Architecture, Structures and Construction (2025) 5:12
https://doi.org/10.1007/s44150-025-00132-8

RESEARCH

Designing for timber circularity: Potential challenges and approaches from the lens of two educational design/build projects

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Received: 1 November 2024 / Accepted: 28 January 2025 / Published online: 12 February 2025
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Abstract

To transition to a Circular Economy, architecture schools are incorporating Design for Circularity (DfC) into their curricula. Integrating circularity into full-scale Design/Build prototypes helps students connect sustainable design theory with practice and application of concepts. This paper examines the gap between circular design intentions and real-world barriers, focusing on DfC with wood in two educational projects. The first, in Belgium, follows a "design from reuse" approach using short-length reclaimed sawn-timber to create a small-scale canopy structure. The second, in the USA, adopts a "design for reuse" approach, using plywood to develop a reusable kit-of-parts. In the analyzed cases, the non-standard nature of DfC requires a holistic life-cycle perspective, presenting challenges in material sourcing and quality assessment, significant variability in sizes and condition, and uncertainty regarding mechanical properties. Furthermore, utilizing frequently smaller reclaimed timber elements increases the number of connections, requiring original solutions. These issues complicate architectural design, structural calculation, and permitting and influenced the design and construction in both cases. An analysis of successful DfC cases shows parallels with lessons learned, identifying common barriers and suggesting solutions. Using reclaimed wood for structural purposes requires thorough planning for transportation, storage, regrading, and reprocessing. Design flexibility is critical to accommodate dimensional variability and mechanical downgrading. When designing for reuse, adequate fabrication tolerances and well-designed connections are key to ensuring structural integrity and easy disassembly. Increased educational projects can build a robust knowledge base, leading to currently lacking standardized procedures and streamlining DfC practices in architecture, engineering, and construction industries. This paper enhances understanding of DfC with wood and Design/Build education by identifying barriers, opportunities, and methods to improve education and training, aiming for a more sustainable built environment.

Keywords Design for circularity · Design for disassembly · Reclaimed timber · Timber architecture · Design/build education

Introduction

The transition to a circular economy (CE) offers an alternative to the current linear, polluting, and wasteful construction practices [1]. A CE is designed to be restorative and regenerative, with the objective of maintaining products, components, and materials at their highest utility and value for as long as possible [2]. However, the transition of the construction industry to a CE will necessitate a significant change in the way buildings, their products, systems and services are designed, produced, and utilized. Prior research has identified education as a critical factor in this transition [3, 4], with higher education institutions having a dual impact by fostering behavioral change on a personal level and promoting professional implementation in practice [5]. Consequently, there is a growing interest in novel educational approaches for a CE as educators from a range of disciplines look to incorporate CE concepts into their curricula [3]. In this context, design sciences are especially relevant in the effort to apply CE principles, as the literature identifies design as a crucial activity for transitioning from a linear to a circular economy [1, 6]. However, designing for circularity (DfC) requires advanced cognitive skills, such

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as systems thinking and future-oriented thinking. Designers must consider the entire lifecycle of materials and products, from their origin to multiple service spans and future uses [6]. To meet this challenge, new methods must be developed to incorporate design for circularity into design education, including the field of architecture, while seamlessly connecting it with the real practice of design and construction.

The Design/Build educational approach offers a potential solution to this challenge by connecting theoretical problem-solving (design) with practical solutions (build) [7, 8]. Specifically, design/build assignments engage students in designing and constructing full-scale prototypes, enhancing their understanding of how design decisions impact the building process, from material procurement, to fabrication and construction of the finished product, and vice versa. The act of building is, thus, also a critical part of the pedagogical experience of a design/build assignment, as this method creates a feedback loop between concept and execution, where the building process also informs and refines the design choices [9]. In addition to technical learning, Design/Build assignments promote direct engagement with the context and participants of a specific project. The collective effort of faculty, students, and often communities toward a shared goal in a particular location allows design/build pedagogy to reach its full potential also as a tool for political intervention and transformation of the built environment, pointing out meaningful social change.

The wood construction industry has emerged as a leading sector in adopting the circular economy, as this approach extends the carbon-storing benefits of wood across multiple life cycles, thereby maximizing its environmental advantages. However, in contrast to the enthusiasm surrounding circularity, the still experimental nature of DfC presents numerous challenges in practical implementation. Designing for increased circularity often necessitates sourcing second-hand materials, where the availability of desired products is uncertain. Even when these materials are available, their attributes, such as mechanical properties, previous in-service conditions and durability, may be unknown. These uncertainties pose significant obstacles to the design processes. Architects and engineers must navigate the complexities of assessing and verifying the quality and safety of reclaimed materials, which can lead to increased time and resource investment. Furthermore, these issues extend beyond the technical realm, impacting liability concerns and insurance, which, in turn, complicates the permitting process, as professionals and regulatory bodies may be hesitant to sign and approve projects that use unconventional materials with unverified properties. Moreover, due to weathering, previous signs of use or varying dimensions, reclaimed building materials often require additional processing for aesthetic reasons or to make them suitable for reuse. For instance, planing reclaimed wood, removing nails and screws, and removing previously applied binders results in an additional time investment during the construction process that is not needed when buying new materials.

