Advancing Circular Economy Strategies in Modular Architecture through Design for Disassembly and Reuse

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Abstract

The current transition to the circular economy of construction is imperatively concerned with diminishing resource depletion, construction waste mitigation, and sustainability. The concept of modularity involves prefabrication of the building elements, accomplishing great efficiency and reduced environmental impact and therefore, creates a perfect ground for transitioning the ideals of the circular economy. The existing research suggested that modular buildings can take advantage of Design for Disassembly (DfD) principles in achieving up to 50% better rates of resource recovery compared to traditional construction methods, including embodied carbon and resource consumption. In addition, the use of material passports and blockchain-enabled tracking systems contributes to greater traceability of building components, ensuring that elements of a building are used at the end of their lifecycle. Through BIM, such designs can be optimized for circularity by enabling precise material quantification and adaptive reuse planning. There are still significant constraints holding up the realization of these benefits, including regulatory constraints, non-standardized modular component options, and financial disincentives relating to material reuse. This study therefore advocates policy intervention, financial incentives, and collaborative frameworks to address these barriers. The research moves forward by discussing some of the issues facing the construction industry and even embracing cutting-edge technological novelties by thinking about moving the industry closer to its transformative journey away from the linear "take-make-dispose" concept and into regenerative politics through circular action by highlighting all the benefits of circular, modular construction. The potential of sustainable architecture would be greatly transformed and promoted with how modular construction is applied, particularly to match circular economy principles which are aiming for a new level of resource efficiency.

Keywords: *Modular architecture, Circular economy, Design for disassembly (DfD), Sustainable construction, Prefabrication*

1. Introduction

The construction industry is one of the largest contributors to global waste and resource depletion, responsible for approximately 40% of global energy consumption and 30% of total greenhouse gas emissions. The sector also generates significant amounts of construction and demolition (C&D) waste, much of which ends up in landfills, exacerbating environmental degradation and resource scarcity. As urban populations continue to grow and the demand for new infrastructure rises, the need for more sustainable construction practices has become increasingly urgent [1].

In response to these challenges, circular economy principles have gained traction as a means to reduce material waste, extend the lifespan of building components, and minimize environmental impacts. The circular economy aims to move away from the traditional linear model of "take-make-dispose" by promoting strategies such as reuse, refurbishment, remanufacturing, and recycling. Within this framework, modular architecture has emerged as a promising approach to achieving sustainability in the built environment [2].

The shift from linear to circular economic models necessitates innovative product design and business strategies. This transition is particularly relevant to modular architecture, where design for disassembly and reuse can significantly enhance sustainability by ensuring that materials are retained and reused efficiently at the end of their lifecycle. By focusing on strategies that slow, close, and narrow resource loops, architects can create modular structures that align with circular economy principles, ultimately promoting material reuse and waste reduction [3].

Modular construction involves prefabricating building components or entire modules in controlled factory settings before transporting them to construction sites for assembly. This method not only improves efficiency and reduces material waste but also enhances the potential for disassembly and reuse. When combined with Design for Disassembly (DfD) principles, modular architecture allows for greater flexibility, adaptability, and resource efficiency. DfD prioritizes reversible connections, standardized components, and material selection strategies that facilitate future disassembly and repurposing, thereby aligning with circular economy objectives [4].

Modularity is a standard design strategy to generate form, create spatial efficiency, and support mass production and prefabricated design, especially in contemporary architecture. However, very few discussions talk about its contribution to sustainability. The previous discussions on modularity have sometimes been broad enough to also connote creating form, generating spatial efficiencies, and achieving mass design during the modern architecture era. Modularity was getting more precise as it matured: material and construction oriented toward prefabricated systems [5]. Nonetheless, there exists seldom a discussion regarding modularity as a design strategy that incorporates sustainability. Sustainability, as a principle, has been extensively explored for its role in encouraging responsible practices in architecture and related fields. Simultaneously, sustainable architecture still talks about energy-efficient, zero-run-off buildings, green or high-tech technology and materials, or biomimicry as an aesthetic consideration, which highlights the building actually during its operation. The post-use phase of a building should also be considered to promote a more circular approach to architecture, ensuring that structures are not perceived as less valuable simply because of demolition. DfD has been one of the approaches in sustainable architecture aimed to direct

design and manufacture processes for possible reuse of building materials whilst minimizing material wastage [6].

Design for disassembly and reuse can advance circular economy strategies in modular architecture. Arisya and Suryantini [5] show that modular design improves flexibility and interchangeability, while Cruz-Rios and Grau [6] describe design for disassembly as key to effective deconstruction when linked to prefabrication and product-service systems. Jayawardana et al. [7] and Minunno et al. [13] report that life cycle assessments yield measurable environmental gains - for example, a 63% reduction in global warming potential and an 88% offset in greenhouse gas emissions with reuse versus recycling. Klinge et al. [8] and Zhuang et al. [2] introduce technical solutions such as reversible timber joints and topological interlocking systems that promote both high accessibility (in 60% of evaluated component types) and high reuse potential (in 70%). O'Grady et al. [9] emphasize that standardized, disassemblable connections enable reuse and recycling of most structural and nonstructural components. Meanwhile, Cruz-Rios and Grau [6] identify economic and supply-chain challenges, including steep initial costs and difficulties in life cycle cost analysis, which may hinder implementation. These studies collectively indicate that integrating design for disassembly with modular construction techniques enhances the circularity of building systems by improving material reuse and environmental performance while also outlining the practical barriers to their widespread adoption [5].

The AEC industry faces challenges in adapting to sustainable practices and technological changes. Many scientists and engineers advocate for interdisciplinary approaches that leverage technologies like Building Information Modeling (BIM) to create modular designs that facilitate disassembly and material recovery. Such technologies can enhance resource efficiency, aligning with circular economy goals. However, key challenges remain unresolved, including the integration of these technologies into mainstream construction practices, the verification of economic feasibility beyond initial costs, and the identification of practical pathways for scaling modular and disassemblable architecture. Future research could explore novel methodologies for integrating these technologies into architectural education and practice, enabling more sustainable building practices [10].

Adaptive reuse strategies discussed in the context of heritage conservation align with circular economy principles in architecture. Various approaches to adaptive reuse were classified, suggesting that modular architecture could benefit from insights into designing for future adaptability and disassembly. Understanding these strategies may help architects create modular designs that not only meet current needs but also allow for future modifications and reuse [4].

