Rethinking Sustainability: A Pedagogical Approach to Explore Design for Disassembly

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Abstract

As climate change and the global waste crisis intensify, the building industry must adopt methodologies that reduce its environmental impact. This study examines a graduate-level design studio centered on Design for Disassembly (DfD), challenging students to design timber structures for multiple life cycles through material recovery, reuse, and adaptability. Students completed two interconnected design assignments, constructing half-scale prototypes that combined theoretical knowledge, digital modeling, and hands-on fabrication. The second assignment required reusing or reconfiguring components from the first, showcasing adaptability and waste minimization. This paper outlines the studio's learning objectives, describes the instructional strategy, assignments and outcomes, and analyzes challenges and opportunities encountered during the course. Students' reflection journals revealed that they developed a deeper understanding of sustainability, critical thinking, and collaborative problem-solving, while confronting challenges like joinery complexity and material constraints. The study underscores the value of DfD in architectural education to prepare designers to address environmental challenges and advance the circular economy.

Introduction

According to the United States Environmental Protection Agency (EPA), in 2018, six hundred million tons of debris produced by construction and demolition (C&D) of buildings. This amount of C&D debris was more than twice the amount of generated municipal solid waste[1]. The C&D debris includes diverse building materials, including wood as well. To address growing concerns about the buildings' embodied carbon and waste processing, architects should design with the building's entire life cycle in mind. Despite the efforts to use wood as a low-carbon materials in building constructions, current design and construction practices result in the majority of wood materials being sent to landfills or used for energy recovery through combustion, with only a small percentage of structural wood being recycled[2]. Hence, reusing and recycling wood can reduce buildings' environmental impacts and contribute to the circular economy.

Among all the efforts to minimize the buildings' embodied carbon, those focusing on embodied carbon of building's structure and shell can be more helpful, as the World Green Building Council indicates that these building's systems have the greatest contribution to Global Warming Potential (GWP)[3]. Besides new sustainable design initiatives, DfD has emerged with the aimed of extending the useful life of building structures and materials by facilitating their disassembly and reuse. This approach challenges designers to consider the entire life cycle of their creations from the early stages, analyzing the impact of their decisions through the end-of-life scenario and into subsequent life cycles. Whether repurposed, retrofitted, or disassembled, buildings and their components can have renewed purposes in other structures, products, or industries. To achieve this, designers must adopt a comprehensive perspective, crafting thoughtful narratives that account for multiple life cycles.

Although architectural education has made strides in incorporating sustainable design pedagogy, many of these initiatives either teach students to technically measure and analyze buildings' embodied carbon during their life cycles or discuss the concepts of reusing, recycling, and upcycling alongside the critical importance of selecting materials responsibly[4,5,6,7,8,9]. However, few pedagogical experiments have been designed to train students in adopting a comprehensive life cycle perspective[10]. To address this gap, a graduate design studio was developed as a pedagogical experiment involving 15 students, introducing them DfD methodologies. The studio required students to complete two interconnected design assignments, which involved constructing half-scale prototypes of timber structural systems and enclosures with a strong focus on material recovery and reuse. The second prototype incorporated new functional, dimensional, and formal requirements, showcasing the adaptability of reused components. As detailed in the following sections, students engaged in both digital and physical modeling, exploring materials and joinery systems designed to enhance future adaptability and reusability. A hands-on learning approach was central to the studio, as students fabricated, assembled, and disassembled their initial prototypes and reused components in their second designs. This practical application of DfD principles enabled them to internalize key concepts such as material recovery, design flexibility, and waste minimization, while also employing techniques like modularity, standardization, reversible connections, and proactive end-of-life planning[11,12,13,14].

The following sections of this paper outline the pedagogical goals, instructional strategies, and overall framework of the course. The design outcomes of two of the five teams, each with distinct design approaches and outcomes, are presented to illustrate the diverse opportunities and challenges that the studio offered. These outcomes serve as evidence of the learning potential fostered by the studio's methodology. Subsequently, insights drawn from the students' reflection journals are analyzed to discuss these opportunities and challenges in greater depth, culminating in the paper's conclusions.

Pedagogical method

Following a "learning by doing" approach, the Design for Disassembly (DfD) studio was designed to emphasize a recovery-oriented design, focusing on the development of timber structures and compatible envelope systems. This pedagogical strategy combined theoretical instruction, precedent research, collaborative learning, hands-on prototyping, and iterative design exercises. Such a course framework was designed to foster critical thinking skills, improve students' teamwork skills, deepen students' understanding of the environmental impacts of design decisions, and enhance their intuitive grasp of structural systems and construction techniques.

