[79] "TOTEM - Tool to Optimise the Total Environmental impact of Materials," EnergyVille. Accessed: Aug. 25, 2025. [Online]. Available: https://energyville.be/en/project/totem-tool-to-optimise-the-total-environmental-impact-of-materials/
[80] "Bepalingsmethode Milieugerelateerde Materiaalprestatie van…," Vlaanderen.be. Accessed: Aug. 25, 2025. [Online]. Available: https://www.vlaanderen.be/publicaties/bepalingsmethode-milieugerelateerde-materiaalprestatie-van-gebouwelementen-mmg
[81] D. Trigaux and L. W. C, "Environmental profile of buildings [update 2023]," OVAM, Mechelen, Belgium, 2023. Accessed: Aug. 25, 2025. [Online]. Available: https://scholar.google.com/scholar_lookup?title=Environmental%20profile%20of%20buildings%20%5Bupdate%202023%5D&author=D.%20Trigaux&publication_year=2023
[82] "BREEAM | Sustainable Building Certification," BREEAM. Accessed: Aug. 25, 2025. [Online]. Available: https://breeam.com
[83] "BREEAM International NC 2016 Technical Manual 2.0 | PDF | Efficient Energy Use | Science." Accessed: Aug. 29, 2025. [Online]. Available: https://www.scribd.com/document/358728365/BREEAM-International-NC-2016-Technical-Manual-2-0
[84] "Mat 01 – Life Cycle Impacts – Article Categories – Knowledge Base." Accessed: Aug. 25, 2025. [Online]. Available: https://kb.breeam.com/section/new-construction/uk/2014-uk/materials-breeam_uk_nc_2014/mat01/?utm_source=chatgpt.com
[85] D. T. Doan, A. Ghaffarianhoseini, N. Naismith, T. Zhang, A. Ghaffarianhoseini, and J. Tookey, "A critical comparison of green building rating systems," *Build. Environ.*, vol. 123, pp. 243–260, Oct. 2017, doi: 10.1016/j.buildenv.2017.07.007.
[86] U.S. Green Building Council, "LEED v4 | U.S. Green Building Council." Accessed: Jul. 23, 2021. [Online]. Available: https://www.usgbc.org/leed/v4
[87] A. Passer and P. Maydl, "Assessment of the environmental performance of buildings: A critical evaluation of the influence of technical building equipment on residential buildings," *Int. J. Life Cycle Assess.*, Jan. 2012, doi: 10.1007/S11367-012-0435-6.
[88] "Madaster | The platform for circular real estate and infrastructure," Madaster Global. Accessed: Aug. 25, 2025. [Online]. Available: https://madaster.com/
[89] F. Heisel and S. Oberhuber, "Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster," *J. Clean. Prod.*, vol. 243, p. 118482, Sep. 2019, doi: 10.1016/j.jclepro.2019.118482.
[90] G. Leindecker *et al.*, "Material and Building Passports as Supportive Tools for Enhancing Circularity in Buildings | SpringerLink," *Springer*, vol. Circular Economy Design and Management in the Built Environment, 2024, Accessed: Aug. 29, 2025. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-031-73490-8_18
[91] "CAALA | Unlocking Sustainability." Accessed: Aug. 29, 2025. [Online]. Available: https://www.caala.de/?utm_source=chatgpt.com
[92] A. Al-Noori, "A review of life cycle assessment methods in various building certification systems," TU Wien, Germany, 2022.
[93] E. Meex, A. Hollberg, E. Knapen, L. Hildebrand, and G. Verbeeck, "Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design," *Build. Environ.*, vol. 133, pp. 228–236, Apr. 2018, doi: 10.1016/j.buildenv.2018.02.016.
[94] R. Bach, N. Mohtashami, and L. Hildebrand, "Comparative Overview on LCA Software Programs for Application in the Façade Design Process," *J. Facade Des. Eng.*, vol. 7, no. 1, pp. 13–26, Jan. 2019, doi: 10.7480/jfde.2019.1.2657.
[95] A. B. Lovins, L. H. Lovins, and P. Hawken, "A Road Map for Natural Capitalism," 2007. Accessed: Jan. 11, 2025. [Online]. Available: https://hbr.org/2007/07/a-road-map-for-natural-capitalism

[96] U. Bogenstätter, “Prediction and optimization of life-cycle costs in early design,” *Build. Res. Inf.*, vol. 28, no. 5–6, pp. 376–386, 2010, doi: 10.1080/096132100418528.