This paper examines how modular design and disassembly techniques can support a circular economy by analyzing key studies in the field. It explores the environmental and economic implications of modular DfD strategies, evaluates technical solutions for disassembly, and discusses the challenges associated with their implementation. By advancing circular economy principles in modular architecture, the construction industry can move toward more sustainable, resource-efficient building practices.

2. Circular Economy in Modular Construction

Reusable modular components play a significant role in promoting a circular economy (CE) by facilitating reuse in architecture and construction. This practice not only reduces waste and construction costs but also enhances material efficiency and resource conservation, leading to lower environmental impacts. The design of reusable modular components and the implementation of a Circular Economy Business Model (CEBM) can provide considerable benefits to society and the environment, aligning with sustainable development goals (SDGs) [11].

The 4R strategy refers to the principles of Reduce, Reuse, Recycle, and Recover, which aim to minimize waste and promote sustainable practices in waste management [12]. The circularity and design for disassembly assessment methods involve evaluating the capacity of construction materials and systems to be dismantled and reused or recycled at the end of their life cycle. In the context of the Drive 0 project, these methods were crucial for developing modularized solutions, particularly in the case of the Irish modularized wall panel [13].

These approaches in modular construction enhance circularity by various strategies. First, modular systems assist with separation, recycling, and reuse at the end of life through Design for Disassembly (DfD), thus minimizing waste and longevity of materials. Controlled prefabrication improves quality control and lessens material waste by costing accurate planning of material input-use and reuse. Modularity also offers flexibility and adaptability to use for future renovations and reconfiguration, allowing changes or even expansions to be made without further impact. It also minimizes construction waste, as offsite construction reduces on-site waste generation and allows better surplus material management. Finally, it standardizes modular components for interchangeability to group and recycle materials easily after disassembly [11].

The life cycle assessment (LCA) of the modular building evaluates the environmental impacts, including greenhouse gas emissions, throughout its entire life cycle. It quantifies the global warming potential (GWP) measured in t CO_2 equivalent during different stages, such as construction, usage, and end-of-life processes. The study provides evidence that modular buildings designed for adaptability and disassembly can significantly reduce GWP by allowing for reuse and recycling of materials. Specifically, the research indicates an 88% reduction in greenhouse gas emissions when modular components are reused instead of simply recycled at the end of their life cycle [14].

The two-stage stochastic programming model contributes to logistics optimization in modular construction by allowing for the simultaneous consideration of various stochastic elements affecting supply chain configurations. In the first stage, decisions regarding the most favorable production scheme are made, considering expected transportation, inventory, assembly, and potential penalty costs associated with demand uncertainties in the second stage. This approach contrasts with simulation-based techniques by providing a mathematical framework that can be implemented across different modelling environments, thus enhancing decision-making under uncertainty in the logistics of modular construction [15].

The circular economy (CE) significantly impacts the management of construction and demolition waste (C&DW) by promoting the principles of Reduce, Reuse, and Recycle while it encourages viewing waste as a resource rather than a disposal problem, leading to a mindset shift in how materials are sourced, used, and disposed of in the construction sector.

In implementing CE strategies, C&D waste can be minimized through increased efficiency in resource use, improved design for disassembly, and the selection of materials that can be easily recycled or reused. Various countries are already actively recycling and recovering C&D waste, but challenges remain due to factors that lead to the dumping of potentially reusable materials [16].

The concept of modularity is closely linked to the principles of the circular economy, particularly through the implementation of Modular Integrated Construction (MiC) that creates value by adopting offsite construction approaches that enhance modularity, allowing for more efficient manufacturing and assembly processes. This technique facilitates the use of factory-made prefinished modules that are designed for easy assembly and potential reuse or recycling at the end of their life cycle, aligning with the circular economy's goals of minimizing waste and promoting sustainable practices [17].

Empirical studies indicate that effective implementation of MiC not only contributes significantly to construction project performance,

improving productivity, speeding up construction, and enhancing quality control, but also aligns with environmental objectives. For instance, it has been found that MiC leads to substantial reductions in greenhouse gas emissions and construction waste, thus supporting cleaner and more sustainable construction practices [15].

The construction industry would be circular in integrity by virtue of its provisions for sustainability and resource efficiency, but not without challenges to its implementation. Government patronage notwithstanding, awareness among stakeholders is low, and financial incentives and a platform for material circularity are quite urgently needed. Many times, the nature of supply chains and the short-term orientation of business goals inhibit the collaborative efforts alluded to by CE. Absent a consensus on CE concepts, the knowledge requisite for an effective implementation is further hindered. An overly material-oriented resource use almost certainly restricts the more extensive possible benefits from CE; on the contrary, resource regeneration and site redevelopment strategies run an additional much value [18].

In fact, modular construction is one of the key answers to a lot of these problems. It is designed for disassembly (DfD) for simple reuse and recycling of building elements, contributing to lower material waste and higher resource efficiency. Prefabrication carries benefits in quality through controlled environment production and minimized waste. It addresses issues of material interchangeability through standardization, allowing for long-term circularity of materials. Moreover, it allows flexibility and adaptability, which undermines the constraint of supply chain whereby these structures are easily modifiable, relocated or repurposed, hence extending their life cycle. Innovative collaboration of all stakeholders- comprising the very principles advocated by modular construction-will ensure successful CE implementation in the construction industry [19].

The life cycle performance of modular buildings includes four main phases: the production phase, the construction phase, the use phase (also known as occupancy or operation), and the end-of-life phase. In the construction phase of modular buildings, the specific tasks involve module fabrication, transportation of modules to the job site, and assembly on site. These activities differ from those in traditional buildings. Throughout all phases of a building's life cycle, materials and energy are utilized for various operations such as raw material extraction, processing, component manufacturing, and the energy needs for heating, cooling, and lighting. While there are similar tasks between conventional and modular methods, there are also unique opportunities in modular construction to reduce energy and material consumption (see Figure 1) [20].

