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RESEARCH ARTICLE

Design for Disassembly (DfD) applications in the United States: Gaps and Drivers Towards a Circular Industrialized Construction Economy

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Abstract

Growing awareness of the construction industry's substantial environmental impacts has driven increasing interest in circular and sustainable building practices. This paper presents a literature and industry scoping review of the U.S. construction sector to identify emerging trends in sustainable and circular design, with a particular focus on Design for Disassembly (DfD). DfD is defined here as the intentional design of buildings and assemblies to enable efficient modification, repair, and reuse of components at the end of their service life. Given the limited peer-reviewed research on DfD in the U.S., the review draws on a broad range of sources, including market analyses, case study reports, and governmental and corporate publications, to map relevant legislation, stakeholder engagement, and evolving industry practices. The synthesis examines stakeholder roles throughout the design process, identifies construction systems, materials, and tools that facilitate DfD, and evaluates their potential to enable material and component reuse at scale.

Findings reveal significant barriers to mainstreaming DfD, including the absence of standardized material specifications for reuse, inadequate infrastructure such as storage capacity and regrading systems, and misalignment between economic incentives and legislative frameworks. At the same time, emerging initiatives in policy development, material innovation, and collaborative procurement models demonstrate opportunities for scaling DfD practices.

By consolidating knowledge from both industry and academic perspectives, this paper provides a structured overview of current capabilities and constraints, offering a foundation for advancing DfD as a core strategy in transitioning the U.S. construction industry toward a more circular and resource-efficient future.

Keywords Design for Disassembly · Design for Adaptability · Circular Economy · Circular Construction · Waste Reduction

1. Introduction

Growing awareness of the construction industry's substantial environmental impacts has driven increasing interest in circular and sustainable building practices. (Santoro, 2024). Within the United States, the construction industry is responsible for approximately three-quarters of raw material consumption and

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produces approximately 600 million metric tons of construction and demolition debris (CDD) annually, of which only 20-30% is reprocessed and repurposed (US EPA, 2023). One reason is that the country's building stock is not designed for reuse or to facilitate resource recovery (Guerra & Leite, 2021). Incentives to implement circularity in design and practice across the architecture, engineering, construction, owner/operator (AECOO) industries are catalyzed by existing and emerging legislation and policy, as well as by professional organizations such as the American Institute of Architects (AIA) and sustainability benchmarking foundations such as the Passive House Institute or the Living Building Challenge, which publish guidelines, reports, certifications, and other market incentives to support sustainable practices (AIA, 2023; Heisel et al., 2024). Consequently, circular and sustainable practices are maturing and increasingly approaching market implementation.

Because these practices are on the brink of implementation, there is a substantial gap in peer-reviewed literature covering these newest and projected developments. This review is part of a larger study drawing on a broad range of sources, including market analyses, case study reports, and governmental and corporate publications, to map relevant legislation, stakeholder engagement, and evolving industry practices. The work aims to determine emerging trends in sustainable and circular design and construction practices and identify technologies and materials that will become relevant to the construction industry within the next ten years. This larger study identified three topics of interest: Urban Mining, Design for Disassembly and Modular Construction, aiming to contribute to the existing literature by providing general and current overviews of the potential applications of these themes in the U.S. AECOO industry. In 2024, a first review on the concept of Urban Mining in the US context was published (Heisel et al., 2024). The paper at hand builds on this first publication and specifically focuses on the concept of DfD.

DfD is defined here as the intentional design of buildings and assemblies to facilitate disassembly at the end of their service life to facilitate recovery, reuse or recycling, and prevent waste generation and landfilling (ISO*,* 2020). The strategy employs reversible, mechanical connections and assemblies that can be taken apart so that materials and components can be reused, remanufactured and/ or recycled at their highest utility and value (EMF, 2022). DfD aims to create a materials depot of reusable construction resources in the built environment that can be accessed efficiently and reincorporated effectively. In the process, material waste due to demolition (as the opposite to systematic deconstruction or planned reassembly) is minimized, since components are documented, planned for disassembly and designed for (certified) reuse. Furthermore, repairs and adaptations of components and buildings are facilitated by DfD throughout their use time (before decommissioning) as DfD strategies incorporate or are often synonymous with design for adaptability (AIA, 2023) and design for maintenance scenarios.

This synthesis examines stakeholder roles throughout the design process, identifies construction systems, materials, and tools that facilitate DfD, and evaluates their potential to enable material and component reuse at scale. By consolidating knowledge from both industry and academic perspectives, this paper provides a structured overview of current capabilities and constraints, offering a foundation for advancing DfD as a core strategy in transitioning the U.S. construction industry toward a more circular and resource-efficient future. It is structured as follows: Section 2 provides a conceptual/theoretical global background on the circular economy and circular construction; section 3 describes the methodology of the industry and literature scoping review; section 4 summarized the current understanding of DfD in the US; organized by: new stakeholders and roles (Section 4.1), required systems and architectural processes (Section 4.2), materials and connection details (Section 4.3); pertinent legislation (Section 4.4); selected case studies (Section 4.5); and tools and innovations (Section 4.6); Section 5 discusses gaps and drivers towards the application of an industrial DfD framework; Section 6 acknowledges limitations of the applied methodology; and Section 7 offers concluding remarks.

2. Conceptual/Theoretical Background

Design for Disassembly (DfD) situates the AECOO industry within the circular economy's (CE) central premise: that economic development can be decoupled from finite resource extraction by designing systems in which materials circulate at their highest possible value and utility for as long as possible (Stahel, 2016). As a restorative and regenerative model, the CE rethinks the linear “take–make–dispose” paradigm, replacing it with closed-loop systems in which technical materials flow through reuse, repair, refurbishment, remanufacturing, and recycling, while biological materials cycle safely back into natural systems (EMF, 2013). Theoretical foundations of the CE draw on industrial ecology, which conceptualizes material and energy flows as part of interconnected systems (Allenby, 1999); performance economy principles, which emphasize extending product lifespans and optimizing asset utilization (Stahel, 2010); and cradle-to-cradle thinking, which advances the idea of safe, perpetual material metabolisms (McDonough and Braungart, 2002). Within this framework, DfD is both a design philosophy and a technical strategy: it embeds reversibility, accessibility, and non-destructive separation into building assemblies from the outset, enabling the recovery of components for direct reuse or high-quality recycling (Bocken et al., 2016). Emerging scholarship links these conceptual underpinnings to practical interventions—such as modular construction, standardized connections, or materials passports—that facilitate component recovery and support secondary markets (Bakker et al., 2014). Recent international standards and policy instruments further institutionalize DfD by articulating measurable requirements for adaptability, maintainability, and traceability, positioning it as a critical operational lever for embedding circularity in the built environment at scale (ISO, 2020).