[97] J. Schade, “Energy simulation and life cycle costs : estimation of a building's performance in the early design phase,” 2009, Accessed: Aug. 24, 2025. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-18520

[98] C. Du Plessis, “Towards a regenerative paradigm for the built environment: Building Research & Information: Vol 40, No 1,” 2012, doi: 10.1080/09613218.2012.628548.

[99] D. Mulhall and M. Braungart, “Cradle To Cradle criteria for the built environment,” Ekonomiaz, 75(04), 182-193., 2010. Accessed: Jan. 11, 2025. [Online]. Available: https://ideas.repec.org/a/ekz/ekonoz/2010416.html

[100] OVAM, “Totem: Tool to Optimise the Total Environmental impact of Materials.” Accessed: Jul. 24, 2021. [Online]. Available: https://www.ovam.be/materiaalprestatie-gebouwen-0

[101] “Het Nieuwe Normaal | Cirkelstad.” Accessed: Aug. 24, 2025. [Online]. Available: https://www.hetnieuwenormaal.nl/leidraden/nieuwbouw/inleiding/?utm_source=chatgpt.com

[102] S. Attia, *Yearbook 2016 Ateliers d’Architecture III: Logement collectif durable et conception régénérative*. SBD Lab, Liege, Belgium, 2017. Accessed: Jan. 11, 2025. [Online]. Available: https://orbi.uliege.be/handle/2268/216612

[103] W. Galle and M. Vandenbroucke, “Veranderingsgericht bouwen: ontwikkeling van een beleids- en transitiekader. Samenvatting.,” OVAM, Report, Brussels, Belgium, Apr. 2015.

[104] E. Stolterman, “The Nature of Design Practice and Implications for Interaction Design Research,” *Int. J. Des. Vol 2 No 1 2008*, vol. 2, Apr. 2008.

[105] C. A. S. Hill and J. Dibdiakova, “The environmental impact of wood compared to other building materials,” *Int. Wood Prod. J.*, vol. 7, no. 4, pp. 215–219, Nov. 2016, doi: 10.1080/20426445.2016.1190166.

[106] A. Del Borghi, “LCA and communication: Environmental Product Declaration,” *Int. J. Life Cycle Assess.*, vol. 18, no. 2, pp. 293–295, Feb. 2013, doi: 10.1007/s11367-012-0513-9.

[107] European Commission, “Sustainable investment – EU environmental taxonomy.” Accessed: Jun. 04, 2023. [Online]. Available: http://rb.gy/j2fgdq

[108] CEN, “Circular economy in the construction sector – Framework, principles, and definitions (Draft Version).” European Committee for Standardization, Brussels, Belgium., 2024.

[109] IEA EBC, “IEA EBC || Annex 89 || Ways to Implement Net-zero Whole Life Carbon Buildings || IEA EBC || Annex 89.” Accessed: Oct. 24, 2024. [Online]. Available: https://annex89.iea-ebc.org/

[110] Nordic sustainable construction, “Danish Political Agreement Tightens the Limit Values for New Buildings and Extends the Impact.” Accessed: Oct. 24, 2024. [Online]. Available: https://www.nordicsustainableconstruction.com/news/2024/june/tillaegsaftale-paa-engelsk

[111] One Click LCA, “Calculate your environmental impacts in minutes,” One Click LCA® software. Accessed: Jul. 19, 2021. [Online]. Available: https://www.oneclicklca.com/

[112] D. Trigaux, K. Allacker, and F. De Troyer, “Life Cycle Assessment of Land Use in Neighborhoods,” *Procedia Environ. Sci.*, vol. 38, pp. 595–602, Jan. 2017, doi: 10.1016/j.proenv.2017.03.133.