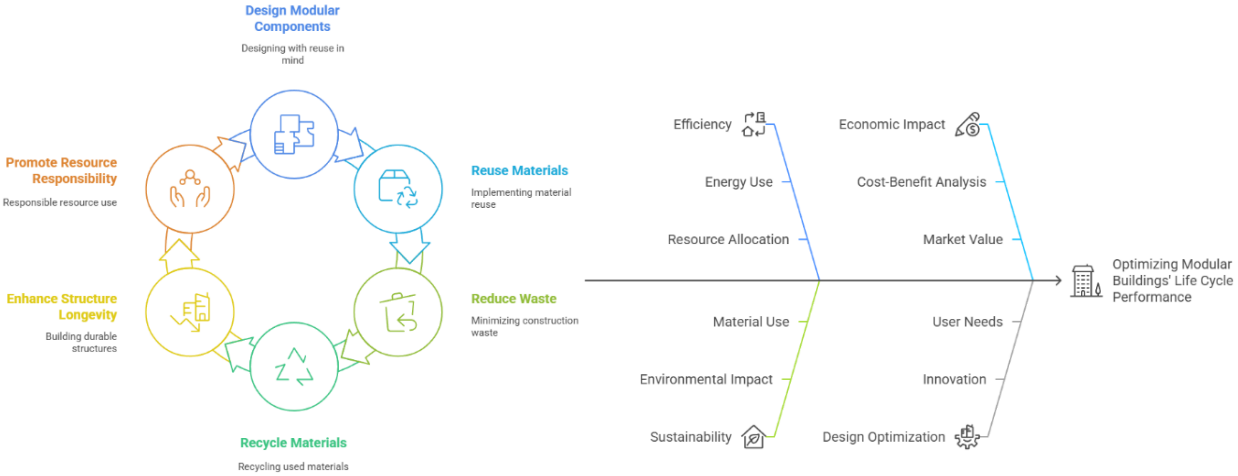

Fig. 1. Circular economy and life cycle performance in modular construction: strategies for sustainable resource utilization, waste reduction, and long-term adaptability in the built environment.

One of the essential issues emerging from the analysis of the literature on modularity and industrialism is the application of circular economy principles in modular design: some key strategies such as design for disassembly, modularity, material selection, and standardization are facilitating sustainable construction [21].

Design for disassembly is singled out for particular mention in almost all studies as a key strategy to facilitate circular economy approaches, allowing for deconstruction and reuse in the future. Cruz-Rios and Grau [6] see DfD as an important strategy which permits companies to cleanly dismantle the building components and nosily recycling them to reduce waste and extend material life-cycles. Along similar lines, Arisya and Suryantini's studies on modularity in DfD show how this method enhances the flexibility, interchangeability, and reutilization of building components, thus establishing its value in circular construction [5].

Aside from DfD, another key design strategy that inherently incorporates circularity is modularity. The study from Arisya and Suryantini encapsulates that modularity provides easier disassembly, hence enhancing reuse and recycling possibilities of components. Zhuang et al. [2] have furthered this discussion with a description of a topological interlocking system, which is advantageous in ensuring the reusability of modular components through optimal connection mechanisms.

Material selection is another key aspect in realizing the circular economy principles. Klinge et al. [8] stated that selection of dismantlable and reusable materials is essential, with timber again cited as the environmentally friendly choice for modular buildings. They emphasized that circular strategies cannot truly operate if the materials are not selected through their end-of-life considerations.

Standardization, along with others, promotes circular modular architecture. By ensuring a degree of sameness in component and connection system design, standardization makes disassembly and reassembly easier. O'Grady et al. [9] demonstrate this in their study of unusual connection systems in disassemble buildings, showing how standardization enhances recovery of materials and reuse efficiency.

All these together - DfD, modularity, material selection, and standardization- set the stage for circular economy strategies in modular construction. Therefore, by adopting such an approach, the sector begins to embrace resource-efficient, flexible, and sustainable building practices-conveyor belt style, which translates to environmentally sound construction while maximizing economic and functional value.

3. Design for Disassembly (DfD) Principles

Design for Deconstruction (DfD) is one of the approaches in modular architecture critical for the processes that enable buildings and

structures to be dismantled systematically so that they can re-enter the loop of circular economy where components or materials are reused, repurposed, or recycled efficiently. Architects and engineers are turning increasingly toward DfD as global environmental issues so that construction waste is minimized, carbon footprints reduced, and resources made more efficient [22].

Over the past few years, major developments in digital technologies, material science, and modular construction methodologies have afforded new life to Design for Disassembly (DfD). It is an example of a circular economy, because it enables the disassembly of buildings in order to repurpose and reuse them in a manner that decreases construction and demolition waste. The incorporation of smart materials, robotic automation, digital tracking systems, and reversible assembly methods has given enhanced importance to DfD as a sustainable construction strategy [5]. Of the many transformative developments under DfD, Building Information Modelling (BIM) and digital twin technologies are defining the future-the influence of real-time material tracking on monitoring the lifecycle of building components and the optimization of disassembly processes [23]. BIM models carry detailed metadata on materials origin, recyclability, and assembly techniques, so that at the end of a building's life, components can be reliably recovered and reused. Digital twins offer simulation-based decision support, permitting architects and engineers to assess several strategies to disassembly prior to implementation, thus reducing waste and maximizing efficiency [24]. Material passports, powered by blockchains, are also playing a critical role in safeguarding material transparency for reuse. These digital assets keep records of provenance, quality, and composition of materials, ensuring that those extracted from disassembled buildings can be reused with sustainability credentials backed by assessment. Through the application of these digital solutions, a more systematic and scalable approach to design for disassembly will find increasing support.

The arrival of smart materials-however shape-memory alloys and polymers-introduced self-disassembling components into the realm of modular construction. Specifically, these materials may change their properties at predetermined conditions (temperature changes, etc.) to help in automatically detaching a building component without much manual effort [25]. For instance, those thermally activated adhesives would become weaker at certain temperatures, thus allowing components to be easily taken apart without damaging the material itself. In fact, this option could save huge amounts of time, labor, and energy by disassembly, material recovery, and recycling-setting the ground for the economic feasibility of modular and circular architecture. Robotics and automation offer great advances in disassembly through reducing dependency on human labor and increasing precision. Robot systems with AI algorithms and mixed-reality interfaces can selectively disassemble and categorize building components while causing little or no damage. Semi-autonomous robotic disassembly provides evidence that drones and robotic arms can be used in a systematic way in disassembling structures to increase safety and efficiency, especially in high-rise buildings or hazardous environments, where manual disassembly presents huge risks [26].