Global statistics estimate that about 40 percent of C&D waste are being reused or recycled (Interreg Baltic Sea Region, 2025). Across the AECOO industries, these numbers vary greatly by material family and geopolitical framework: The European Union reports an average recovery rate of about 89% (Caro et al., 2024), the US publishes a “next use” rate of about 76 percent (EPA, 2024), while other regions report ranges of 3-10% and below (Ma et al., 2020). Globally, construction steel reaches a global industry-average recycling rate of about 95 percent, aluminum about 71%, while recycling of wood waste for example is estimated at only 15 percent. Importantly, these numbers are diversion statistics and thus include downcycling, backfilling and energy recovery operations. Numbers for pure recycling are generally much lower; and only limited examples of high-value and high-utility (CE definition) material recycling exist in the construction industry (e.g. H2-based steel recycling) since most post-consumer recycling processes manufacture lower-utility products from recycling feedstock (e.g. window glass to container glass, metal alloys, cascading use of wood) (Devlin et al., 2023). Considering not diversion but feedstock statistics, only 6.9 percent of the 106 billion metric tons of materials used globally come from recycled or secondary sources—a decline of 2.2 percentage points since 2015 (Circle Economy, 2025). And reuse of construction materials is generally estimated below 1 percent (Byers, 2024), although 20-30% of C&D may be suitable for reuse (Heisel et al., 2024; Skanska, 2024). DfD can be understood as a method to better match supply (salvage, disassembly) and demand (material stock) by supporting reuse as the most sustainable circular economy strategy over less direct reclamation methods, i.e. remanufacturing and recycling. DfD promotes the design of a holistic plan to enable multiple use cycles for virgin and salvaged materials that are introduced in construction. Intentionally designing for end-of-use repurposing and reuse of materials in a building is an effective way to retain economic value across several use cycles, while meeting regulation requirements and waste diversion goals, and reduce the detrimental ecological impacts of the industry with respect to material extraction/ production and associated carbon emissions. DfD helps reduce landfill volumes and emissions, prevent new resource extraction and requires less or no energy-intensive processing compared to virgin production through the design for reuse and repair (Sasidharan & Chani, 2012).

Emerging legislation in the United States addresses different (partial) elements of this shift: Some policies and incentives specifically focus on the end of use of buildings, requiring the diversion of a percentage of materials or specific material groups from landfill; other legislation provides economic compensation for recycling or reuse (Heisel et al., 2024). Designs that ease the disassembly and harvest of materials at end of use with reduced energy, costs, and damage to the components work in parallel with these new requirements - however are not yet specifically addressed in code or legislation.

3. Methodology

The European, Asian, and Australian contexts offer comprehensive literature reviews, as well as articles outlining the transition to CE principles in the AECOO industries (Banihashemi et al., 2024; Nie et al., 2024; Ostapska et al., 2024; Passarelli, 2024). However, in The U.S. context, peer-reviewed publications generally highlight more specific (sub-)topics such as Life Cycle Assessment (LCA) strategies to evaluate sustainability impacts of DfD design scenarios (Eliote et al., 2024; Roberts et al., 2023), or low-carbon material alternatives to maximize reprocessing and recycling potentials of disassembled building components (Hu, 2023). Only two literature reviews were identified that focus more generally on DfD: However, Ostapska et al. (2024) and Rios et al. (2015) both describe limitations in sourcing scientific papers that identify practical applications of DfD, whether in built projects or firm practices, and consequently focused their analysis on case study analyses, stakeholder interviews, and the use of online search engines in their methodologies. Given the observed lag in implementing DfD at scale within the U.S. construction industry as well as the limited peer-reviewed literature on the topic within the specific geographic contest, this paper aims to provide a structured overview of current capabilities and constraints, offering a foundation for advancing DfD as a core strategy in transitioning toward a more circular and resource-efficient future by consolidating knowledge from both industry and academic perspectives. The scope of the paper is defined geographically and legally by the United States of America, and by AECOO industry activities spanning 1900 to 2050, more specifically projecting 5-10 years into the future with respect to planning and design and 30 years for policy ambitions.

This paper is part of a larger, multi-year project aiming to characterize the status and readiness of the US construction industry with respect to circularity. An initial evidence inventory was conducted to identify relevant search terms for these emerging technologies, materials, and practices, using terms to restrict the search including “topics,” “trends,” “tech,” and “materials,” combined with terms related to the area of research, such as “construction,” “sustainable,” and “circular.” Webpages and publications were filtered based on the scope outlined above. These very broad results were evaluated and categorized manually in summary sheets grouped by 27 materials and 17 concepts (Heisel et al., 2023).

As part of this evaluation, two variables were determined for each of the identified materials and concepts: the estimated amount of time in years to reach market maturity within the United States, and a ranking from 1-5 reflecting the expected impact on the AECOO industry (where 1 represents no-to-low impact and 5 represents high impact). These scores were determined by characteristics of each material concept, including the scale of the supply chain and product/ resource availability, progress in standardization for widespread application, and progress/ development of complementary technologies.

Materials and concepts were then mapped along the x and y axis according to their quantitative variables concluded from the above characteristics: (x) time to maturity ranging from 0-10 years, and (y) impact on a scale of 1-5. Graphically mapping the materials and concepts in this way organized the results into four quadrants ranging from low impact and low time to maturity to high impact and high time to maturity. Three clusters were identified from the *high impact, low time to maturity* and *high impact, high time to maturity* quadrants for a deep dive into their application potential: Urban Mining, Design for Disassembly, and Modular Construction.

Heisel et al., 2024 reviews the current state of urban mining in the U.S. AECOO industry, framing it as a critical circular economy strategy for reclaiming materials from decommissioned buildings not originally designed for disassembly. Drawing from market reports, case studies, policy documents, and industry sources, the paper maps emerging legislation, stakeholder roles, and implementation strategies, and assesses material-specific opportunities and barriers across concrete, timber, steel, glass, and brick. The study identifies key gaps—including limited documentation of building components, underdeveloped processing infrastructure, and fragmented supply chains—and highlights drivers such as waste diversion policies, adaptive reuse trends, and technological innovations in scanning, grading, and robotic processing. Case studies demonstrate how collaborative planning between deconstruction and new construction projects can maximize salvage value, while “takeaways” outline criteria for selecting suitable buildings and practices to optimize recovery. The paper concludes that advancing Urban Mining in the U.S. will require coordinated legislative, technical, and market interventions, alongside the development of standardized material passports, specialized workforce skills, and design approaches that facilitate future reuse.

Using a similar approach, the paper at hand focuses on the concept of Design for Disassembly within this larger project.