Beyond the challenges of incorporating reclaimed materials into new designs, a forward-thinking approach is required to design buildings and systems that facilitate the future reuse of their materials and components. Practical considerations include ensuring that design elements are easily accessible for disassembly, creating standardized connections that facilitate quick removal, and balancing structural integrity with modularity to ensure longevity while allowing for future adaptations.

Therefore, addressing practical challenges is crucial for the broader adoption of DfC practices. This paper unveils the mismatch between enthusiasm for DfC and the actual barriers to its implementation, through the lens of two Design/Build educational projects. The somewhat simplified and less formal constraints of experimental Design/Build educational projects provide an opportune setting for the development of a robust body of knowledge on practical challenges and solutions. This knowledge base could contribute to an effort toward the standardization of procedures, thereby reducing the hurdles to reusing wood for structural purposes and streamlining DfC practices in the architecture, engineering, and construction industries. Hence, this paper aims to enhance the body of knowledge on DfC with wood and Design/Build education by characterizing barriers, opportunities, and methods to improve education, training, and the broader application of circular design strategies with timber, thereby contributing to the creation of a more sustainable built environment.

Method and paper structure

This paper is divided into two parts. The first part presents a targeted literature review of successful projects that have experimented with DfC strategies with wood. The goal of this review is to develop a general repertoire of challenges, opportunities and approaches encountered in the field. This analytical framework will then be used to analyze the original case studies that follow in this paper. The second part presents two case study analyses from D&B educational projects. The first case study, from Belgium, concerns the use of reclaimed sawn timber as the main structural element of a pavilion. The second case study, conducted in the United States, involved the use of digitally cut plywood for a reusable kit of parts for reciprocal frames. The general context of both cases and their design brief will be presented. Subsequently, the design process, including the challenges encountered and the solutions implemented leading up to the end result, will be described in detail. Finally, the experience of these two case studies will be discussed in the context of the targeted literature on the topic, with the intention of

better characterizing the barriers, opportunities, and methods to improve education, training, and, eventually, broader application of circular design strategies with timber.

Literature review and analytical framework

Context

There is growing interest in reclaiming wood from manufacturing, packaging, construction and deconstruction. UNECE [10] proposes the most circular level to be reducing consumption, the next level extends material lifespan from whole buildings and large timber components, cascading down in size to the alternative reuse of materials. The UNECE document [10] reviews European wood construction systems for circularity and provides links to country-specific efforts. Due to the scale mismatch between a large volume of wood product manufacturing, construction and demolition waste and small reuse markets, much is burned for fuel, used for animal bedding or mulch. End-of-life scenarios for products such as Plywood, Oriented Strand Board (OSB), Laminated Veneer Lumber, highly depend on local regulations and supply chains.

Reclaiming wood building materials depends on governmental regulations, business models and agile practices that adapt to changing conditions. A large impediment is determining the structural reliability of reclaimed wood. Material quality, size and structural integrity vary, and approved procedures for testing and grading of members are quickly evolving [11]. For example, the Australian standard for recycled timber proposes some guidance on visual re-grading of reclaimed timber pieces. Following this standard, although elastic properties remain largely the same, the long-term degradation and load effects usually lead to regrading with a reduction from 50 to 65% of strength properties [12]. Likewise, draft versions of two new Norwegian standards for the visual assessment of recycled timber were open for consultation and comment at the beginning of 2024 and are now under development [13]. In this fast-changing context, officials from Washington and Oregon states, USA, have proposed that the International Building Code follow their lead in assuming salvaged lumber can be used structurally. Due to the local proliferation of products, sawn 2x dimensional lumber is assumed to have the strength of "spruce-pine-fir stud grade" and others can be assumed to be "hem-fir No. 2 grade" [14, 15].

The wood species, quality (density, amount of defects, warping / cupping other distortions, moisture), finishes and fasteners, etc. depend on the source. The UK Wood Recycler's Association [16] grades materials according to the amount of processing required due to metal fasteners, coatings, chemical treatments, and compromised content but does not certify the strength of the wood. Because in the U.S. Pacific Northwest, homes were originally constructed of high-quality Douglas Fir, since 2016, Portland, Oregon has required homes older than 1940 (originally 1916) to be deconstructed rather than demolished, encouraging the growth of small recycled wood businesses [17]. Usability of wood reclaimed depends on the amount of time available for deconstruction and oversight or quality control. The success of reclaimed wood businesses depends on match of source and demand and the ease of transport between sources, processing sites and reuse customers. Ease of deconstruction depends on specific building construction. For example, Portland homes built in the 1970s or later typically used adhesives for finishes that would compromise re-use efforts.