Combinatorial design principles inspired by Wang tiles and prefabrication approaches are presented as a new method for increasing adaptability in modular construction. This method allows designers to create complex structures from a limited stock of modular components that can be rearranged or repurposed without extensive modification [24]. Standardizing module sizes and connection interfaces will allow buildings to maximize reuse and configuration, thereby minimizing the need for new materials and waste. It is through robot-assisted manufacturing and digital fabrication that the precision and efficiency of these combinatorial modular designs are furthered. To achieve the highest degree of circularity in modular architecture requires cross-disciplinary collaboration amongst architects, engineers, producers, and policymakers. The DfD-oriented design should incorporate elements related to manufacturing, assembly, and end-of-life disassembly from the earliest phases of the development process. Manufacturers could prefabricate modular components with standardized connective junctions, whereas policymakers could offer tax incentives and regulatory assistance to promote DfD compliance.

Reversible BIM modelling embeds information on the modular components' recycling, reusability, and structural dependencies to accommodate disassembly. While the core focus of BIM is the construction and maintenance of buildings, Reversible BIM gives paramount importance to deconstruction, interchangeable components, and circularity of materials [27]. With this integration, buildings positively react to change, spaces become amendable for alternative use, and selected materials can be recovered, which strengthens the argument for adaptive modular architecture in a circular urban context. To support different strategy implementations for DfD, evaluation frameworks for modular construction development are increasingly being populated by researchers and industry practitioners. These frameworks evaluate green material selection criteria concerning facility life, including durability, recyclability, and toxicity; ease of disassembly; fastening methods; and accessibility of components [23]. Life-cycle scenarios also reflect on the possibilities for reuse and secondary applications of modular components. Such metrics would allow the building industry to assess and enhance the sustainability of modular buildings for long-term environmental and economic dividends.

4. Benefits and Implementation Challenges

Modular architecture has excellent potential to promote circular economy principles within an industry that has historically contributed to environmental degradation owing to its great role in championing disassembly and reuse strategies. Among the advantages of this model are resource efficiency, as easy disassembly and reuse enhance material life cycles, thereby minimizing the consumption of row resources and associated environmental impacts. Flexibility and adaptability also prevent premature demolition, allowing the building to be unlocked or dismantled, depending on new needs, thus safeguarding its values in time [28].

Architects and engineers are increasingly looking for durable, recyclable, and bio-based materials in conjunction with advanced connection systems that facilitate efficient disassembly while preserving structural integrity. Such new-type innovations help to promote prescribed sustainable options and the feasibility of circular construction models. Furthermore, while DfD requires upfront investment, the benefits in terms of economics are much greater in the long term. Reusing modules and components significantly lowers material costs, reduces demolition expenses, and opens opportunities for revenue generation through resale or leasing of reclaimed elements.

The economic costs of modular construction and Design for Disassembly are likely to be high due to highly specialized design, prefabrication, and high-end materials; however, their long-term economic benefits have not been investigated to any extent. The reuse of modular components over multiple projects would considerably reduce material procurement costs in the long run. Economic savings are also derived from low demolition costs and low labor costs because of factory-based prefabrication that reduces construction time. Material banks and secondary markets for reclaimed building components would further economically justify these short-lived investment buildings. Future research should proactively develop financial models that address life-cycle cost savings, including resale value of modular components, maintenance efficiency, and policy incentives for circular construction investments [29].

Circular modular construction will also promote reducing environmental impact through reduced wastage, reuse of materials, and minimized dependence on energy-demanding manufacturing processes. All this contributes to sustainability objectives and also accords with the worldwide threshold to reduce carbon emission from the built environment. Another great opportunity

presents standardization of components and closed loop systems in which modular elements can be designed for multiple cycles of use, thereby facilitating continual recycling and reintegration into new constructions (see Figure 2). This maximizes resource utilization relative to waste produced, upholding the viability of circular economy principles in architectural design and construction.

Despite the extensive research on circular economy strategies in modular architecture, notable gaps remain. There is limited understanding of the economic implications of implementing design for disassembly in modular buildings and how these strategies can be effectively communicated to stakeholders. Additionally, the integration of digital fabrication technologies into modular design for disassembly requires further exploration. Future research should address these knowledge gaps, focusing on developing clear economic models and case studies that illustrate the financial benefits of design for disassembly in modular architecture. Investigating the role of digital fabrication in enhancing modular design flexibility and material reuse. Exploring interdisciplinary collaborations to create comprehensive frameworks that facilitate the adoption of circular economy principles in the AEC sector [30].

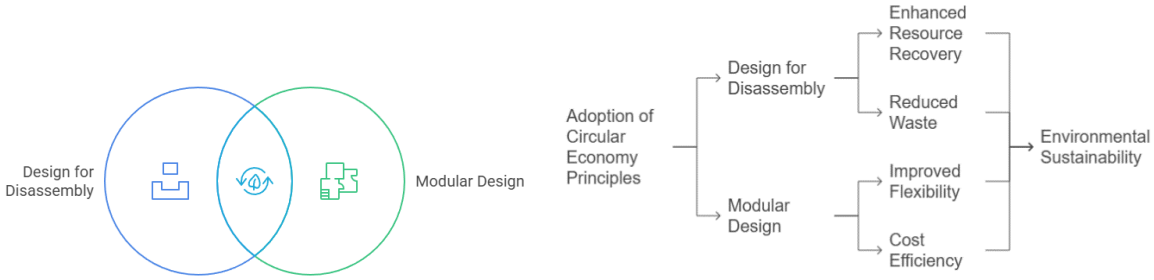

Fig. 2. Maximizing the benefits of circular economy in design for disassembly and modular design: enhancing resource efficiency, waste reduction, and sustainable construction practices for a resilient built environment.

Using circularity and design for disassembly assessments in building practice comes with several challenges. A major challenge is that there is no comprehensive set of indicators that would allow one to assess the circularity in an effective way. Oftentimes these indicators are also not prioritized clearly, leaving an insufficient evaluation. Furthermore, the focus and weightings for different material aspects and impacts may not be appropriately balanced so that they will significantly affect the overall assessment. Moreover, considering different stages of material re-application is also very limited. Finally, clarity in definitions and terminologies used within these methods needs further improvement. Assessment of circularity concerning building practice is thus complex and multi-criteria [13].

Challenges and limitations accompany the incorporation of design for disassembly (DfD) and modular architecture for enabling a truly circular built environment. One of the main challenges here is design complexity and realization since DfD requires meticulous planning and collaboration between architects, engineers, manufacturers, and contractors. The design process becomes even more complex with the interactions of material selection, connection methods, and disassembly procedures, all of which would have to be optimized simultaneously for reuse and efficiency. logistics represent a significant challenge since being able to execute proper disassembly, transportation, and reintegration of modules requires well-developed reverse logistics systems and precise tracking of materials to guarantee successful circularity [31].