Students spent substantial time investigating potential barriers to reusing and repurposing construction systems for subsequent life cycles, which required them to balance theoretical exploration with practical fabrication. Their time in the woodshop was complemented by the conventional architectural practice of developing digital models that detailed their assembly strategies.

The instructor's interdisciplinary background in architecture and structural design enabled integration of analytical insights with design and construction experiments. This allowed the instructor to offer guidance and solutions whenever students encountered questions or concerns about the structural stability of their prototypes.

Evaluation of student performance was based on a comprehensive set of metrics. The clarity and inventiveness of each team's research trajectory were assessed, alongside their ability to solve design problems resourcefully and conduct thorough research. Moreover, the transition from digital to physical models, as evidenced by finely fabricated prototypes and precise architectural drawings, was a key indicator of technical and creative proficiency. In addition, responsiveness to theoretical research, direct feedback, and group discussions also contributed to the evaluation. Furthermore, students' collaboration was evaluated through peer evaluations incorporated into the assessment of each project.

Course framework

Preparatory activities

The studio commenced with a lecture on life cycle of buildings, the environmental impact of embodied carbon, and statistical insights into construction and demolition waste. The lecture also challenged the misconceptions surrounding wood structures as inherently eco-friendly, highlighting the necessity of end-of-life planning to avoid dumping them into the landfill or releasing their embodied carbon back to the environment by combustion. Moreover, students were introduced to the concept of designing for multiple life cycles, including material recovery requirements and layering strategies.

Precedent research

In the first phase of the studio, students worked in teams of three to investigate precedent projects. These precedents were chosen to be timber structures and compatible envelope systems that reflect the principles of DfD. These principles included creating joinery systems that were visually, physically, and ergonomically accessible, avoiding chemical connections that hinder material separation, standardizing and modularizing components, and maintaining simplicity in structural forms to facilitate ease of construction and deconstruction. As part of their research, students analyzed the dimensional requirements and material limitations of various systems, their potential for reuse, the fabrication processes, and whether modifications were necessary for being employed in the second life cycle. The feasibility of scaling these systems for future building's extensions was also studied.

First design exercise

After completing their precedent studies, students began the first design assignment, fully informed of the agenda and program of the second assignment. This awareness allowed them to approach the initial exercise with foresight, integrating considerations for adaptability and reuse into their designs from the outset. In the first exercise, students were asked to create a timber structural system paired with an envelope, along with a detailed plan for the system's sustainable end-of-life scenario. The design brief required the development of a sustainable alternative to one of the temporary educational spaces on campus, where undergraduate studios were situated during the architecture school buildings' renovations.

Several factors made this design program and site particularly suitable for the DfD-focused exercise. First, the site's accessibility and the students' personal experience within the existing educational spaces provided a deep familiarity with the functional requirements, allowing them to concentrate on applying DfD principles to the structural and envelope systems. Moreover, students were encouraged to challenge conventional "shoebox" design of the existing building by proposing innovative and compelling building configurations that adhered to DfD guidelines.

Second, the historical significance of the existing structure, which had served the architecture school for over half a century, highlighted the environmental and emotional stakes of its end-of-life disposal. This context inspired students to explore sustainable alternatives for temporary single-story buildings that could be disassembled, reused, and adapted for future needs, avoiding landfill waste.

Third, the program required the design to accommodate a student population working, navigating, and staying warm in the temporary space. This prompted students to think critically about modularity, replicability, waterproofing strategies, and thermal insulation for comfort.

Fourth, the one-story structure with medium-span requirements was ideal for exploring DfD strategies, as its components could be reused either at the same scale or repurposed for smaller-scale applications. This flexibility supported the goals of the second design assignment, where the same components would be adapted to create a different program.

The primary design objective of the first assignment was to maximize the potential for reusing and repurposing system's components while minimizing the amount of construction and demolition waste sent to landfills. A material reuse threshold of 75% by weight was established for the second lifecycle. For the remaining 25% of materials not reused, students were asked to propose sustainable end-of-life approaches, such as recycling or safe disposal. To ensure the feasibility of reuse, a strict no-chemical-connection policy was implemented. Students avoided adhesives, sealers, and binders, which complicate the separation and recycling of wood elements. The footing system, considered non-reusable, was excluded from the reuse percentage calculations.