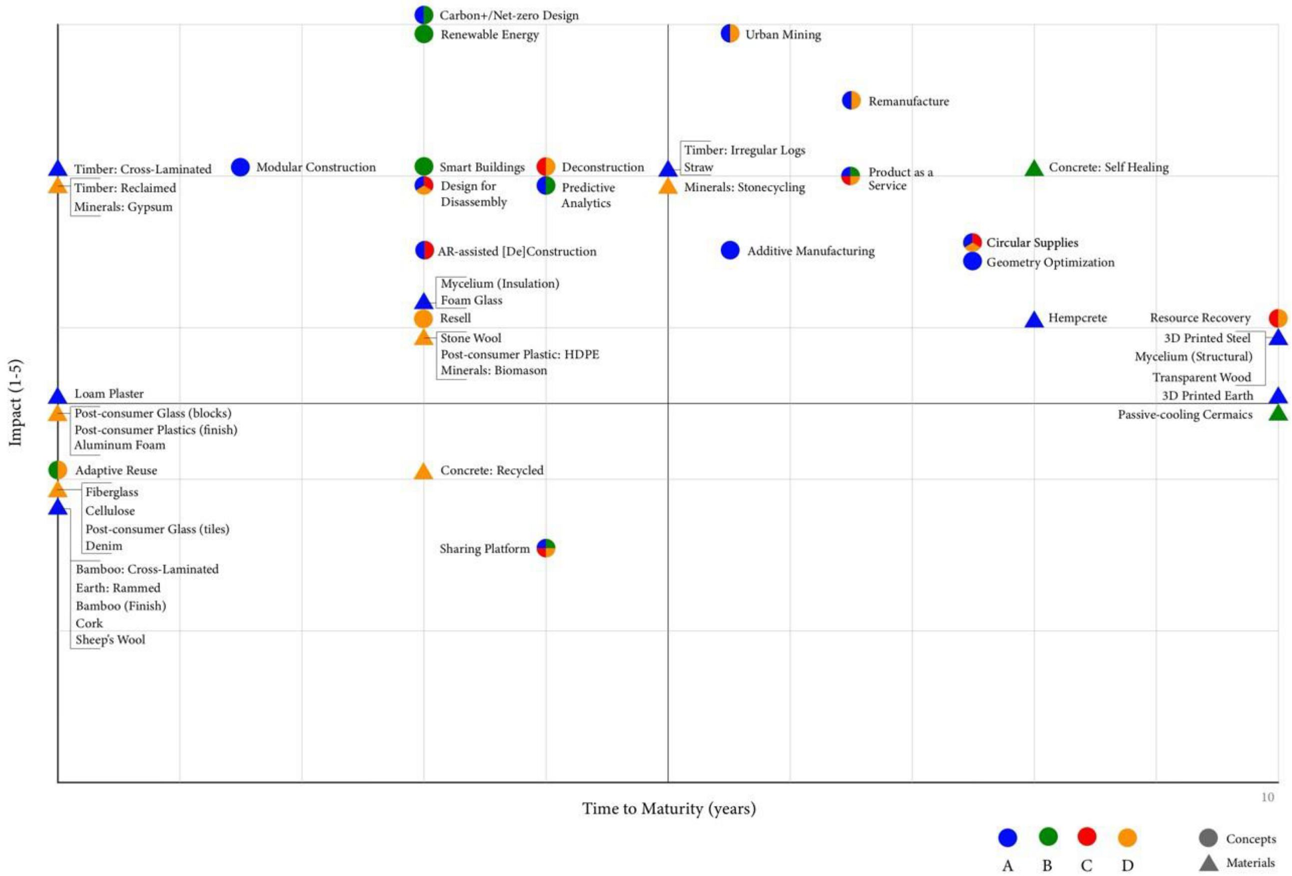

Figure 1. Impact vs. Time for Current and Emerging Sustainable Material and Construction Practices. (Reprinted from Heisel et al., 2024).

An initial review using Scopus and the search terms “circular construction” and/ or “design for disassembly,” yielded review articles that address emerging technologies and business practices in the AECOO industry globally. When refining the results by topical and geographic relevance to the United States, the resulting articles mostly describe selected materials, construction stages, or emerging tools, but do not offer general surveys of the industrial or political landscape, nor do they offer an overview of practical and applicable trends and strategies towards the implementation of DfD in future built projects and practices. Consequently, the scoping review for this paper was conducted using the search terms “circular construction” and/ or “design for disassembly” using the online search engine Google to capture a wider range of sources and source types. Filtered for geographic relevance to the US and publication dates within the past 5 years, 50 articles, reports, and industry/ product applications were selected for further analysis and comparison, spanning from material research to product development, architecture/ manufacturing company websites, organizational and institutional websites, and market reports. Furthermore, 50 legislation and project specific case study sources were identified using the same search methodology to determine the gaps between the theoretical or prototypical developments in the US AECOO industry and the legislative framework and operational infrastructures that are established to facilitate their implementation.

Sections 4 synthesizes the results of this review by positioning global understandings of DfD strategies and conditions within US-specific material, industry and policy frameworks to identify local gaps and drivers of implementation at scale. Sections 4.1-4.3 specifically focuses on stakeholders and their roles, construction systems and material considerations with respect to DfD. Sources include the findings and reports of industry leaders, organizations, researchers, and private companies such as the American Institute of Architects (AIA), the US Environmental Protection Agency (EPA) or the Whole Building Design Guide (WBDG) which consolidates resources from 15 US government agencies for architectural practitioners. Sections 4.4-4.6 identify US case study buildings, and local codes and legislation that implement identified strategies to varied degrees of success to help verify and evaluate identified gaps and drivers. Sources here include reports from the US Department of Energy (US DOE), the US Green Building Council (USGBC) which develops and implements the LEED green building rating system, and reports from university research programs.

4. Results

4.1. Stakeholders and Roles in DfD

Compared to design projects in the linear economy, stakeholder relationships and roles change when designing and constructing a DfD project, especially due to the required projection on future (re)use cases of materials and components. The anticipated disassembly of components must be incorporated into the assembly and construction steps of components by the architect in collaboration with multiple stakeholders across disciplines. *Table 1* illustrates this process chronologically and implements findings into the design stages and practitioners' relationships in the US context.

Figure 2 displays stakeholder relationships during the decommissioning stage of a DfD project in the US context, which must incorporate the transfer of materials and components from an existing building to a new project. In this scenario, the *Supplier Project* is a building in the process of disassembly, while the *Recipient Project* represents a building that is in the design phase and plans to absorb the disassembled components of the Supplier Project.

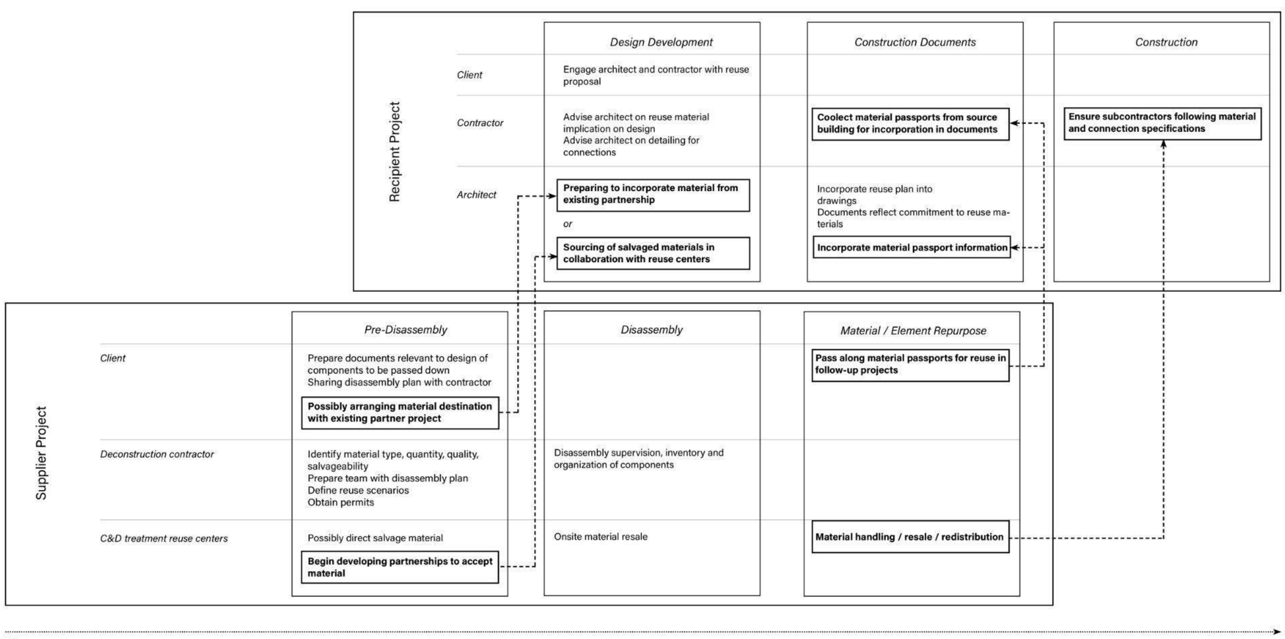

Figure 2. Stakeholder Roles and Relationships in the Disassembly Stage of a Supplier Project and the Design and Construction of a Recipient Project (Collated from AIA, 2023; Cruz Rios et al., 2021)