Furthermore, another barrier to progress is the absence of standardized metrics and evaluation tools for performance of the circularity of modular buildings. The non-existence of some universally accepted benchmarks leads to difficulties in performance between various design approaches (see Figure 3). The development of holistic instruments for evaluation should, therefore, drive improvement which, in the end, ensures more trust in the market. Besides those, regulatory obstacles and acceptance in the marketplace are other important hindrances since persistent building codes and regulations may not fully support the consequential requirements of circular modular construction. It is, therefore, of paramount importance to foster the necessary regulatory reforms, policy support, and collaborative action from the industry to ease the widespread adoption [32].

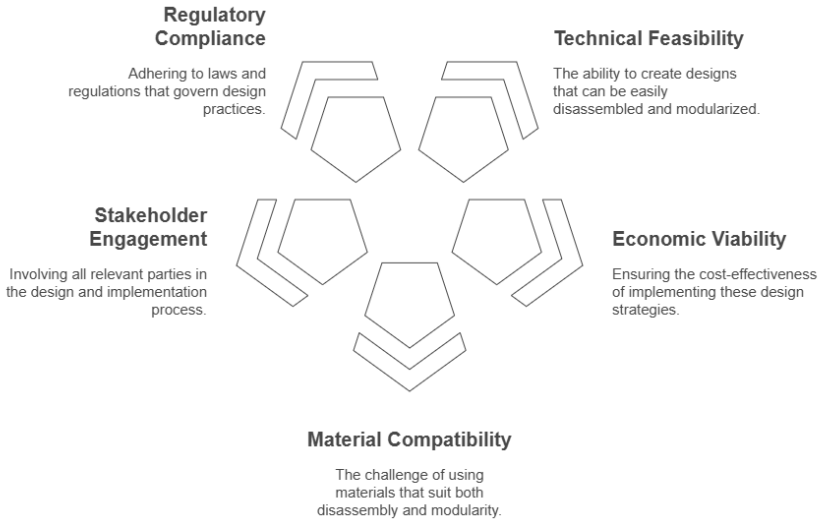

Fig. 3. Overcoming barriers in circular economy design implementation: strategies for addressing technical, economic, and regulatory challenges.

Tab. 1. Evaluation of environmental benefits, economic impacts, and implementation challenges

Strategy type	Environmental benefits	Economic benefits	Implementation challenges
Design for Disassembly (DfD)	63% reduction in global warming potential, 90% reduction in human toxicity	Potential for cost savings through component reuse	Building owners' values, challenges in life cycle cost analysis
Reuse of components	88% offset in greenhouse gas emissions compared to recycling	Reduced material costs for future constructions	Lack of market for reused components
Modular construction	Reduced construction waste	Improved efficiency in construction process	Higher initial costs, complex supply chains
Material recycling	Reduced raw material extraction	Potential for material cost savings	Lower environmental benefits compared to reuse
Adaptability of building elements	Extended building lifespan, reduced need for new construction	Increased long-term value of buildings	Requires initial design considerations
Waste reduction	<1% waste creation in modular buildings designed for disassembly	Reduced waste management costs	Requires changes in construction practices
Tracking technologies	Improved material management and reuse potential	Enhanced asset value tracking	Implementation and data management costs
Circular business models	Improved resource efficiency	New revenue streams, improved customer relationships	Legal uncertainties, lack of demand
Prefabrication	Reduced on-site waste	Increased construction speed and efficiency	Requires significant upfront investment
Topological interlocking system	Maximized sustainability of components	Potential for cost-effective reuse	Requires new design and manufacturing processes

The verification of specific claims such as emissions reduction and resource efficiency present one of the main obstacles in assessing the true impact of modular circular construction. Although case studies and computational modelling form estimates to substantiate such claims, the non-availability of standard measurement frameworks and full proprietary data access leaves uncertainty. Third-party verification systems, blockchain-based material tracking, and enhanced protocols for data-sharing will help foster some transparency and credibility in reporting sustainability metrics [33].

In summary, the approach of integrating the Design for Disassembly (DfD) principles into modular architecture offers a paradigm shift that is significantly sustainable, waste reducing, and resource-efficient (see Table 1). By allowing the recovery, reuse, and repurposing of materials, DfD deregulates a circular approach to construction away from the general conventional linear models. However, the benefits can only be realized when some key challenges such as standardization, costs, and wider industry acceptance are resolved. The major obstacle is the capital investment upfront in designing buildings to be disassembled and the requirement of specialized knowledge and training within the construction industry [34]. With the advances in technologies, buildable information modelling or model-based management systems, and digital twins, as well as systems for tracking materials based on blockchain, will be important in recovering and reusing the building components for the benefits of DfD. Such tools can assist in lifecycle assessment, ensure traceability of the resources, and ease the decision-making regarding building disassembly and reuse. An increasing role is played by automation in modular construction manufacturing in very precise, cost-effective, and scalable applications of DfD principles [35].

Additionally, it will need greater collaboration between architects, engineers, policymakers, and manufacturers to change old mindsets in the industry from traditional linear construction models to circular practices [36]. Incentives will include tax benefits for reusing materials, legislation forcing principles of a circular economy, and development of reclaimed materials marketplaces.

The current conditions favor and allow for entry of modular design and construction toward a more circular economy, with growing demand for sustainable buildings as well as advancement in automation and material science. The would-be future research should be reflected in more durable materials, better reversible fastening systems, and scalable business models for reuse components including interdisciplinary collaboration of technology developers with construction firms and policymakers [37]. With all these aspects, the construction industry can build an even more resilient and resource-efficient built environment, wherein buildings are not simply designed with current needs in mind, but for future adaptability and sustainability.

5. Case Studies: Pioneering the Integration of Design-for-Disassembly (DfD) in Modular Architecture

Design-for-Disassembly, or DfD, implementing modular architecture, is at the center of a paradigm shift in an industry that is attempting to go greener and circular in approach. As environmental issues are becoming more globally acknowledged, more and more are the exigent demands for developing methods that uphold resource efficiency and waste minimization. Further, if paired with DfD principles, modular construction presents a very good answer for such problems by allowing easy disassembly, recovery, and reuse of building materials after the end of their useful life.