Second design exercise

At the outset of the first design exercise, students were informed that the second design assignment involves designing a Reader's Pavilion for installation on campus. The pavilion was intended to serve as an inviting all-season shelter for avid readers, providing a space to relax, refresh, and reengage with their activities. The design required a shaded, pleasant environment in spring and summer and a waterproof roof for the fall and winter. The pavilion's structural system was expected to accommodate between 3 and 20 readers at a time, with flexibility for replicability to expand its capacity, if desired. Students were encouraged to incorporate private or protective corners within the pavilion, but full enclosure or environmental conditioning was not mandatory. The pavilion's design needed to reflect a culture of reuse and circular economy principles, emphasizing both aesthetic appeal and precision in fabrication. Furthermore, the disassembly and reassembly of the pavilion around campus were critical considerations, aligning with the broader objectives of design for disassembly (DfD).

Design assignments' requirements and resources

Both design exercises permitted the use of high-tech fabrication tools to develop the structural system. However, the resulting systems needed to be assembled and disassembled avoiding heavy machinery and equipment to reduce labor intensity and facilitate construction by individuals with varying skill levels.

Students were required to produce a comprehensive set of design documents for each exercise, including sketches, architectural drawings, renderings, wall sections, and detailed drawings. Additionally, teams had to construct a half-scale model of a bay of their proposed structural-envelope system. The model's materiality was expected to align closely with the actual design proposal, using wood as the primary structural material. While cladding and window materials were encouraged to match the proposed design, this was not strictly required. Furthermore, students were asked to create a step-by-step graphic manual illustrating the assembly and disassembly processes.

To support the construction of their models, student teams received partial funding for materials, supplemented by a donation of reclaimed wood pallets from a local company. Using reclaimed wood not only reduced material costs but also allowed students to explore fabrication techniques that revitalized timber elements, reinforcing the studio's objectives.

Design outcomes

All five teams began their design process by studying modular frames, friction-based systems, wooden and metal joints. Then, they developed their first prototype by adapting these systems to their specific design program and context, considering the scale of a bay within their system. All five teams met the 75% material reuse threshold and some of them highly exceeded this target. In the following, the design outcomes of two teams are described. These teams challenged themselves by reusing curved elements or small and short components from their first prototype. Their design journeys demonstrates their efforts to modularize and standardize structural elements that are inherently challenging to reuse in a second life cycle.

Team 1

Team 1 began their design with studying modular timber construction systems, nut-and-bolt connections for easy assembly and disassembly, as well as timber shaping methods like notching and steaming to achieve curvature (see Fig. 1). The team aimed to explore the reuse of curved timber elements. Thus, they directly applied these techniques in their first prototype (see Fig. 2). They constructed a custom wood steamer box, enabling them to shape ash wood into curved forms integrated into their structure (see Fig. 3). For cladding, they incorporated denim insulation, showcasing innovative use of materials to meet thermal performance goals while remaining sustainable.

The curved timber elements were repurposed in their final assignment as primary structural and functional components, merging structure with pavilion seats (see Fig. 4 and Fig. 5).

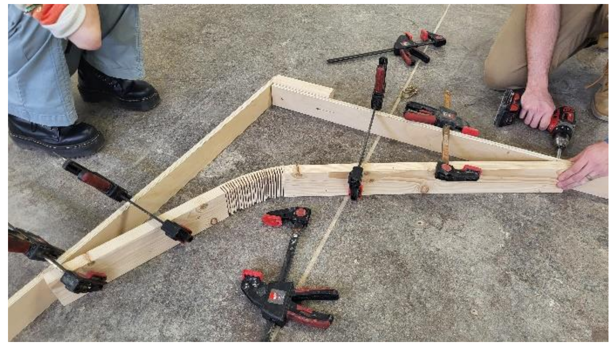

Fig. 1. During the precedent studies, Team 1 explored wood curving techniques, such as steaming and cutting notches, and studied different types of wood that can be curved by steaming.

This project demonstrated their ability to refine and scale their initial design concepts into a cohesive system that addressed functional, aesthetic, and sustainability goals. The sequential assembly and disassembly of their designs, documented in detailed diagrams, making the entire process legible for non-expert workforce.