Table 1. Stakeholder Roles in Design for Disassembly Projects by US Design Stages (Collated from AIA, 2023; Guy & Ciarimboli, 2007; Heisel et al., 2024)

	Client	**Architect**	**Contractor**	**Engineer (Mechanical / Structural)**
Pre-Design	Request design team qualifications; Propose DfD benchmarks; Engage contractor for collaboration on DfD	Proposal of DfD application to the project; Determine site constraints, use timeline and contract period; Plan DfD strategy/ goals; Coordinate stakeholders (contractor, vendors, reuse centers)	Briefing and training for DfD	
Schematic Design		Design check of deconstruction outline	Advise architect on deconstruction process, salvage priorities and the recycling requirements of different materials	Early involvement in design consultation; Advise materials that can be salvaged and reused, focus of DfD system
Design Development		Detailed construction plan	Advise architect on deconstruction implication on design; Advise architect on detailing for connections	Mechanical system designed with appropriate lifespans; Structural system designed for optimized reuse potential with mechanical connections; Advising on structural connections; Approve and regard materials for use in design
Construction Documents		Incorporate deconstruction plan into drawings Documents reflect commitment to DfD	Advise architect on construction practices and deconstruction plan drawings / specifications	
Construction Administration	Oversee maintenance staff, contractor qualifications for DfD; Anticipate expedited construction times	Record and update "as built" documents and material passports; Brief maintenance staff on DfD strategy; Ensure material and connection specifications	Maintain quality of details as designs; Train sub-contractors for DfD; Ensure subcontractors following material and connection specifications	

Decision making regarding reversible structural connections occurs during design development when building details are in development or already resolved. A collaboration between architect and engineer is necessary for determining how building elements come together at joints (which impacts material choices, visual aspects of the project, and may even alter conceptual considerations). At this stage, structural optimization is relevant to simplify the process of deconstruction itself. At all stages, architects and other specialists have the responsibility of conveying and promoting the benefits of DfD within the context of a circular economy to the client.

The planning process for the architect of a DfD project differs from the typical design process mainly by the need to design and choreograph both the assembly and the disassembly of all building components. Variations in design processes are outlined in *Table 2.* For the architect this not only means collaborating with engineers and deconstruction specialists earlier in the design process but also taking an active role in the development of mechanical connection details, material selections, and structural simplifications that can change the design and spaces of the project. Additionally, the architect is projecting the future of each component with the aim of reuse or repurposing, seeking to design a flexibility into each individual element (Delta Institute, 2018).

Table 2. Relevant processes, timelines and scales for Design for Disassembly
(Collated from AIA, 2023; Delta Institute, 2018; WBDG, 2023)

Architectural Process	Phase	Collaboration	Scale
LCA and Cost Analysis: Based on initial building use, incorporating building and material end of use	Pre-Design stage; Schematic design; Design development	Reuse specialist/ consultant	Building
Material selection and lifespans, including use of reused materials: Replacement and connection between different elements, durability of material and reuse potential (lower, for example, for 'wet' materials); Cost implications of using reclaimed materials, regrading by engineer or deconstruction/ reuse specialists for safe use	Design development	Engineer, reuse specialist/ consultant	Component
Inventory of materials and components: Specifications, warranties, manufacturer details (including Material Safety Data sheets), intended design/ service life, reuse options, standardization of elements for reuse potential	Design development	Engineer, reuse specialist/ consultant	Component; Building
Connections: Access and readability, as well as ease of disassembly and tools used by deconstruction team	Design development	Engineer	Component; Building (especially for connection systems)
Structure: May opt for simpler forms, fewer structural points for ease of deconstruction, depending on machinery intended for deconstruction	Design Development	Engineer	Building
Separation of layers: Systems and material layers separated to facilitate replacement/ maintenance and end-of-use deconstruction	Design development	Engineer	Building
Detailed plan of disassembly process: Strategy behind designed reusable elements, plan with instructions for deconstruction at end of life including equipment and categorization/ storing indication for dismantled components	Design development; Construction documents	Deconstruction specialist, engineer	Building
Collaboration with Manufacturer, Engineer, Consultants: Early involvement in design development to incorporate passive services, detailed assembly methods and construction documents, designing multifunctional structural systems	Schematic design; Design development; Construction documents	Manufacturer, engineer, consultants	Building; Component

4.2. Construction Systems Supporting DfD

Table 3 specifies a series of systems which are supporting Design for Disassembly. Generally, self-supported assemblies and systems with discrete elements that have the potential to be mechanically connected can be easily deconstructed with minimal damage to other components. Panel systems (such as Structurally Insulated Panels) that combine different materials and functionalities are most effectively reused in a new system if their structural integrity is not compromised when removed (and cut to new dimensions.) This strategy reuses the components as a unit and the materials within the panels do not have to be pulled apart (Guy & Ciarimboli, 2007). At the same time, deconstruction waste is being reduced or eliminated because of the minimized impact on site, easier sorting of recovered materials and maximized reuse and repurposing of building components (Roberts et al., 2023).

Table 3. Examples of Design for Disassembly Systems in the US Context by Shearing Layer (Collated from EPA, 2010a; GME, 2024; O'Grady et al., 2021; Peitz, 2023)

Layer	System	Connections	Assembly	Disassembly
Skin	Structural Insulated Panels (SIPS) roof assembly	Fastened with screws	Simplified connection and assembly; Combining roof sheathing, insulation, ceiling finish in one component.	Removed and reused as components, can be cut into smaller panels when disassembled
Skin	Tiled interior finishes	Interlocking, minimal adhesives	Modular systems of interchangeable units installed with minimal adhesion/ mechanical fastening	Smaller standard dimensions individually replaceable, potential take-back and recycling systems for manufacturers
Skin	Raised access floor system	Mechanical	Allows MEP systems to run through	Easy separation of MEP and flooring system during disassembly with minimal damage
Structure	Prefabricated concrete	Mechanical, removable fasteners; Bolted, with pre-embedded bolt holes/heads	No application of in-situ concrete, components that fulfill multiple functions (structure, finish, protection)	Discreetly removable components, must be used with same function
Structure	Modular block wall system	Dry stacking	Pre-engineered systems that function without mortars, adhesives, or reinforcing	Easily demounted and reused in a variety of site conditions
Structure	Light gauge steel framing	Mechanical	Compatible with demountable connections, such as bolts, screws, etc.	Easy to disassemble
Structure	Cross-Laminated Timber (CLT) systems	Mechanical	Unit components that can be mechanically connected, flexible grids designed for adaptability and reconfiguration	High disassembly and reuse potential; bolt design critical to allow disassembly
Structure	Timber frame	Mechanical	Mature construction system; use of clips, angles, plates, bolts, over nails for facilitated disassembly	Damage to individual components must be assessed (e.g. nails)
Structure	Steel open web truss	Bolted	Mechanical ducts/utilities have space to run through	Easily demountable, reusable in new structure with same application

4.3. Materials and Connection Details for DfD

Considerations on material selection and detailing for DfD vary due to the unique characteristics of any architectural project. However, independent of project characteristics, specific DfD recommendations can be made based on material family and associated material specifications. Maximizing the reuse potential for each component with minimal or no reprocessing should be a goal for all material components and assemblies in a DfD project, as this results in the least energy- and/or material-intensive way to repurpose the material (Cruz Rios et al., 2021; Heisel & Hebel, 2022).