Reclaiming wood requires dismantling buildings, sorting usable materials and cleaning the wood of fasteners and transforming irregular pieces into usable stock form, and inventorying, marketing, packaging and transporting/delivering. The Urban Machine company [18] has automated much of this process through a conveyor belt that senses metal, trims fasteners, heats them to slightly char and weaken the surrounding wood, then robotically removes the fasteners.

Design approaches for disassembly and reuse

The overall DfDR principles of Adaptability, Construction Design, Disassembly Design, Circularity and Documentation found in ISO 20887:2020 [19] can be tallied using the InFutURe Wood project's ReBuilding Index and related visual spider chart [20]. The index provides a qualitative assessment framework for design, offering a comprehensive understanding of a design's adaptability, deconstruction potential, and reuse capability. It also identifies areas for improvement. Specifically, the index evaluates designs across five key categories: Adaptability, Construction & Design, Disassembly Design, Circularity, and Documentation. Each category is further broken down into 3 to 5 principles and associated strategies (see Table 1). The assessment yields a score for each level—category, principle, and strategy—and culminates in an overall score, with lower scores indicating areas where improvements are most needed. Improved Design Strategies include Spatial Versatility, Convertibility & Expandability as well as accessible components and services with independent cassettes that "can be altered or exchanged without affecting others or materials". Standardized (prefabricated) assemblies are most interchangeable when they have rational modular dimensions. The components must be durable to withstand deconstruction, with dimensions suitable for reuse [20].

Timber resellers have found markets for structural members, secondary framing, flooring and interior finishes. For

Table 1 ReBuilding index [20] with principles linked to ISO 20887:2020 strategies

Category	Principle	Strategy
1.0 Adaptability	1.1 Versatility	S.1.1 a – b
	1.2 Convertibility	S.1.2 a – c
	1.3 Expandability	S.1.3 a – c
2.0 Construction Design	2.1 Simplicity	S. 2.1 a-b
	2.2 Standardization	S. 2.2 a-d
	2.3 Accessibility	S. 2.3 a-c
	2.4 Independence	S. 2.4 a-b
	2.5 Durability	S. 2.5 a
3.0 Disassembly Design	3.1 Safety	S. 3.1 a-b
	3.2 Deconstruction process	S 3.2 a-c
	3.3 Finishes	S. 3.3 a
	3.4 Connections	S. 3.4 a-g
4.0 Circularity	4.1 Reusability	S. 4.1
	4.2 Refurbishability	S. 4.2
	4.3 Remanufacturability	S. 4.3
	4.4 Recyclability	S. 4.4
	4.5 Reclaimed material	S. 4.5
	4.6 CE Market	S. 4–6
5.0 Documentation	5.1 General design documentation	S. 5.1 a-d
	5.2 Construction documentation	S 5.2 a-b
	5.3 Disassembly documentation	S. 5.3 a -c
	5.4 Material and manufacturers information	S. 5.4 a – c
	5.5 Documentation handling and transference	S. 5.5 a-b

example, several companies in North America collect 2×4 and 2×6 lumber scraps from multi-story housing construction sold for use as truss web members or window and door headers. Other companies remanufacture OSB, plywood, or mill ends for designer tabletops interior finish panels and furnishings.

Experimental projects demonstrate how short members can be combined into longer structural composite trusses & 3D structures [21]. A bottom-up material-based approach to designing from reclaimed wood starts from the inventory of linear members, which generates a set of candidate forms. These include truss variations [22], reciprocal frames [23] and sculptural pavilions [11].

Some projects embrace the variation of scraps. Huuhka [24] provides concepts to utilize short and non-standard elements through modular spaces and framing systems that do not require standardization, illustrated with student projects. Like the Vankunsten ReBeauty project [25], they illustrate aesthetic opportunities with recontextualized elements. Similarly, Ruan [26] proposed using the irregularity of scrap wood to give a bridge a novel organic quality. Wibranek [27] began with a careful examination of San Antonio, TX, USA's available wood, assessing durability and structural properties, followed by design experiments including interlocking light wood box framing, irregular massive siding and composite columns [28].

Lightweight construction methods with smaller members can be appropriate for reclaimed materials. Parigi [29] shows how reciprocal frames, that span long structures with shorter rods, can be adapted to work with an inventory of existing members. Composite shells can be created with planar pieces connected by fasteners [30], including unitized CLT panels connected with butterfly joints [31] or interlocking planes [32]. Brikawood [33] markets small interlocking panels to create a kind of hollow block.