Fig. 2. The first prototype developed by Team 1. Curved beams are used in the roof system. Source: Nicholas Frantzeskos, Christina Donabella, Alexa Cutruzulla

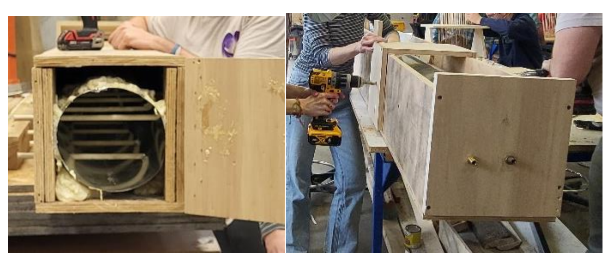

Fig. 3. Team 1 made a wood steam box and used it for curving ash wood elements.

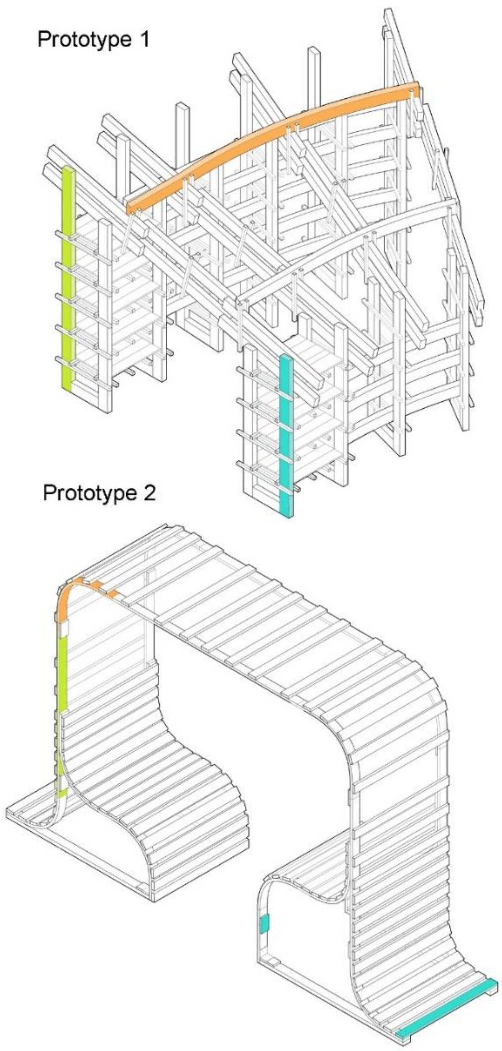

Fig. 4. The diagram shows how Team 1 transformed and reused elements from the first prototype to build the second prototype. Source: Author formatted the initial drawing provided by Nicholas Frantzeskos, Christina Donabella, Alexa Cutruzulla.

Fig. 5. Team 1 reused wood elements, particularly curved elements, from the first prototype to make the reader's pavilion.

Team 2

Team 2 began their design process by studying CNC-milled plywood systems with reusable fasteners for easy disassembly, timber grid systems with column-beam connections for flexibility and reuse, and modular stacking systems that allowed components to serve multiple roles without significant modification. The team's first assignment focused on a stacking system inspired by a precedent used stacking wooden chairs for creating a space frame wall. They designed a space frame wall with a mechanical joinery system to enable disassembly and future reuse (see Fig. 6 and Fig 7). However, the team later reflected that their initial approach could have been more forward-thinking regarding material reuse in the second project, particularly in terms of segmentation and joint strategies.

Fig. 6. Team 2 developed their first prototype with a space frame wall system. Source: Emily Connor Vollo, McCormick, and Jacob Maciejewski

In their second design assignment, the team tackled the challenge of reusing small and short timber pieces. They conceptualized a reciprocal dome structure, which allowed for distributed loads and efficient use of smaller materials (see Fig. 7 and Fig. 8). Fabricating and assembling the reciprocal dome were highly complex and labor-intensive. Thus, they employed augmented reality (AR) tools, such as Hololens, to project the 3D model of the reciprocal frame and accurately situate each member in the correct position (see Fig 9). Using AR technology could increase speed and reduce the intensity of the fabrication and assembly process. Despite the challenges, the team successfully created a structurally stable pavilion while reusing a significant portion of their materials.