[113] K. Allacker, D. M. de Souza, and S. Sala, “Land use impact assessment in the construction sector: an analysis of LCIA models and case study application,” *Int. J. Life Cycle Assess.*, vol. 19, no. 11, pp. 1799–1809, Nov. 2014, doi: 10.1007/s11367-014-0781-7.

[114] T. Mattila, T. Helin, R. Antikainen, S. Soimakallio, K. Pingoud, and H. Wessman, *Land use in life cycle assessment*. in Finnish Environment. Helsinki: Finnish Environment Institute SYKE, 2011.
[115] European Commission. Joint Research Centre., *Land-use related environmental indicators for life cycle assessment: analysis of key aspects in land use modelling.* LU: Publications Office, 2016. Accessed: Jul. 03, 2022. [Online]. Available: https://data.europa.eu/doi/10.2788/905478
[116] "LANCA® characterization factors," Fraunhofer Institute for Building Physics IBP. Accessed: Oct. 10, 2025. [Online]. Available: https://www.ibp.fraunhofer.de/en/expertise/life-cycle-engineering/applied-methods/lanca.html
[117] T. Perminova, N. Sirina, B. Laratte, N. Baranovskaya, and L. Rikhvanov, "Methods for land use impact assessment: A review," *Environ. Impact Assess. Rev.*, vol. 60, pp. 64–74, Sep. 2016, doi: 10.1016/j.eiar.2016.02.002.
[118] T. Häkkinen, T. Helin, C. Antuña, S. Supper, N. Schiopu, and S. Nibel, "Land Use as an Aspect of Sustainable Building," *Int. J. Sustain. Land Use Urban Plan.*, vol. 1, pp. 21–41, Jun. 2013, doi: 10.24102/ijslup.v1i1.202.
[119] G. Pristerà, D. Tonini, M. Lamperti Tornaghi, D. Caro, and S. Sala, "Taxonomy of design for deconstruction options to enable circular economy in buildings," *Resour. Environ. Sustain.*, vol. 15, p. 100153, Mar. 2024, doi: 10.1016/j.resenv.2024.100153.
[120] M. Al-Obaidy *et al.*, "Expert system for building disassembly potential evaluation and inspection," *J. Build. Eng.*, p. 112148, Feb. 2025, doi: 10.1016/j.jobe.2025.112148.
[121] Z. R. Rockow, B. Ross, and A. K. Black, "Review of methods for evaluating adaptability of buildings," *Int. J. Build. Pathol. Adapt.*, vol. 37, no. 3, pp. 273–287, Oct. 2018, doi: 10.1108/IJBPA-01-2018-0013.
[122] B. Dams *et al.*, "A circular construction evaluation framework to promote designing for disassembly and adaptability," *J. Clean. Prod.*, vol. 316, p. 128122, Sep. 2021, doi: 10.1016/j.jclepro.2021.128122.
[123] R. Askar, L. Bragança, and H. Gervásio, "Design for Adaptability (DfA)—Frameworks and Assessment Models for Enhanced Circularity in Buildings," *Appl. Syst. Innov.*, vol. 5, no. 1, Art. no. 1, Feb. 2022, doi: 10.3390/asi5010024.
[124] ISO, "ISO 20887:2020(en), Sustainability in buildings and civil engineering works - Design for disassembly and adaptability - Principles, requirements and guidance." Accessed: Aug. 02, 2024. [Online]. Available: https://www.iso.org/obp/ui/en/#iso:std:iso:20887:ed-1:v1:en
[125] Kamp C, "Circular building: 't Centrum," Kamp C. Accessed: Jul. 19, 2021. [Online]. Available: https://www.kampc.be/tcentrum/circulair-bouwen-t-centrum
[126] WEST architectuur, "KANTOOR - C." Accessed: Sep. 25, 2023. [Online]. Available: https://westarchitectuur.be/realisaties/kampc
[127] Beneens, "We build camp circular." Accessed: Jul. 19, 2021. [Online]. Available: https://www.beneens.be/circulair
[128] M. Al-Obaidy, L. Courard, and S. Attia, "A Parametric Approach to Optimizing Building Construction Systems and Carbon Footprint: A Case Study Inspired by Circularity Principles," *Sustainability*, vol. 14, no. 6, Art. no. 6, Jan. 2022, doi: 10.3390/su14063370.
[129] LUTZ architectes, "Green Offices, premier bâtiment administratif Minergie-P-Eco ·." Accessed: Sep. 25, 2023. [Online]. Available: https://www.lutz-architectes.ch/realisation/green-offices-premier-batiment-administratif-minergie-p-eco
[130] Vonlanthen Holzbau AG – Holz in Topform, "INNOVATIV – BAUEND AUF GENERATIONEN." Accessed: Sep. 25, 2023. [Online]. Available: https://www.vonlanthenholzbau.ch/
[131] Minergie, "Minergie International - Sustainable buildings." Accessed: Sep. 25, 2023. [Online]. Available: https://www.minergie.com/
[132] "The making of Circl." Accessed: Sep. 14, 2024. [Online]. Available: https://circl.nl/themakingof/en/