Consequently, a qualitative research approach was adopted, focusing on case studies designed to investigate cases of the application of Design for Disassembly (DfD) in modular architecture. The case study method was deemed appropriate as it would provide knowledge and experience from the real-life applications of modular and disassemblable design, allowing for capturing both successes and setbacks during the implementation process. There are, however, a number of conditions of this method. For

instance, since it mainly depends on secondary data, the analysis is subject to the restrictions posed by the range and availability of the data provided to the public. Some details regarding proprietary projects, such as a breakdown of costs on a unit basis and long-term performance data, are generally not available for this analysis: thus, it may limit the depth of analysis on the economic and lifecycle assessment dimensions. Furthermore, case studies are contextualized; therefore, their findings are often not easily generalized to all geographical regions or building types. There are differences in the local construction practices, regulations and material availability; therefore, applicability of DfD strategies can vary even in different settings. Lastly, there may be certain biases in expert interviews and project reports as one may be influenced by emotional interpretations and personal opinions. However, the case study research methodology is not able to deny or outdo such limitations, but indeed it adds valuable information that serves as the basis for future research addressing such issues specifically long-term economic feasibilities and how well such DfD can be scalable in modular architecture.

Tab. 2 Case study analysis of design for disassembly (DfD) in modular architecture: comparative evaluation of global projects, key strategies, quantifiable environmental and economic benefits, and emerging innovations.

Project Name	Location	Year Completed	Total Area (m²)	Key DfD Strategies	% Reusable Materials	Carbon Savings (tons CO_2)	Notable Innovations	New Insights
Wiki House	Global	Ongoing	Varies	Open-source modular housing, 3D-printed connections	80%	600	Digital fabrication-driven DfD, CNC-cut interlocking panels	Democratizes sustainable construction through open technology
Bellerivestrasse 36	Switzerland	2025	5,600	Adaptive reuse, prefabricated façade panels	95%	1,800	Transparent façade, PV panels, sustainable renovation	Highlights circularity in office refurbishments
Valckensteyn	The Netherlands	2023	11,000	Prefabricated steel and concrete modules, disassemblable structure	80%	3000	Fast-tracked assembly, modular housing for urban densification	Reinforces modularity for affordable housing
Krokodil	Switzerland	2019	37,000	Hybrid timber-concrete construction, modular prefabrication	85%	3,200	BIM-driven modular planning, adaptable housing units	Demonstrates large-scale timber modular solutions
Triodos Bank	The Netherlands	2019	12,500	Cradle-to-cradle design, modular wooden components	100%	3,500	100% reusable and recyclable materials, BIM-driven reuse plan	Sets a new standard for sustainable financial sector buildings
The Circular Building	UK	2016	100	Modular construction, mechanical fasteners	100%	75	Fully demountable structure, digital material passports	Demonstrates complete material recovery potential
The EDGE	The Netherlands	2015	40,000	Layered design approach, reversible connections	85%	2,900	Smart materials integration, AI-managed energy efficiency	Enhances digital tracking of building components
Brock Environmental Center	USA	2015	930	Prefabricated elements, minimal site impact	95%	120	Net-zero energy and water use, compostable materials	Demonstrates scalability of DfD in environmental projects

The data-gathering process demanded that both secondary data. Selection of the case studies was based on upholding several parameters such as adherence to DfD principles, innovative approaches to modular design, and its promotion of sustainability through circular economy principles. Furthermore, with an emphasis on those implemented or near their completion, real-life application was also considered in the selection to advocate for the feasibility of practical implementation of DfD principles. Selected case studies also encompass different geographies and project types, including residential, commercial, and public buildings, to offer a comprehensive understanding of how DfD can be adapted across contexts (see Table 2). Modular design gives the construction a considerable edge when it comes to sustainability; because, being modular implies that such buildings can be

dismantled and moved or repurposed, and thus limit the need for new construction and minimize material waste. Such flexibility is needed since cities today are challenged by climate change, rapid population growth, and the growing need for affordable housing. On the other hand, temporary modular structures are highly efficient, such as disaster relief shelters, which can be quickly assembled and disassembled, allowing material recovery for future use and enhancing urban resilience.

While the ecological and long-term economic benefits of modular construction through material reusing and cost optimization are evident, high initial costs and lack of standardization still pose a major challenge. Global WikiHouse [38] works to open-source its modular housing by means of CNC-cut interlocking panels to promote sustainable construction and adaptation. Bellerivestrasse 36 [39], with prefabricated facade panels, and with sustainable renovation for adaptive reuse. Krokodil [40] is a hybrid timber-concrete modular prefabricated. On the other hand, Valckensteyn [41] presents prefabricated, disassemblable steel and concrete modules, which are meant to be used for urban densification. Triodos Bank [42] has pioneered cradle-to-cradle design in terms of materials by 100% reuse. The Circular Building [43] and The EDGE [44] feature modular build, smart integrated materials, and at the same time efficient use of AI management. Besides, Brock Environmental Center [45] represent strategies for net zero energy and long-term circular economy gains.

6. Conclusion

The future of circular modular construction strongly depends on the advancement of emerging digital tools, innovative materials, and collaborative frameworks that facilitate Design for Disassembly and reuse strategies. Furthermore, with seamless integration of these in-built environment-inducing changes towards sustainable and resource-efficient living, these aspects would ultimately help buildings shift from linear to circular waste minimization systems optimized materials and a fully considered lifecycle for every component. Consistent with past studies on modular construction sustainability, this new study affirms waste and carbon reduction. However, unlike earlier studies, it identifies economic and logistical constraints of high upfront costs and limited supply chains. An unexpected insight, standardized connections and digital material passports appear to be key in increasing circularity. Limitations of the case study include scope and lifecycle cost uncertainty. Future studies should address policy, technology, and business models that overcome these constraints.

This is one of the most promising developments in this area: integrating Building Information Modeling and other digital design tools in streamlining the DfD process. These technologies give real-time insights into reuse potential and lifecycle performance of materials and thus enable designers, architects and engineers to make informed decisions. However, BIM is perhaps most of all a platform for managing complex building systems and their individual components and thereby facilitates planning, design and execution of modular buildings that can easily be disassembled at the end of their useful life. Such digital intertwining fuels the efficiency and effectiveness of already established practices within the circular economy because it allows optimizing all lifecycle phases-from design and construction to use and deconstruction.