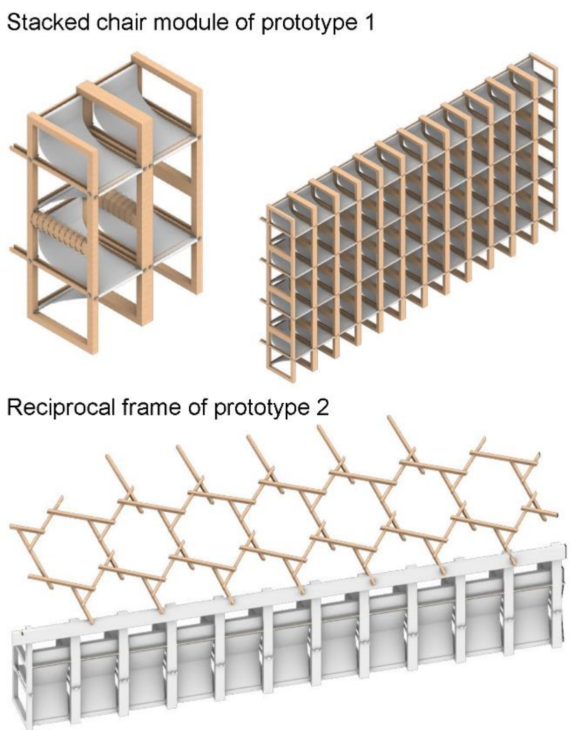

Fig. 7. Team 2 transformed and reused elements from their first prototype to build a reciprocal frame. Source: Author formatted the initial drawing provided by Emily Connor Vollo, McCormick, and Jacob Maciejewski.

Fig. 8. The reciprocal frame developed by Team 2 as their second prototype. Source: Emily Connor Vollo, McCormick, and Jacob Maciejewski

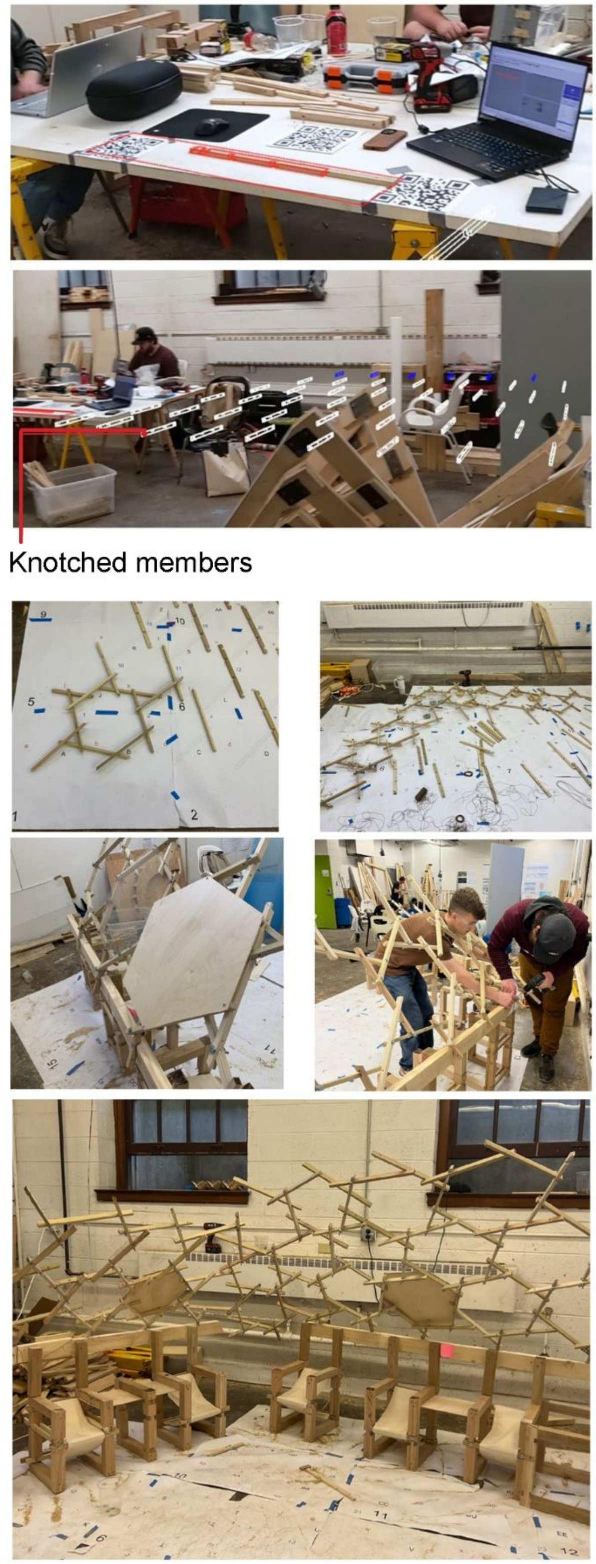

Fig. 9. Team 2 used augmented reality to project the 3D model of the reciprocal frame and build the prototype

Discussion

Students reflected on their learning experience in this course through their journal, outlining the lessons learned, challenges faced, and their evolving understanding of sustainability and material reuse. Four main themes can be identified through the reflection journals uncovering patterns of shared challenges and key takeaways among the students.