[133] “ABN AMRO Bank.” Accessed: Sep. 14, 2024. [Online]. Available: https://www.abnamro.nl/nl/prive/index.html
[134] “de Architekten Cie.” Accessed: Sep. 14, 2024. [Online]. Available: https://www.cie.nl/
[135] “Koninklijke BAM Groep / Royal BAM Group |.” Accessed: Sep. 14, 2024. [Online]. Available: https://www.bam.com/en
[136] A. Mastre and T. Cooper, “Circular Product Design. A Multiple Loops Life Cycle Design Approach for the Circular Economy: The Design Journal: Vol 20, No sup1.” Accessed: Jan. 10, 2025. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/14606925.2017.1352686
[137] Circle Economy, “A Future-Proof Built Environment - Insights - Circle Economy.” Accessed: Sep. 15, 2024. [Online]. Available: https://www.circle-economy.com/resources/a-future-proof-built-environment
[138] ResourceFull, “Foundations ’t Centrum built without cement,” ResourceFull.eu. Accessed: Aug. 04, 2021. [Online]. Available: https://www.resourcefull.eu/tcentrum-kampc-cementless-foundations
[139] European Commission, “Better regulation: guidelines and toolbox.” Accessed: Sep. 05, 2025. [Online]. Available: https://commission.europa.eu/law/law-making-process/better-regulation/better-regulation-guidelines-and-toolbox_en
[140] “Monitoring Progress towards a Resource-Efficient and Circular Economy,” OECD. Accessed: Sep. 05, 2025. [Online]. Available: https://www.oecd.org/en/publications/monitoring-progress-towards-a-resource-efficient-and-circular-economy_3b644b83-en.html
[141] “ISO 52016-1:2017,” ISO. Accessed: Sep. 05, 2025. [Online]. Available: https://www.iso.org/standard/65696.html
[142] “IEA EBC Annex 67 Energy Flexible Buildings - ScienceDirect.” Accessed: Sep. 05, 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378778817317024
[143] “ISO 15686-8:2008,” ISO. Accessed: Sep. 05, 2025. [Online]. Available: https://www.iso.org/standard/39070.html
[144] “ASHRAE,” ASHRAE: HVAC Service Life Database. Accessed: Sep. 05, 2025. [Online]. Available: https://weblegacy.ashrae.org/publicdatabase/service_life.asp?utm_source=chatgpt.com
[145] CEN, “CEN/TC 350/SC 1 - Circular Economy in the Construction Sector,” iTeh Standards Store. Accessed: Dec. 12, 2021. [Online]. Available: https://standards.iteh.ai/catalog/tc/cen/51316ef3-3dea-4483-8aab-cd1a8033cd41/cen-tc-350-sc-1
[146] E. Standards, “EN 15804:2012+A1:2013 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products,” iTeh Standards. Accessed: Apr. 13, 2025. [Online]. Available: https://standards.iteh.ai/catalog/standards/cen/a7de5991-2e9f-4e93-b34c-f1d794cbca02/en-15804-2012a1-2013