It will be essential, alongside these digital advancements, to develop new connection systems. Components must be reversible and form adaptable joint systems to ensure that modular components can readily be separated, reused, or repurposed while a building retains its structural integrity. Furthermore, innovative use of sustainable materials to close the loop will enhance these developments so that the structures constructed are not just easily dismantled but also utilize materials that are fully recyclable or biodegradable. Constructing material banks for reusable building components and digital material passports for property owners and contractors form an important step toward a fully circular construction ecosystem. These material banks will contribute significantly to the minimization of new resources while providing a means to ensure the long-term sustainability of building materials. Additionally, digital material passports will hold valuable information on the source, composition, and lifecycle of materials in modular buildings. Ultimately, such data is intended for the monitoring of the performance and conditions of those materials, facilitating reuse while better informing design and building contractors' practice decisions. Combining these approaches would take the construction industry a step closer to a closed-loop system in which resources would continually cycle, thus reducing waste and environmental impact.

To speed up the uptake, stakeholders in the industry should concentrate on making the modular components standardized and bringing in the digital twin technologies for lifecycle analysis. Another essential linkage is the cooperation among the three sectors-academics, industry, and government regulation. We can accelerate the adoption of circular modular architecture and help ensure much wider sharing and implementation of innovative technologies, best practices, and policy frameworks through strengthening partnerships across these sectors. Most importantly, while tying collaborations between industry leaders and researchers, circular principles are seamlessly imbedded at all stages of design and construction as gaps between theoretical models and practical application are reduced. On building a wide-scale adoption of these values, there would also be the existence of government policy and financial incentives jointly. Regulations that would favor material recovery, standardization, and incentives for circular construction would create an enabling environment for these industries. The structures of government policy embedded into the edifice of massive scales adoption of these ideals would also provide the element of financial incentives. Regulations more favoring material recovery, standardization, and incentives for circular construction will provide enabling conditions required by the industry. Regarding building wide-scale adoption of these ideals, government policies alongside financial incentives would also jointly exist. Regulatory frameworks that favor material recovery, standardization, and incentives for circular construction will create enabling conditions needed for the industry.

However, while the early challenges in terms of cost, policy alignment, and quite a bit of inertia on the part of the industry remain, it is obvious that the enhanced benefits of circular modular architecture far outweigh the challenges. Much resource efficiency, cost savings, and reduced environmental impacts from developing, building, and operation can come from merging DfD and reuse strategies with flexibility and adaptability in any built environment. In doing so, these benefits prepare circular modular architecture for a pivotal position in future construction, especially in light of issues like rapid urbanization, climate change, and resource scarcity. Research, technical advancements, and inter-sector collaboration will be the primary driving forces in unlocking the present and future capability of modular construction. By refining digital tools, working on materials technology, and having a circular mindset, barriers to the broader acceptance of these modalities can be ameliorated. Artificial intelligence, smart technologies, and data-driven decision-making will create new levels of efficiency, resilience, and sustainability within the construction industry.

Finally, circular modular architecture gives a vision of tomorrow when buildings are no longer static but adaptive systems that respond to the exigencies of society while limiting adverse impact. By prioritizing Design for Disassembly, material reuse, and

modular flexibility, we can obtain buildings that would be functional and aesthetically pleasing but built for longevity, resource efficiency, and environmental responsibility. As we continue to forge new pathways and alliances in innovation, circular modular architecture will emerge as a key driver of sustainable urban development, giving the world a template for future construction that works in tandem with nature and long-term societal wellbeing.

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References

1. N. M. P. Bocken, S. W. Short, P. Rana, and S. Evans, "A literature and practice review to develop sustainable business model archetypes," J. Cleaner. 65, 42–56 (2016).
2. G.-L. Zhuang, S. Shih, and F. Wagiri, "Circular economy and sustainable development goals: Exploring the potentials of reusable modular components in circular economy business model," J. Cleaner. (2023).
3. O. E. Ogunmakinde, "The circular economy in the construction industry: From research to practice," J. Circular Econ. 2(3) (2024).
4. D. Misirlisoy and K. Günçe, "Adaptive reuse strategies for heritage buildings: A holistic approach," Sustainable Cities Soc. 26, 89–98 (2016).
5. K. F. Arisya and R. Suryantini, Modularity in Design for Disassembly (DfD): Exploring the Strategy for a Better Sustainable Architecture (IOP Publishing Ltd, Indonesia, 2021), IOP Conf. Ser.: Earth Environ. Sci. 738, 012024.
6. F. Cruz-Rios and D. Grau, Design for Disassembly: An Analysis of the Practice (or Lack Thereof) in the United States (American Society of Civil Engineers, 2020), Construction Research Congress 2020.
7. J. Jayawardana, M. Sandanayake, A. K. Kulatunga, J. A. S. C. Jayasinghe, G. Zhang, and S. A. U. Osadith, "Evaluating the circular economy potential of modular construction in developing economies—A life cycle assessment," Sustainability 15, 16336 (2023).
8. A. Klinge, E. Roswag-Klinge, L. Radeljic, and M. Lehmann, Strategies for Circular, Prefab Buildings from Waste Wood (IOP Publishing Ltd, Brussels, 2019), IOP Conf. Ser.: Earth Environ. Sci. 225, 012052.
9. T. M. O'Grady, R. Minunno, H.-Y. Chong, and G. M. Morrison, "Interconnections: An analysis of disassemblable building connection systems towards a circular economy," Buildings 11, 535 (2021).
10. B. Becerik-Gerber and K. Kensek, "Building Information Modeling in Architecture, Engineering, and Construction: Emerging Research Directions and Trends," J. Prof. Issues Eng. Educ. Pract. 136, 139–147 (2010).
11. K. H. Yu, Y. Zhang, D. Li, C. E. Montenegro-Marin, and P. M. Kumar, "Environmental planning based on reduce, reuse, recycle, and recover using artificial intelligence," Environ. Impact Assess. 86, 106492 (2021).
12. P. Daly, "A critical review of circularity 'design for disassembly' assessment methods applied in the development of modular construction panels: An Irish case study," e-Prime - Adv. Electr. Eng. Electron. Energy 5, 100252 (2023).
13. R. Minunno, T. O'Grady, G. M. Morrison, and R. L. Gruner, "Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building," Resour. Conserv. Recycl. 160, 104855 (2020).
14. P.-Y. Hsu, P. Angeloudis, and M. Aurisicchio, "Optimal logistics planning for modular construction using two-stage stochastic programming," Autom. Constr. 94, 47–61 (2018).
15. 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. Cleaner. 178, 618–643 (2018).
16. I. Y. Wuni and G. Q. Shen, "Barriers to the adoption of modular integrated construction: Systematic review and meta-analysis, integrated conceptual framework, and strategies," J. Cleaner. 249, 119347 (2020).
17. R. M. Lawson, R. G. Ogden, and R. Bergin, "Application of modular construction in high-rise buildings," J. Archit. Eng. 18(2), 148–154 (2012).
18. M. Keller, B. Halkier, and T.-A. Wilska, "Policy and governance for sustainable consumption at the crossroads of theories and concepts," Environ. Policy Gov. 26, 75–88 (2016).
19. M. Kamali and K. Hewage, "Life cycle performance of modular buildings: A critical review," Renew. Sustain. Energy Rev. 62, 1171–1183 (2016).
20. T. M. O'Grady, R. Minunno, H. Y. Chong, and G. M. Morrison, "Interconnections: An analysis of disassemblable building connection systems towards a circular economy," Buildings 11, 535 (2021).
21. G. L. F. Benachio, M. do C. D. Freitas, and S. F. Tavares, "Circular economy in the construction industry: A systematic literature review," J. Cleaner. 260, 121046 (2020).