Complementary tensile members can increase flexibility and decrease weight of wood structures. For example, Shigeru Ban temporary office on top of the Centre Pompidou [34], Paris, France, utilizes cables to facilitate an arched truss created with panels. Kinetic hinged origami panels can flatpack [35], such as a conceptual fan-fold reciprocal frame with a fabric tensile membrane [36]. Larger scale foldable constructions [37, 38] could provide the advantages of volumetric modular housing with more transportation ease.

While there can be economic value to deconstruction of light wood framing and heavy timber beams, the current generation of mass timber buildings has not yet reached the age for disassembly. "Design for manufacturing" principles, which incorporate the manufacturing criteria and constraints of mass timber products such as cross-laminated timber (CLT) and mass ply panels (MPP), have been applied only to a limited extent. Mass timber manufacturing waste creates

unusual offcuts, which currently have limited reuse, either in remanufactured panels or in non-structural applications. In addition to shape, their use in composite structures and the long-term performance of adhesives can make reuse of CLT challenging. Irregularly shaped CLT panels may be cut into regular panels, logs or blocks to facilitate reuse by reducing the geometric variability. More structurally efficient is a demonstration ceiling slab with thickness where needed by laying out and robotically sculpting layers of MPP scrap [39]. A lighter hollow floor (that would require additional fire resistance) was framed with Laminar Veneer Lumber from small diameter trees [40].

Reversible connectors support the flexible use of linear members. A series of reversible connection systems have been proposed for temporary buildings, supporting their future deconstruction and reuse. For example, linear framing members can be connected by Tsunagi (swivel) clamps [41] or tension belts [42]. Ratchet straps were used to bind stressed skin panels in both section and plan in Aalto University Wood Program's Liina 2011 [43] emergency shelter. Bureau SLA's People's Pavilion [44] used tension members as belting to bundle wood into major structural elements for multi-story temporary construction. Asa et al.'s [45] Embraced Wood covered irregular bundles of wood with a clay surface that could be removed for later disassembly.

Beyond applications in temporary buildings, a significant amount of R&D focuses on developing advanced connector systems in the mass timber sector to streamline construction by relocating the labor-intensive task of installing connectors from on-site to the prefabrication stage. These connectors allow for quick connections between pre-installed components, enabling faster construction and easier future deconstruction. In addition to these special connector systems, conventional dowel-type fasteners allow for different degrees of deconstruction and reuse, depending also on the resulting damage on the disassembled parts, in relation to the type and magnitude of load transferred and the type, size and distribution of the fasteners used [12]. Wood-to-wood connections, using either traditional carpentry joints or CNCed notches are, in principle, reversible. However, localized damage, deformations and shrinkage and swelling, can diminish the potential for disassembly, especially in complex geometries.

In summary, the literature review presents a number of design approaches aimed at increasing the circularity of wood structures, such as adaptability, modularity, and design for disassembly. Overall, the use of prefabricated and standardized components and reversible connectors allows designers and builders to create structures more in line with circular design principles. Furthermore, the innovative strategies and case studies discussed, from small interlocking panels to large folding structures, demonstrate that circular design approaches can be integrated into a wide range of structures, also opening up new possibilities for architectural expression. The two educational experiences exemplified in this paper demonstrate two approaches: (1) Material-based "Design From Reuse" which upcycles reclaimed wood into composite structural elements or modules according to material availability and properties; and (2) forward-looking "Design For Reuse" that involves the design of elements for extended lifespan, ease of disassembly, and maximum retention of material properties in a second life cycle.

Case 1 – building beyond borders 23–24 - garden pavilion

Context and design brief

The Building Beyond Borders Postgraduate certificate is a one-year, 30 ECTS program from Hasselt University that engages architecture graduates and professionals in exploring regenerative and distributive design processes and building methods. The program concludes with a small-scale Design/Build project, reflecting the year's discussions and knowledge. Sixteen students from 13 nationalities participated in the third edition of the program (2023-24).

The program starts with four thematic Theory & Reflect sessions consisting of lectures and workshops by both academics and practitioners on social and participatory design, biodiversity and landscape, circular materials and construction, and bio-climatic and low-tech principles. In the Hands-on Atelier, throughout the year, students follow practical hands-on workshops on urban harvesting and bio- and geo-based building materials and construction methods, combined with construction site and company visits. The Theory & Reflect sessions and the Hands-on Atelier aim to provide students with a mix of theoretical knowledge, insights into the implementation in practice and practical hands-on experience with the processing and application of bio- and geo-based materials.