CURRICULUM VITAE

Personal data

Name: **Muheeb Al-Obaidy**

Date of birth: 15th February 1981

Nationality: Belgium

Place of birth: Baghdad, Iraq

Contact: LinkedIn, Google Scholar, ORCiD, Scopus, ORBi

Education

2020 - 2025 **Ph.D. in Architectural Engineering**
SBD Lab, Faculty of Applied Sciences, University of Liege, Liege, Belgium

2004 - 2012 **M.Sc. in Architectural Engineering**
Faculty of Architectural Engineering, University of Technology, Baghdad, Iraq

1999 - 2004 **B.Sc. in Architectural Engineering**
Faculty of Architectural Engineering, University of Technology, Baghdad, Iraq
Ranked first among university graduates with a degree of 99/100 for the final project.

Experience

2024 - present **Founder & CEO**
ONYX Group (Sustainable Architecture, LCA & EPD), Turnhout, Belgium

2022 - present **Project leader & LCA Expert**
Construction Department, Colruyt Group, Halle, Belgium

2020 - 2021 **Architectural Engineer**
TRiAS Architecten, Turnhout, Belgium

2019 – 2020 **Researcher and Technical Advisor**
Pixii - Passive House Platform, Antwerp, Belgium

2017 - 2018 **Scientific Researcher**
Faculty of Engineering and Architecture, Ghent University, Ghent, Belgium

2010 - 2015 **Senior Architectural Engineer and Design Manager**
Sama Al-Aamaar & Al-Raif Group, Baghdad, Iraq

2009 - 2010 **Professor's Assistant**
Ajman University of Science and Technology, Ajman, U.A.E

2008 – 2010 **Architectural Engineer**
Al Bayaty Architects & Engineering Consultancy, Abu Dhabi, U.A.E

2004 – 2008 **Architectural Engineer**
Creative Design Constructions, Baghdad, Iraq

Membership

- Flemish Council of Architects (Order of Architects - Antwerp A910854)
- Committee of Buildwise/E35001 - CEN/TC 350 (Circular Economy in the Construction Sector)
- Committee of NBN/I323 - ISO/TC 323 (Circular Economy)
- Committee of CEN/TC 473 (Circular Economy)
- COST Action CA20139 WG4 (Sustainability and Durability)
- COST Action CA21103 WG3 (Circular KPIs framework)
- CircleAid – Circular Flanders (Circular building design expert)

Publications

- Al-Obaidy, M., Courard, L., Passarelli, R., Giannasi, E., & Attia, S. (2026). BCEF: Early Design Framework for Circular and Low-Impact Buildings. Results in Engineering, 110824. doi:10.1016/j.rineng.2026.110824
- Bertini, A., Al-Obaidy, M., Dasse, M., Amaripadath, D., Gobbo, E., & Attia, S. (2025). Parametrization of variables affecting the whole life carbon performance of nearly zero energy residential building renovation. Building and Environment, 113013. doi.org/10.1016/j.buildenv.2025.113013
- Al-Obaidy, M., Carens, H., Campain, C., Giannasi, E., Mori, M., van Vliet, M., & Attia, S. (2025). Expert system for building disassembly potential evaluation and inspection. Building Engineering, 103, 112148. doi.org/10.1016/j.jobe.2025.112148
- Attia, S., Al-Obaidy, M., Mori, M., Campain, C., Giannasi, E., Van Vliet, M., & Gasparri, E. (2024). Disassembly calculation criteria and methods for circular construction. Automation in Construction, 165, 105521. doi:10.1016/j.autcon.2024.105521
- Attia, S., Hoxha, E., Piccardo, C., Schau, E., Novais Passarelli, R., Van Acker, J., Stepinac, M., Al-Obaidy, M., & Bujar, J. (2024). Life Cycle Assessment for Taller Timber Buildings Summer School. (3). Liege, Belgium: Sustainable Building Design Lab. https://orbi.uliege.be/handle/2268/320811
- Attia, S., Petersen, S., Hoxha, E., Gobbo, É., Bertini, A., Dasse, M., Abu-Ghaida, H., Heiranipou, M., Al-Obaidy, M., Norouziasa, A., & Stephan, A. (2024). Framework to Model Building Carbon Emissions. (Version 5). Liege, Belgium: Sustainable Building Design Lab. doi:10.13140/RG.2.2.15338.73925
- Al-Obaidy, M., & Attia, S. (2024). DeCon, Deconstruction assessment tool. webtool. https://hdl.handle.net/2268/313887
- Attia, S., Al-Obaidy, M., Mori, M., & Campain, C. (2024). Review lists and publications on disassembly calculation methods and criteria for buildings. Cambridge, United States: Harvard Dataverse. doi:10.7910/DVN/SHLD4D
- Al-Obaidy, M., Courard, L., & Attia, S. (2022). A Parametric Approach to Optimizing Building Construction Systems and Carbon Footprint: A Case Study Inspired by Circularity Principles. Sustainability, 14 (6), 3370. doi:10.3390/su14063370
- Al-Obaidy, M., & Attia, S. (2022). Environmental product declaration dataset of ’t Centrum circular building in Westerlo, Belgium. Cambridge, United States: Harvard Dataverse. doi:10.7910/DVN/Z1CS97
- Al-Obaidy, M. (2021). A circularity evaluation framework for office buildings design in Belgium [Poster presentation]. ArGEnCo/UEE Department/Research Unit day, Liège, Belgium. https://hdl.handle.net/2268/264064
- Al-Obaidy, M., Santos, M., Baskar, M., & Attia, S. (2021). Assessment of the circularity and carbon neutrality of an office building: The case of ’t Centrum in Westerlo, Belgium. In IOP Conference Series: Earth and Environmental Science (pp. 16). Bristol, United Kingdom: IOP Publishing. doi:10.1088/1755-1315/855/1/012025