- ***Concrete:*** Precast beams, columns, and slabs of concrete have a high potential for reuse on the condition that no concrete is poured in place to connect discrete elements. Stainless steel connections and removable fasteners are ideal in connecting, and eventually disconnecting individual elements for repurposing (Salama, 2017). While reversible structural connection details for prefabricated concrete elements are available in Scandinavia (Paananen & Suur-Askola, 2019), there is no known project in the US specifying true DfD in concrete. Available US examples include the reuse of highway concrete slaps in residential housing (Gorgolewski, 2017), the use of "weaker" mortar joints between elements for easier disassembly, or the use of bolted and/or post-tensioned connections in the assembly of concrete elements (Küpfer et al., 2023).
- ***Timber:*** Timber has high potential for DfD at varying scales. According to an EPA Lifecycle Construction Resource Guide, lumber is the most successfully reused building material in the US (*EPA*, 2010b). Dimensional lumber and mass timber elements, such as cross-laminated (CLT) or glue-laminated (glulam) timber beams are similar to steel structures when considering the DfD potential in that elements can be readily reused if disassembled, assuming mechanical connections are not significantly deformed after use. If ends are damaged or do not fit the next application, they can be replaced with new plates to facilitate the connection or trimmed off to provide a new base for reconnection (Teshnizi, 2015). Therefore, standardized and interchangeable connections are optimal for planned disassembly. The longevity of mass timber is optimal for repurposing deconstructed components and current research aims to optimize the connection details to facilitate multiple use cycles (Peitz, 2023; Bergsagel et al., 2025). Reuse of timber components also optimize the carbon storage by delaying the end-of-life release of sequestered carbon (Peitz, 2023).
- ***Steel:*** When reversible connections are utilized, elements are easily removable to be reused with the same application in a new structure. Welded or deformed connection points might have to be cut to be removed, which shortens the material's length and structural capacity. Like timber elements, damaged or obstructive connection points and ends need/ can be repaired or removed to maximize the elements' utility in reuse. The structural capacity of steel elements and connections can be enhanced before reuse with additional stiffeners or flanges. A successful deconstruction case study for this material was the deconstruction of the Boulder Community Health Hospital in Colorado, which reclaimed 94% of the building's materials and reused the building's structural steel in both the construction of the city's new fire station and the affordable housing development located on the same site (Kelleher & Stanek, 2023). DfD considerations for steel include reversible alternatives to concrete encasings to fulfil fire safety requirements as well as the documentation of steel type and loading scenarios in materials passports.

  In addition to reuse, there is also the possibility to recycle steel at its end of use. Though reuse is the preferable end-of-use pathway within the framework of DfD, the recycling of steel is a high efficiency process (as long as supported by renewable energy sources), and most of today's steel is produced (at least partially) from recycled feedstocks (Cooper & Allwood, 2012).
- ***Masonry:*** Masonry skins have the potential to be disassembled if mortar or other adhesive connections are applied and/or replaced by mechanical solutions so that each block/ brick can be removed without damage to the unit itself. Cement-based mortars tend to limit the salvage potential for brick, as bricks often break before such binding agents. Solutions that assemble masonry using dry connections are increasingly popular for brick veneer or other facade applications but can also be applied in engineered systems to perform structurally (Biggs, 2022; Guy & Ciarimboli, 2007; *FRONT*, 2021). Alternative adhesives that are

non-toxic and weaker than the brick material itself (such as lime mortars) allow disassembly or deconstruction without damage to the brick (Brick Industry Association, 2023; Webster & Gumpertz, 2005).

Methods for connecting materials and elements in constructions that are designed to be disassembled must be articulated. *Table 4* synthesizes basic dry connections and their potential to be incorporated in DfD systems. The benefits and drawbacks of such connections must be examined by the architect and stakeholders of a DfD project with respect to their structural performance, reversibility, impact on materials and elements as well as aesthetic and conceptual considerations.

Table 4. Connection Requirements/ Values in the US Context
(Collated from Balodis, 2017; Bergsagel & Heisel, 2023; Urban Machine, 2024)

Application	Connection Type	Reversibility Potential	Damage to Components
Generally structural	Screws	Reversible and strong connection, application of common tools	Screw holes in components may limit reusability
	Bolts, clips, fasteners, plates	Strong connections, potentially reusable connections for same or similar application in new structure	Seizing up over time may cause issues with removal, larger holes may limit reusability or result in element downsizing
	Nails	Reversible connection, may be difficult to locate and remove (created demand for new technologies such as denailing gun or automated robotic denailing)	Nail holes in components may limit reusability. Broken or hidden nails can limit timber machining. End of elements may be compromised, resulting in element downsizing
	Rivet	Easily located, designed for permanence, may be difficult to remove over time	End of element may be compromised, resulting in element downsizing
Generally non-structural	Dry stacking, interlocking	Easily reversible, each unit is accessible and may be removed for maintenance separately	Minimal damage
	Velcro	Adhered to element, easily reversed yet only applicable with same connector	Removal of Velcro may damage component
	Straps	Easy to locate and remove	Straps may damage material at outside edges

Specific connection details are critical to consider when evaluating designs for their potential to be disassembled. Key parameters to consider are how common specific connection details and hardware are in the market, the strength of the connections, their spacing and the number of components necessary, as well as their location, accessibility and ease of removal.

4.4. US Legislation on DfD

One of the mechanisms for incentivizing and enforcing DfD is emerging legislation that targets reduced embodied carbon, deconstruction, and material reuse. *Table 5* outlines current US legislation recently passed at the federal, state, and city levels.

Table 5. Existing US Legislation by Scale and Focus (Collated from individual sources specified below)

Scale	Legislation / Guidance	Implementation Timeline	Focus Area	DfD Relevance
Federal	EPA's C-MORE: Construction Materials Opportunities to Reduce Emissions (EPA, 2024; OCSPP, 2023)	Continuous (Grant program has been discontinued)	Programs (such as technical assistance, labeling, and threshold-setting) supporting access to new markets for low embodied carbon materials	Low-carbon material requirement can lower barriers to future circularity and reuse (DfD)
	Rocky Mountain Institute (RMI) Roadmap to Zero (RMI, 2025)	By 2050	Framework for reaching zero embodied carbon in federal buildings	
	US General Services Administration (GSA) P100 + PBS Memorandum (USGSA, 2023)	Net-zero by 2045	Mandatory design standards for-GSA owned buildings, new optional benchmarks targeting embodied carbon and construction decarbonization (including material salvage)	
	EPA Community Housing Resource Center (CHRC) Pilot Project (EPA, 2010a)	2004 (Initiated) 2010 (Follow-up study)	Grant to the Community Housing Resource Center (CHRC) to build DfD project, create US precedent study	DfD guidelines
	AIA "Buildings That Last" Guidance (AIA, 2024)	2030 (Goal for architects to track progress towards carbon-neutral design)	Country-wide guidelines for adaptable design, disassembly methods, reuse integration	
State	Buy Clean Programs (Federal Partnership) (BlueGreen Alliance, 2025; Kvam, 2023)	Colorado, Washington, Oregon, California, Minnesota, Connecticut, New York	Promote use of low-carbon, US produced construction materials with low embodied carbon	Low-carbon material requirement can lower barriers to future circularity and reuse (DfD)
	Green Construction Codes (ICC, 2022; DCRA, 2017)	District of Columbia (D.C. Green Construction Code) California (California Green Building Standards Code, CALGreen)	Mandatory green building codes addressing building and material reuse, based on IgCC but amended for state-specific goals	
	International Green Construction Code (IgCC) (IgCC, 2024)	Rhode Island, North Carolina, Oregon	Statewide adoption of IgCC clauses, mandating standards for sustainable design in specific building types	
	International Residential Code (IRC) (Justia Law, 2025)	Washington	Allows reclaimed sawn lumber to comply with new lumber standards without being regraded	Streamlining material reuse
	Department of Environmental Quality (DEQ) Framework (Oregon Metro and Department of Environmental Quality, 2021)	Oregon	Formalizes deconstruction and salvage guidelines, supporting component recovery and resale	Deconstruction / Material reuse