From the second half of the first semester, in the Research & Design Studio, students deepen their knowledge by choosing one of the following research tracks, i.e. Social & Participatory Design, Urban Harvesting, Earthen Building Materials, and Circular Wood Construction [46]. The Research & Design Studio's role is to build up knowledge that is considered essential for the subsequent Design/Build project. After the research tracks, students immersed themselves in the main Design/Build task from the beginning of the second semester. The Design/Build project of the 23–24 edition was located in Houthalen-Helchteren, a Belgian municipality situated on either side of a busy connecting road to the Netherlands. Based on its expertise in participatory design,

Hasselt University has already been involved for many years in a large infrastructure project, the Complex project North-South Limburg, to rethink this road connection, which is one of Belgium's busiest roads. Its heavy traffic has not only a huge impact on road safety and traffic flow but also on the quality of life of the neighbouring communities. The upcoming infrastructure works not only aim to solve the mobility problem but also offer opportunities to bring the communities closer together again and create sustainable and liveable village centres. One of the projects that will contribute to this is the former vicarage in Helchteren, which will be renovated into a community project. In the 23–24 edition of the Postgraduate certificate Building Beyond Borders, students advised the architectural firms responsible for the renovation of the vicarage on bio-and geo-based material use. Besides that, they designed and built together with the local community two interventions in the garden of the vicarage that will facilitate the community to meet, i.e. a pizza oven in earth-based materials and a garden pavilion, Pavilion 1. The project's brief of the pavilion, developed with the local community, was to design and build a covered outdoor gathering space to accommodate 10 people, with a footprint smaller than 40 square-meters - to avoid the need for a conventional building permit. It had to provide rain shelter but could be open on the sides, thus eliminating the need for mechanical systems.

Process and outcome

To align with circularity principles, Pavilion 1 utilized bio- and geo-based materials, featuring a primary timber frame and earth-block infills. In addition, the aim was to minimize the need for extracting virgin materials by mainly using reclaimed materials. For the foundations reclaimed gravel, sand, and pavement elements were used. For the frame infill, earth blocks were sourced through a partnership with a producer of earthen building materials from Brussels that uses valorized loam from excavation sites to produce unfired blocks, earth plasters and rammed earth mixes. For the timber frame, a local interior contractor agreed to donate scrap wood from their production line.

Upon beginning the design process, the first major challenge was the variability in the sections, lengths, and strength classes of the donated wood scrap. This unpredictability led to the constraint of designing the frame of the pavilion using only short-length, small-sectioned lumber to prepare for a worst-case scenario. Consequently, the initial design featured an intricate spatial truss with numerous connections. This complexity, combined with the unknown size availability and strength classes of the reclaimed pieces, required additional testing and the consultation of an outsourced timber engineer, which exceeded the budget and schedule for the Design/Build part of the program. For this reason, the design process had to proceed in another direction to limit the uncertainties.

After a couple of weeks of design iterations, a more conventional A-frame was chosen to simplify the construction detailing and calculations (Fig. 1). However, the A-frame design required more robust sections and longer pieces of timber than anticipated. At this moment, it was critical to determine whether to purchase new sawn timber pieces, according to the specifications needed, which would deviate from the initial goal of using mostly reclaimed materials. After a round of negotiations, the partner company agreed to donate Spruce-Pine-Fir timber initially used for scaffolding and left in the yard, which had larger sections but was still limited in length, necessitating a design adapted to the available dimensions and a combination of several smaller pieces to create larger structural elements for the A-frames.

During the design, careful consideration was given to shielding the wood-based elements and the earth blocks from the weather as much as possible. The pavilion was constructed at a sufficient height above ground level, and an overhanging roof was incorporated to protect the timber columns and the earth block masonry from direct exposure to rain. At the front façade, this overhang is rather limited to allow openness and direct contact with the garden. Given the semi-permanent nature of the pavilion, the relatively low durability of softwood against prolonged moisture exposure and Belgium's all-year-round rainy weather, reclaimed oak, sourced from a reclaimed materials dealer in a neighbouring province, was selected for the vertical and horizontal structural elements, whereas pine from reclaimed scaffolding was used for the roof trusses (Fig. 2). Due to previous weathering and long-term exposure on construction sites causing warping and dimensional variation, the reclaimed timber needed to be planned prior to reuse, to provide straight pieces with consistent sections. Self-tapping screws were used to join the timbers together for ease of implementation. Despite their slightly lower disassembly and reuse potential compared to bolted connections, the flexibility of not requiring predrilled holes and therefore tighter tolerances was deemed to be a better fit on a low-tech site with relatively unskilled builders. The floor, seating and top of the wall are made from short-length oak leftovers, treated with a biobased and nature friendly oil to prolong durability.