22. M. D. Webster and 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,” in Proceedings of the Greenbuild Conference (Atlanta, GA, November 2005).
23. National Institute of Building Sciences, New paper: BIM and digital twins coexist to drive sustainability (2024), retrieved from https://www.nibs.org/blog/new-paper-bim-and-digital-twins-coexist-drive-sustainability.
24. E. Ouda and M. Haggag, “Automation in modular construction manufacturing: A comparative analysis of assembly processes,” Sustainability 16(21), 9238 (2024).
25. P.-Y. Hsu, P. Angeloudis, and M. Aurisicchio, “Optimal logistics planning for modular construction using two-stage stochastic programming,” Autom. Constr. 94, 47–61 (2018).
26. M. Pan, Y. Yang, Z. Zheng, and W. Pan, “Artificial intelligence and robotics for prefabricated and modular construction: A systematic literature review,” J. Constr. Eng. Manag. 148(9), 04022060 (2022).
27. 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. Cleaner. 178, 618–643 (2018).
28. J. dos S. Gonçalves, S. Claes, and M. Ritzen, “Measuring circularity of buildings: A systematic literature review,” Buildings 15(4), 548 (2025).
29. F. Karaca, A. Tleuken, H. H. Awan, R. Askar, M. S. Çıdık, A. Iskakova, A. Turkyilmaz, T. Laudal, S. Durdyev, H. A. Varol, A. Salles, D. Bajāre, T. Tambovceva, G. Zsembinszki, G. C. C. Puma, Z. Kapsalyamova, D. Kripa, D. Azhgaliyeva, X. Nano, L. F. Cabeza, and L. Bragança, “Stakeholder perspectives on the costs and benefits of circular construction,” Sci. Rep. 14, 30039 (2024).
30. C. Odenbreit, J. Yang, A. Kozma, A. Romero, N. Popa, F. Hanus, and R. Obiala, “Design for disassembling, reuse, and the circular economy: A demonstration building, ‘Petite Maison’,” CE/PAPERS (2023).
31. S. O. Ajayi, L. O. Oyedele, M. Bilal, O. O. Akinade, H. A. Alaka, and H. A. Owolabi, “Critical management practices influencing on-site waste minimization in construction projects,” Waste Manag. 59, 330–339 (2017).
32. A. Klinge, E. Roswag-Klinge, L. Radeljic, and M. Lehmann, “Strategies for circular, prefab buildings from waste wood,” IOP Conf. Ser.: Earth Environ. Sci. 225, 012052 (2019).
33. Y. Zhang and Z. Wen, “Tackling uncertainty in life cycle assessments for the built environment,” Building and Environment, vol. 208, p. 108567, 2022.
34. R. Minunno, T. O'Grady, G. M. Morrison, R. Gruner, and M. Colling, “Strategies for applying the circular economy to prefabricated buildings,” Buildings (2018).
35. G. L. F. Benachio, M. do C. D. Freitas, and S. F. Tavares, “Circular economy in the construction industry: A systematic literature review,” J. Cleaner. 260, 121046 (2020).
36. G. Dokter, L. Thuvander, and U. Rahe, “How circular is current design practice? Investigating perspectives across industrial design and architecture in the transition towards a circular economy,” Sustainable. Consum. 26, 692–708 (2021).
37. G.-L. Zhuang, S.-G. Shih, and F. Wagiri, “Circular economy and sustainable development goals: Exploring the potentials of reusable modular components in circular economy business model,” J. Cleaner. 183, 883–893 (2019).
38. WikiHouse. (n.d.). WikiHouse. Accessed: March 19, 2025. Available from https://www.wikihouse.cc/
39. C.F. Møller Architects. (n.d.). *Bellerivestrasse 36 Zürich*. Accessed: April 2, 2025. Available from https://www.cfmoller.com/p/Bellerivestrasse-36-Zurich-i3572.html
40. Dlubal Software. (2022). "Crocodile" Building in Lokstadt Area Development in Winterthur, Switzerland. Accessed: April 2, 2025. Available from https://www.dlubal.com/en/downloads-and-information/references/customer-projects/001251
41. Powerhouse Company. (n.d.). Valckensteyn. Accessed: March 20, 2025. Available from https://www.powerhouse-company.com/valckensteyn
42. Triodos Bank. (2020). The bank with a new wooden spine. Accessed: March 20, 2025. Available from https://www.triodos.co.uk/articles/2020/the-bank-with-a-new-wooden-spine
43. UCL Circular Economy Lab. (2018). Case Studies; 22 Gordon Street, Arup Circular Building. Accessed: March 20, 2025. Available from https://www.ucl.ac.uk/circular-economy-lab/sites/circular_economy_lab/files/bif_circular_economy_options_for_hvac_final_report.pdf
44. ArchDaily. (2016). The Edge / PLP Architecture. Accessed: March 19, 2025. Available from https://www.archdaily.com/785967/the-edge-plp-architecture
45. Chesapeake Bay Foundation. (n.d.). The Chesapeake Bay Brock Environmental Center. Accessed: March 20, 2025. Available from https://living-future.org/case-studies/the-chesapeake-bay-brock-environmental-center/