Table 5 (Cont.) Existing US Legislation by Scale and Focus (Collated from individual sources specified below)

Scale	Legislation / Guidance	Implementation Timeline	Focus Area	DfD Relevance
City	Building Performance Standards (BPS) (Veckta, 2024; Akila, 2023; GSA, 2025)	New York City, NY (Local Law 97) Boston, MA (Building Emissions Reduction and Disclosure Ordinance) Washington, D.C. (Clean Energy DC Omnibus Act) Seattle, WA (Building Emissions Performance Standard) San Francisco, CA (Existing Buildings Ordinance) St. Louis, MO (Energy Performance Standards) Denver, CO (Building Performance Standard)	Operation carbon caps, leading to investments in low-carbon materials and refurbishments	Low-carbon material requirement can lower barriers to future circularity and reuse (DfD)
	Climate Emergency Workplans (City of Portland BPS, 2023)	Portland, OR (Climate Emergency Workplan) Cambridge, MA (Net Zero Action Plan)	Low-carbon alternatives, adaptive reuse, whole building LCAs	Low-carbon material requirement can lower barriers to future circularity and reuse (DfD)
	Deconstruction Ordinances (IgCC, 2024; Armstrong & LaMore, 2018)	Portland, OR San Antonio, TX Baltimore, MD Palo Alto, CA San Jose, CA Bolder, CO Boise, ID	Mandates deconstruction of specific building types or projects built within time period	Deconstructio n/ Material reuse
	Construction Demolition Diversion Ordinance (King County Solid Waste Division, 2023; Armstrong & LaMore, 2018)	Lee County, FL Cook County, IL King County, WA Milwaukee, WI Portland OR Fitchburg, WI Palo Alto, CA Austin, TX San Francisco, CA Seattle, WA Chicago, IL Aspen, CO Emeryville, CA Rancho Cucamonga, CA San Jose, CA	Mandates diversion of either specific materials from landfill, or percentage of total building materials to be salvaged	
	Climate Action Plan (Carbon Direct, 2024)	36 cities across multiple states [1]	Reducing greenhouse gas emissions, including minimizing building carbon footprint	Reducing embodied carbon

[1] Albuquerque, NM, Atlanta, GA, Austin, TX, Baltimore, MD, Boston, MA, Charlotte, NC, Chicago, IL, Cleveland, OH, Columbus, OH, Dallas, TX, Denver, CO, Detroit, MI, Honolulu, HI, Houston, TX, Indianapolis, IN, Ithaca, NY, Kansas City, MO, Los Angeles, CA, Louisville, KY, Memphis, TN, Miami, FL, Minneapolis, MN, New York, NY, Oakland, CA, Oklahoma City, OK, Philadelphia, PA, Pittsburgh, PA, Phoenix, AZ, Portland, OR, Raleigh, NC, Sacramento, CA, San Antonio, TX, San Diego, CA, San Francisco, CA, San Jose, CA, Seattle, WA.

The United States is unique when compared to European nations in that much legislative power, especially regarding the built environment (building permitting, construction codes, planning and zoning) rests in the hands of local governments rather than the regional or national governments. Environmental legislation is limited on a national level and considered politically risky to pass in Congress. State and local governments tend to implement more specific legislation and mandates with tangible guidelines for implementation that can override federal guidelines or requirements.

Several states have chosen to adopt the International Green Construction Code (IgCC) as a subclause to the IBC (*Table 5*). The IgCC addresses material diversion by requiring a percentage of C&D waste to be diverted from landfills (ranging 50-75%). While this can be accomplished through means other than DfD (source separating materials for downcycling) DfD is the most circular and environmentally sound practice for end-of-use materials management.

The LEED certification in the United States creates ratings in Building Design and Construction, Interior Design and Construction, and Building Operations and Maintenance. Points are accumulated for design decisions that address sustainable targets, including carbon, waste, materials, and energy (*LEED, 2023*.) A drawback of this certification system is the limited evaluation for the end of use of the buildings and their materials. Specifically, LEED does not yet award points for DfD, differentiating it from similar frameworks like BREEAM in the UK or DGNB in Germany. However, under the Material and Resources (MR) category, credits are awarded for reused and salvaged materials (Building Product Disclosure and Optimization), salvaging and reusing materials (Construction and Demolition Waste Management), reusing interior walls and other nonstructural components (Interiors Life-Cycle Impact Reduction), and designing for adaptation including disassemblable interior partitions and modular components (Design for Flexibility) (*USGBC*, 2023). The Living Building Challenge is another certification program which encourages material reuse and salvage as options to meet material sourcing requirements as part of the Materials Petal. Within the same framework, the Equity and Beauty Petals enforce adaptable and deconstructable buildings as community assets (*International Living Future Institute*, 2025).

Other rating systems that grant credits for DfD are the Green Globes under the nonprofit Green Building Initiative (GBI) and the Cal Poly scoring system, which evaluate the material choices made for the project in relation to design constraints and costs.

4.5. DfD Case Studies in the US

Heisel, et al. 2024 synthesizes a series of US case studies which have been successfully deconstructed, and which have documented the end-of-use material streams for reclaimed materials. While those case studies exemplify different relationships between supplier and recipient projects as referenced in *Section 4.1, Figure 2*, they were not designed explicitly for the purpose of disassembly.

Several case studies across the United States have been designed for and constructed with the specific goal of disassembly in mind. *Table 6* compares a selection of these projects with the DfD strategies introduced in Sections 4.2 and 4.3. It is important to note that none of these projects have been disassembled to date and thus only represent the design phase and stakeholder collaboration of a DfD project. The analysis remains theoretical, as the proof of the success of the selected strategies regarding the reversibility of connections and the reutilization of materials and products in future projects is still missing.

Table 6. Case Studies of Design for Disassembly in the US Context *(Collated from Life Cycle Building, 2013; Sasidharan & Chani, 2012; Balodis, 2017)*

Case Study	Building Type	System	Components/ Elements	Materials	Connections	Notes
OPEN_1 House/ Bensonwood Homes (NH)	Residential	Frame structure	Frame structure	Lumber	Mechanical	Uses Brand's layer diagram to separate materials and systems with different lifespans/maintenance timelines
			Modular prefabricated wall panels (with sheathing, cellulose insulation, finishes)	Lumber framed		Exposed
			Open web trusses	Steel		Plenum for ductwork and utilities
			Structural insulated roof panel system			Can be cut into smaller pieces that have same structural integrity
Intelligent Workplace (Carnegie Mellon University, Pittsburgh, PA)	Institutional	Raised access floor system	Open web truss	100% prefabricated recycled steel	Mechanical (bolted)	Mechanical ducts/ utilities run through trusses
			Decking roof system	Metal		
			Prefab modular cladding	High-performance glazing		Reduced on site waste
			Insulated roof panels			
			Raised access floor system			
Wal-Mart Eco Store (Lawrence, KA) / William McDonough + Partners	Commercial (designed to be converted to Residential)		Open web Trusses	Laminated lumber	Bolted	
			Modular blocks	Concrete		Removable and reusable
Herman Miller SQA / McDonough + Partners	Industrial	Frame	Open web trusses	Steel	Bolted	
Chartwell School (Seaside, CA) / EHDD Architecture	Institutional	Truss frame	Structurally insulated roof panels		Bolted	
Nasa Sustainability Base (Palo Alto, CA) / McDonough + Partners	Institutional	Steel truss/ "Exoskeleton"	Truss frame/ "Exoskeleton" and panelized metal envelope		Bolted	Trusses are visible and accessible from the building's exterior, designed to be easily repaired or removed in case of a seismic event.