At the back of the pavilion, an infill wall made of stabilized unfired earth blocks braces the A-frame for horizontal stability. An earth mortar is used, which allows easy reclamation of the blocks when the masonry needs to be dismantled in the future. The walls are combined with an earth block bench that acts as a counterweight to prevent the pavilion from being lifted or deformed by the wind and, at the same time, offers visitors to the garden a place to sit and rest. The front part of the A-frames is attached to reversible screw foundations, allowing easy disassembly and reuse,

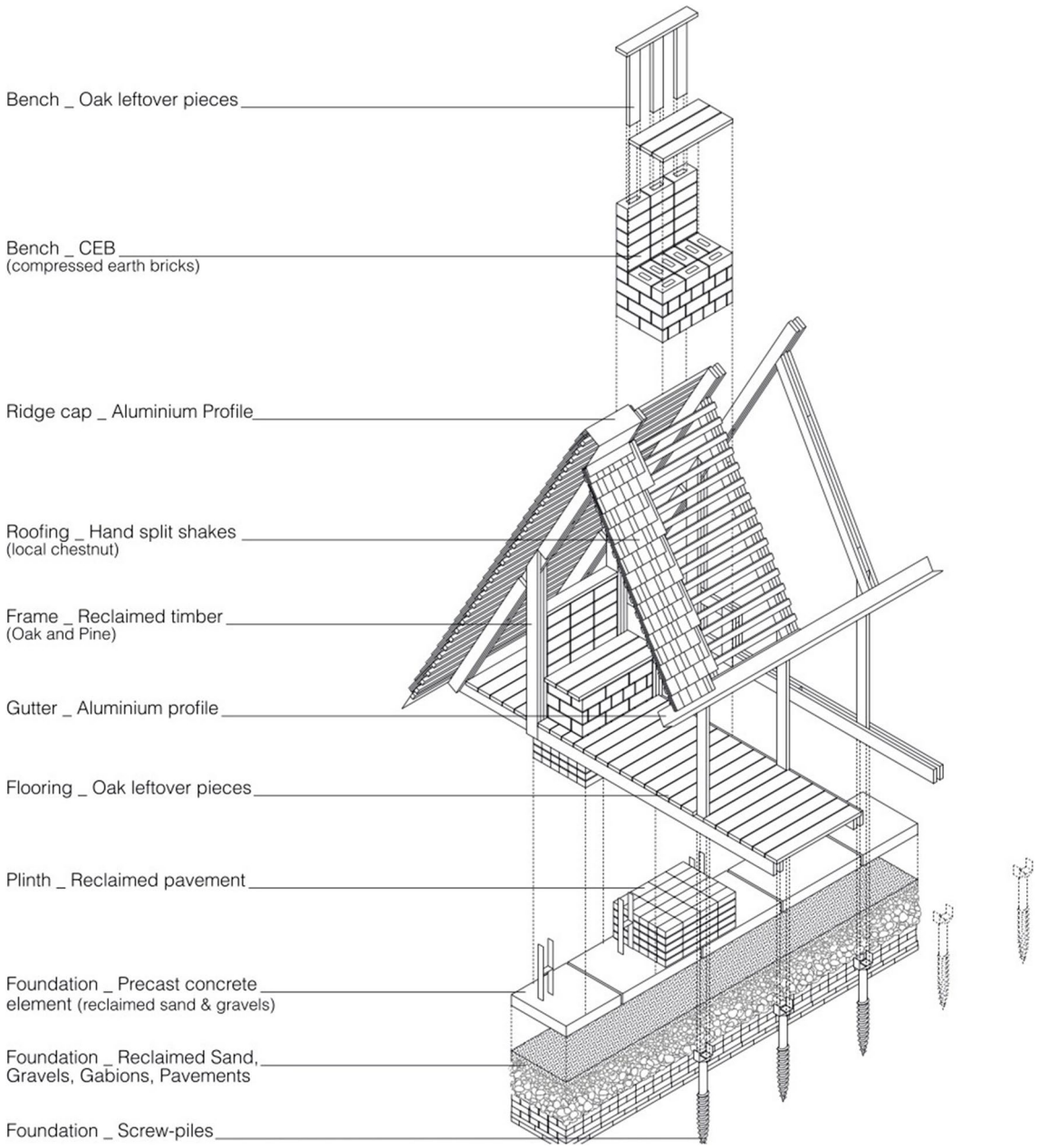

Fig. 1 Exploded axonometric view of the main components of the final pavilion design (drawing by Louise Daussy)

whereas, at the back, a line foundation supports the earth block bench and walls.

Not only the wood for the A-frame (reclaimed oak and pine) and the floors (oak leftovers), but also the other materials were reclaimed elsewhere as much as possible. For example, for the foundations, students harvested and used various pavement stones, gravel, gabions, and sand from buildings that were to be demolished due to the infrastructure works (Fig. 3).