1. Evolving mindset about sustainability and material reuse: Students asserted that they gained a deeper understanding of the environmental implications of architectural design. One student remarked on their newfound perspective, stating, “As designers, we usually don’t think beyond the first life cycle of a space, and decide to worry about it when the time comes. I learned this semester that we could be more intricate while also staying flexible on how we design spaces.” Another added, “This studio has given me a new perspective which allows my design to be reused easily and provides a more sustainable effect.” The reflections consistently highlight an enhanced awareness of material life cycles and strategies for maximizing reuse.

Moreover, many students believed that the studio shifted their perspectives on sustainable design and challenged their initial assumptions about materials and construction. For instance, several reflections referenced the need to plan for multiple life cycles of a building from the outset. One student remarked, “Thinking about components rather than individual parts or materials may be helpful when thinking about reuse and future life cycles.” One student reflected, “This studio showed me that the green buildings that are already built can also be the new buildings and remain just as green. If we can continue to innovate and push for reuse of materials, then these buildings that are built today can be repurposed for the new buildings of tomorrow.” Another added, “I learned that when designed intentionally, wood construction can be multi-generational.”

2. Hands-on learning and practical experience: Many students appreciated the studio’s hands-on nature, which allowed them to directly engage with materials and construction techniques. For example, one student reflected, “Designing is always easier on paper, but when it is time for construction, I believe the real exploration begins.” Another student highlighted how this approach fostered confidence and problem-solving skills: “Learning first-hand what I am capable of with my hands and how I am capable of making things happen gives me the confidence that I can do anything.”

***3.* Collaboration and teamwork:** Students appreciated the collaborative aspect of the studio and working in teams. One student reflected: “Working in a group project with [student name] and [student name] is the most fun I ever had doing group work. I loved our group dynamic, had lots of laughs and great memories.”

4. Challenges in design and construction: Several students detailed the challenges of designing for disassembly, especially the technical complexities of joinery and reusing materials. They highlighted the importance of iterative design and problem-solving, often referring to moments of failure as valuable learning opportunities. For example, one noted, “Throughout this studio, there was lots of designing, constructing, and failure... but I think that challenge was necessary and will definitely help with my future design considerations around sustainability and reuse.” Another student noted the trade-offs involved in material reuse: “The challenge was to make it structurally sound while making it simple enough to mass-produce.”

While most students expressed enthusiasm for the studio, a couple reflected on challenges or frustrations. One student felt constrained by the focus on disassembly, stating, “The focus on disassembly sometimes constrained the aesthetic and functional possibilities of our designs." Another found the additional complexity introduced by sustainability requirements to be demanding, noting, "The process of milling pallets into usable materials was extremely labor-intensive and time-consuming."

The studio experience also revealed practical insights into instructional strategies. A semester-based term of at least 14 weeks is optimal for conducting a DfD studio. Shorter terms would require significant reductions in assignments, compromising the depth of student learning. Additionally, group sizes of three were found to be ideal, as larger teams tended to struggle with workflow inefficiencies.

Conclusion

This study described a graduate-level design studio centered on DfD methodologies, where students were challenged to design timber structures for multiple life cycles. The goal of this pedagogical experiment was to immerse students in the process of designing buildings for multiple life cycles, giving them the autonomy to make decisions during the first life cycle and observe their impact on subsequent ones. Through two interconnected design assignments, students created half-scale prototypes that emphasized material recovery, reuse, and adaptability. The studio integrated theoretical instruction with hands-on learning, allowing students to understand the implications of their design decisions across life cycles.

Reflection journals revealed that students gained a deeper understanding of sustainable practices, advanced their hands-on and collaborative work skills, and exercised critical thinking skills to address material constraints and structural stability. This experiment highlights the potential of integrating DfD methodologies into architectural education to equip future designers with the skills and mindset needed to address environmental challenges through sustainable design.

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