The above case studies set precedent for the DfD concepts that are emerging as guidelines in the US and that are ready to implement within the existing economic and material infrastructures.

4.5.1. Design decisions incorporating contractor and engineering feedback (reference Section 4.1, Table 1) Project delivery methods, such as Integrated Design Process (IDP) and Design-Build (DB) methods, are already used in the US. These allow for early planning of material (re)use, coordination across the design and means of implementing structural, MEP, and finish systems (planning to separate ductwork and utilities, for example, and providing space for them in truss systems or raised floor systems), and documentation of components (Mañes-Navarrete et al., 2025).

4.5.2. Supplier and recipient project relationship (reference Section 4.1, Figure 2) One design implication of DfD is to consider building conversions and alternative uses for the designed structural systems within the first phases of the project. With more adaptive reuse work being undertaken in major US cities, firms can plan for these future changes within current designs. For example, triggered by the Covid-19 pandemic, office space was converted into over 20,100 units of housing in 2021 (*CNBC,* 2021). This trend was most prominent in U.S. cities such as Philadelphia, PA, Washington, D.C., Los Angeles, CA, New York, NY, and Cleveland, OH.

4.5.3. Architectural processes (reference Section 4.1, Table 2) Material selection for sustainable design is increasingly supported by legislation, and the uses of mass timber and steel reflect a transition to designs with discrete components and dry connections (referenced in *Section 4.3*.) The choice of simpler structural forms such as frame structures (discussed in *Section 4.2, Table 3*), mechanical connections for all major systems (discussed in *Section 4.2, Table 4*), and the separation of building layers with accessible components for facilitated maintenance and deconstruction (referenced in *Section 4.2, Table 3*) are all design decisions which promote disassembly at end of use. This directly addresses several of the legislative and certification deconstruction requirements/ guidelines (referenced in *Section 4.4)*. Additionally, it ensures that the quality of the pool of reclaimed materials is available for future buildings after the disassembly of these projects by providing larger stock sizes of materials with less end damage (*PMI*, n.d.)

4.6. Digital Tools and Innovations for DfD and Material Recovery

At present, the US market lacks standards for documentation of materials and components. The variation in construction practices and regulations between states is one factor responsible for this, preventing the development of a uniform system of standards and methods. Industry/ start-up companies seeking to fill this void are developing materials exchange platforms as well as methods, means and technologies for their users to document assets for exchange or resale (*Rheaply*, 2023; *iWasteNotSystems*, 2023).

Generating material passports and catalogs which can facilitate DfD marks another innovation area. Building and materials passports are a critical component in DfD. In construction, material passports track material quantities, qualities and other attributes (Heisel & Rau-Oberhuber, 2020; Heisel & McGranahan, 2024; ISO, 2024). These are considered living documents, and require updating as the building ages, supplemented with information from repairs or retrofits to the buildings. At the end of use, a building or materials passport can inform contractors and other disassembly/ deconstruction stakeholders of the location and quantities of materials and components, their conditions, ease of removal and reuse potential and advise on the applied connection details, the required methods of removal and necessary tools to disassemble a building for reuse (Rios et al., 2015). Materials passport platforms such as Madaster can track commodity prices for materials in relation to their current market values, allowing building owners to estimate the price of individual elements within their building, as well as develop an understanding of how such prices might appreciate/ depreciate over time (Madaster, 2023). The US does not require the submission of building and materials passports in new construction.

In the absence of building or materials passports for existing buildings, LiDAR scanning technology is beginning to be employed in Scan-to-BIM applications and software which creates digital representations of existing buildings (Heisel et al., 2022). But even when documentation exists, buildings change overtime, and these changes are not always documented. One can imagine this technology being used to monitor the state of DfD buildings, tracking wear and other changes that might indicate a component's need for repair or replacement. This combination of building monitoring with an associated materials passport would be considered a digital twin, an emerging field of research within the AECOO industry that is also relevant for product manufacturers when combined with concepts of extended producer reliability (EPR) or product-as-service business model (Cruz Rios & Grau, 2020). It may also be beneficial to building owners, who at the building's end of use plan to sell deconstructed materials. Increasingly, such tools employ Artificial Intelligence (AI) in material or element detection from point clouds or building analysis towards itemized bill of quantities. In the US context, several commercial applications exist for the scanning and reconstruction of digital twins in the built environment (adaptis, 2025; Leica Geosystems, 2025; Matterport, 2025) - although these are still mostly employed to support new construction rather than design for disassembly or reuse. A digital twin can also be visualized onsite using emerging technology such as Augmented Reality (AR). AR disassembly (or deconstruction) enables a digital overlay of geometry and information from digital twin to real space. Given the density of information afforded by this technology, developing augmented reality-aided workflows to guide labor can reduce the number of decisions which need to be made onsite by visualizing the predetermined DfD plan in sequence. AR will be able to overlay information on best tool placement, step sequence, tutorials, material values and element conditions, market status (e.g., whether an element has been sold already) and toxicity levels or other present contaminants and abatement requirements. These concepts are in early-stage development in the university context globally, including in the US (CCL, 2025).

Prefabrication of building elements in controlled, off-site locations and the concept of modular construction (AIA, 2023b, Heisel et al., 2023b) inherently align with DfD principles: Key features such as factory-built components, standardized connections, and dismountable assemblies - while developed for ease of construction and transport - also support future reuse, adaptability, retrofitting and component salvage. Panelized systems with embedded services streamline disassembly and lower waste, reinforcing circular building design paths. Modularity additionally simplifies relocation and lifecycle flexibility, key outcomes of DfD design intent. The disassembly of these components is often the reverse of the assembly process, and therefore prefabrication is an ideal construction method when considering DfD (Arisya & Suryantini, 2021). The US context features a variety of research projects and industry leaders in the field of prefabrication and modular construction (Boxabl, 2025; DIRTT, 2025; Palomar, 2025; True Modulars, 2025; Veev, 2025) - although the end of use of these modular structures only rarely plays a role in the promotional materials.

5. Discussion

5.1. Takeaways

By reviewing existing DfD literature, reports and products in the United States, this paper synthesizes existing practices to create an overview of local application strategies of this concept, as well as the current status and progress of market infiltration/ readiness. The framework in which this synthesis is presented aids the implementation of new design strategies and processes. Stakeholder roles outlining collaboration between client, architect, contractor, and engineer are articulated for each stage of the design process, from Pre-Design to Construction Administration. *Table 1* represents new levels of collaboration between professionals necessary to design a project with components that are designed to be repurposed. *Figure 1* illustrates the relationships and design implications of projects across several material use cycles. LCAs or material inventories are examples of new processes in architectural design stages necessary for the long-term planning of material reuse spanning several materials use cycles, as synthesized in *Table 2*.