One of the key design objectives was to maximize the use of regenerative or reclaimed materials. Selecting an appropriate roofing material that ensures adequate waterproofing and durability while maintaining a low environmental impact and blending aesthetically within the garden posed a significant challenge during design. Students explored several cladding options including urban-harvested polycarbonate tiles from the buildings that will be demolished as well as bio-based alternatives. Inspired by a wooden shakes manufacturing workshop during the first half of the program, they decided to use hand-split shakes. This manufacturing method ensures a longer service-time than mechanically processed shingles without



Fig. 2 From left to right: Fabrication of the A-frame; fixing the A-frame to the screw pile foundations; fixing the roof rafters onto the A-frame (photos by building beyond borders postgraduate certificate 23-24)

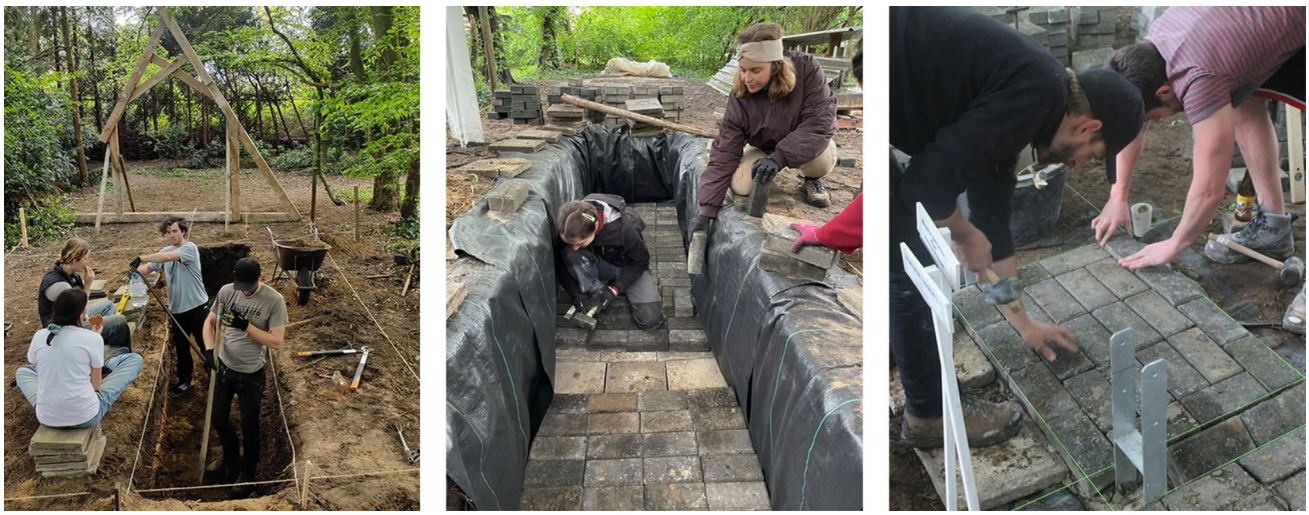

Fig. 3 Dry-foundation assembly. From left to right: Digging trenches; laying up urban harvested cement blocks; masoning piers with urban harvested cement blocks (photos by building beyond borders postgraduate certificate 23-24)

the need for chemical preservatives by maintaining part of the fibre macrostructure, rather than cutting through it. Besides that, hand-making shakes is a participatory activity providing a positive boost to team spirit, collaboration and community building, which were also key objectives of the project. To secure enough material for shakes, students joined a tree auction from a local plantation forest, where they purchased eight chestnut trees. The logs were cut to length and divided into quarters in the forest, and then transported to the site. Over 16 weeks, students manually split the quarters into around 2000 shakes and fixed them to the main structure (Fig. 4). To ensure adequate waterproofing of the roof, the shakes were applied with a large overlap.

During a 2-week building festival, students organized several workshops and lectures to distribute the knowledge they gained during the program and to involve the neighbourhood in the construction of the pavilion. Throughout the building phase, neighbours frequently stopped by to lend a helping hand, offer tools, bring some food, or keep the students company. In this way, the vicarage project has already been a community project from the start of the construction of the interventions in the garden (Fig. 5). The entire project is comprehensively documented in the 152-page, 2024 edition of the Building Beyond Borders magazine, written and illustrated by the students, detailing the full design and build process. This provides not only a clear overview of the finished project but also valuable insights into the design decisions made and the knowledge gained by the students throughout the program.