- Attia, S., & Al-Obaidy, M. (2021). Design criteria for circular buildings. In Crossing Boundaries. https://hdl.handle.net/2268/258348
- Attia, S., Santos, M. C., Al-Obaidy, M., & Baskar, M. (2021). Leadership of EU member States in building carbon footprint regulations and their role in promoting circular building design. In Crossing Boundaries. Maastricht, Netherlands: https://iopscience.iop.org/article/10.1088/1755-1315/855/1/012023. doi:10.1088/1755-1315/855/1/012023
- Al-Obaidy, M. (2020). Design support for circular buildings: a guiding methodology for architects in early design [Poster presentation]. Doctoral Seminar on Sustainability Research in the Built Environment DS2BE 2020, Hasselt, Belgium. https://hdl.handle.net/2268/246268

A circularity evaluation framework for newly constructed office building design

Muheeb Al-Obaidy

The concept of circularity is gaining traction in the construction sector. The evaluation of building circularity potential remains inconsistent due to the lack of standardized Building Circularity Indicators BCIs. Existing BCI methodologies vary significantly in their definitions, scopes, Key Performance Indicators KPIs, and technical approaches, leading to limited continuity and hindering progress toward standardization. This Ph.D. thesis addresses these gaps by proposing a comprehensive and innovative Building Circularity Evaluation Framework BCEF. The BCEF integrates key advancements in the field, incorporating the most critical KPIs identified through an extensive literature review. BCEF was developed from a life cycle perspective; the framework tracks material flows from their origins to disposal or waste processing, ensuring a holistic evaluation. This framework complements established sustainability tools, such as Life Cycle Impact Assessment LCIA, by integrating an expert system to assess disassembly potential. The BCEF was validated through three case studies. Analysis of the three case studies revealed that resource-intensive construction processes and extended service life significantly influence circularity performance. Based on the findings, recommendations for enhancing building circularity are provided. Methodologically, the results demonstrate that the BCEF is a multi-indicator framework capable of evaluating building circularity at the whole-building level. A sensitivity analysis was conducted to enhance the validity, reliability, and applicability of the findings. The BCEF's practical applications make it a valuable framework for contractors, consultants, and policymakers to assess circularity in early project stages. It also offers a foundation for researchers to further refine and standardize BCIs.

Urban and Environmental Engineering Dept.
Faculty of Applied Sciences | University of Liège