For the design of specific elements and their connections, *Table 3* organizes design specifications including methods of assembly and disassembly by shearing layers (site, structure, skin, services, space plan, stuff) to emphasize the importance of separating material functionalities in a building for maintenance, disassembly, and reuse. Considerations for each material in terms of component type, potential for DfD, and optimal connection type (*Table 4)* vary due to design and material specifications.

When comparing DfD principles with existing legislation (*Table 5*), the gaps in legislation and certification systems to incentivize changes in early stages of architecture and construction projects become apparent. The current emphasis on waste diversion rates and recycling of recovered material to meet requirements at end of life does not address DfD, which instead requires adjusted stakeholder roles in pre-design, schematic design, and design development stages of the projects. There are currently no initiatives or guidelines that organize the reuse of material components between supplier and recipient projects, leaving the match making up to the individual client and design team often resulting in additional cost and project administration.

As evidenced in the analyzed DfD case studies *(Table 6)*, detailed plans for disassembly can be developed and implemented. However, inventories of materials/ components and stakeholder collaborations for end-of-use material streams are difficult to pre-establish in the design phases. Issues with project/material ownership and material regrading/ recertification, as well as a lack of take-back and reuse center programs point to an underdeveloped circulatory infrastructure in the United States.

Lastly, material passports, AR, and prefabrication are identified as tools and innovations that aid processes such as material inventories and disassembly plans. There is a strong need to standardize the data management and sharing on material and component characteristics so that this information can be passed from project to project, with some of this technology beginning to emerge.

5.2. Gaps and Drivers

There are several gaps that currently exist in implementing DfD at scale which are listed below. New products, services and design projects geared towards DfD should address the following concerns in their development, implementation and business plans (Delta Institute, 2018; Guerra & Leite, 2021b; Rios et al., 2015b).

- ***Disassembly plan dissemination:*** DfD requires the passing down of construction and material information for future disassembly/ deconstruction. One solution to protect the information and track the way it is passed on is to create a digital platform for storing, maintaining, and providing access to a building's materials/ connections/ assemblies/ etc. regardless of changes in ownership or administration.
- ***Material reuse:*** Especially due to the novelty of reuse (and to some extent recycling) materials within the construction industry, there is market uncertainty surrounding a reused element's reintroduction into a new building system. Market acceptance and demand for reused and salvaged material is driven by the designer and client's commitment to DfD, in addition to legislative and market incentives. Technologies and methods for regrading and lower code and legislative barriers to the reuse of materials are essential to building a strong market fostering supply and demand (Heisel et al., 2024).
- ***Infrastructure:*** DfD requires C&D recycling centers/ reuse centers, storage facilities, specialists to regrade and standardize materials for repurposing, and reuse partnerships to support the circular cycles of materials. The US has underdeveloped infrastructure to support building material reuse, limited take-back programs, only scattered implementation of extended producer responsibility, and no standardized processes for DfD or deconstruction (yet). New types of partnerships between industry stakeholders, non-for-profit or non-governmental institutions, academia and municipalities are required to support and scale the reuse of materials. DfD specifically includes designing for reuse, therefore incorporating the need to establish such partnerships as part of the materials and components specifications.
- ***Whole life/ use cycle perspective:*** The cost of construction with virgin material is conceived to be lower than the cost of construction with reclaimed or remanufactured materials. However, real cost comparisons strongly depend on the applied scope. While immediate construction costs of DfD projects might be higher,

whole life/use costs including maintenance and end-of-use disassembly and resale (compared to demolition and tipping fees) can be costs competitive or even more advantageous, especially when considering additional tax incentives and other available financing tools (depending on location and jurisdiction). Similarly, demolition at first seems cheaper than deconstruction, however both strategies are often cost competitive when accounting for the resale value of salvaged and harvested materials (Heisel et al., 2023c). Studies presenting the projected cost and carbon benefits of all life and cost stages are beneficial to encourage clients to consider DfD. Still, the current economy and the processes of construction are not (yet) effective in supporting reuse. As these processes are increasingly facilitated by new infrastructures of reuse stakeholders, services, and businesses compatible with DfD, the costs of reuse should lower. Stakeholders advocating for DfD claim that eventually the cost of construction with reused material will drop below the costs of construction with new materials also for the initial construction costs alone (Bretana et al., 2020).

- ***Environmental legislation:*** Legislation pertaining to environmental protection, resource management, waste management, the reduction of emissions, landfill fees, and carbon taxes, can all be met by architects and clients with DfD strategies. However, outside of waste regulation, most legislation currently regulates the construction of new projects, instead of focusing on the decommissioning of buildings at the end of use or supporting the reuse of its materials and components. It is expected that state and municipal legislation may continue to tighten the operating framework, directly or indirectly incentivizing and supporting DfD processes.
- ***On-site construction practices:*** Within the US, subcontractors are given a great deal of freedom regarding procuring materials and construction practices. At times this can result in little control or oversight by the architects and general contractors on how the building ultimately comes together. DfD requires detailed specifications and immediate construction management to prevent shortcuts or business as usual solutions on site (e.g. no spray foam) and ensure the reversibility of details and the reusability of materials and components at their highest utility and value.

6. Limitations

The aim of this review is to understand current and estimate future industry developments in DfD implementation, as well as to identify the transformations necessary in architectural processes to advance adaptation. The review is therefore in large parts sourcing non-peer-reviewed (grey) literature, such as product catalogues and promotional websites of start-ups developing innovative technologies, or architecture offices describing their own projects. Biases in market reports and company websites are to be expected, especially for unique products, material systems, and case studies. While a lot of care has been taken to verify information through second sources and/ or first-hand information, these data sources represent a possible limitation to the paper's results. However, due to the number of sources used and the synthesis of data points with general, global and peer-reviewed literature on DfD principles or institutional reports and guidelines, the authors feel confident in overcoming these possible pitfalls of the applied methodology.

7. Conclusions

Generally, the DfD practices and concepts explored in this paper increasingly find implementation in the US although slower than in other contexts. Simultaneously, legislative, technological, and economic infrastructures are being developed to support these practices. Circular construction and the ambition of circular resource use initiated a shift within the AECOO sector, calling for the development and implementation of a circular economy framework in the US.

In absence of top-down requirements, stakeholder and consumer relationships are developing to support circular use cycles of resources, including the tracking of material quantities and qualities, the planning of end-of-use reprocessing and the transitioning of stakeholder ownership. Deconstruction contractors and reuse centers are already supporting material salvage, harvest and reuse by taking on such responsibilities. DfD calls for collaborations to span across extended timelines, with architects designing solutions for future deconstruction contractors, or current owners developing material passports and documentation for future owners.

A close alignment and direct feedback between Urban Mining research, deconstruction practices and DfD can help AECOO stakeholders refine their understanding of the design and processing needs in DfD projects (Heisel et al., 2024). From difficulties with material contamination to inadequate connection design and implementation, missing stakeholder compatibility or difficulties in closing material loops, practical research on Urban Mining can supplement DfD research.

As the architecture and construction industries in the United States evolve to bring questions of circularity and reuse to the foreground, product, technology, and material manufacturers are developing ways to meet this new demand of clients and professionals. They create part of the infrastructures that allow - and require - new practices to be implemented. By designing for disassembly, clients, architects and industry stakeholders create the demand for tools and products - as well as the space for innovation - that provide solutions for a sustainable built environment. We hope the case studies and practical guidelines outlined in this review are valuable to this continued implementation of circular design concepts and the incremental shift towards a circular economy.

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