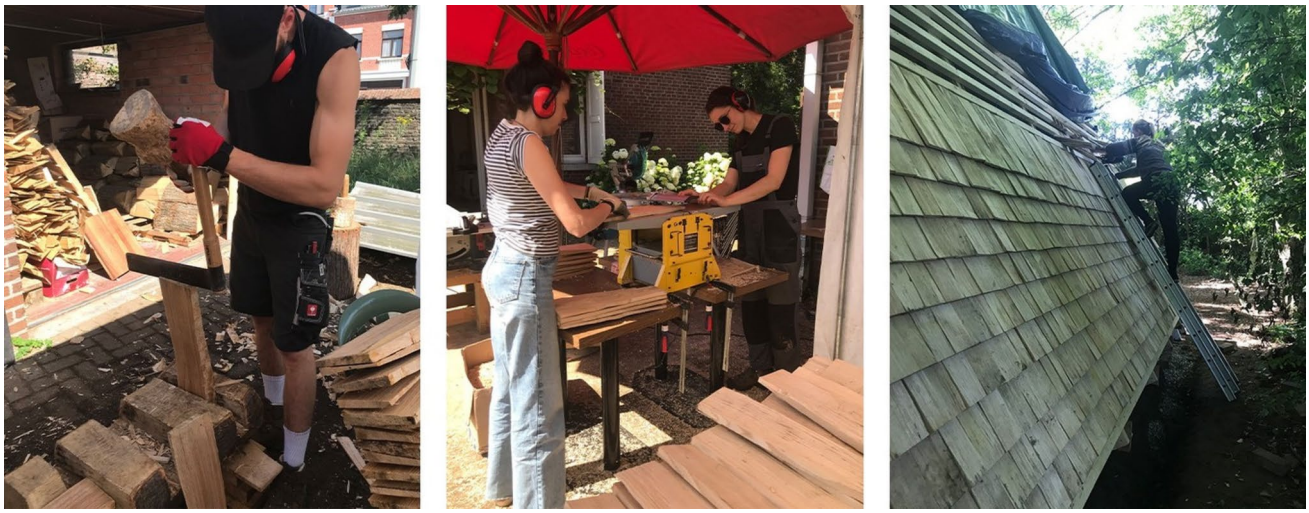

Fig. 4 From left to right: Splitting quarter sawn logs shakes; cutting shakes to size; applying shakes to the A-frames (photos by building beyond borders postgraduate certificate 23-24)



Fig. 5 The finalized pavilion. (photos by Olmo Peeters)

Case 2 – timber tectonics in the digital age - fall 2023 park shelter

Context and design brief

The Timber Tectonics in the Digital Age course is an 11-week hybrid design-build studio co-developed by Oregon State University (OSU) and the University of Oregon (UO). This course is tailored for advanced undergraduate and graduate students from OSU's Wood Science and Engineering, Civil and Construction Engineering, and Architectural Engineering disciplines, as well as UO's Architecture program. It provides a practical framework for interdisciplinary collaboration at the onset of the creative process. Students from wood science, engineering, and architecture assume the roles of manufacturer, engineer, and architect, collaborating primarily online in integrated design teams to develop crucial hard and soft skills needed in today's wood construction industry.

The curriculum emphasizes the intersections of material science, technology, architecture, and engineering within wood tectonics, highlighting the significance of teamwork and interdisciplinary communication. In the initial weeks, students establish a foundational understanding of wood properties, wood products, timber connections, and structural systems while being introduced to digital experimentation using parametric design tools. This combination empowers them to create flexible and adaptive designs that respond effectively to material and structural requirements and fabrication constraints.

As the course progresses, students apply their skills and knowledge in small design teams, focusing on digital fabrication workflows supported by physical prototyping.

Following the first review, various ideas are consolidated into a single project, allowing the class to regroup and collaboratively finalize key aspects such as structural design, fabrication documentation, and construction planning. Through this comprehensive approach, students navigate the complexities of integrating digital modeling, fabrication, structural simulation, and wood construction within a design-build framework, learning essential principles of design for manufacturing, assembly, and reuse.

Nineteen students from the two institutions participated in the Fall 2023 edition of the course and worked closely with a real client, the city of Salem, Oregon, to develop a proposal for a seasonal pavilion in one of the city's parks. The project required a system that could be easily disassembled during the rainy season, stored, and quickly redeployed for repeated use. These requirements highlighted the practical application of circular economy principles emphasizing "design for assembly, disassembly and reuse" strategies. To meet these goals, a structural kit-of-parts was proposed for constructing reciprocal frame systems.

Process and outcome

The design process was guided by a bottom-up approach, starting with an examination of force transfer mechanisms in reciprocal systems. This involved considering material and fabrication constraints, along with the characteristics of individual components and their connections, which ultimately shaped the overall structural and architectural configuration.

Reciprocal frame systems are structural configurations where individual elements support and are supported by one another in a closed-loop arrangement. These systems use shorter, smaller elements to span larger distances. While this project focused on "design for reuse" rather than "design from reuse," the potential for incorporating reclaimed materials was considered. In such systems, reclaimed materials can be reprocessed into smaller pieces, accommodating their variability and meeting the required geometries. For this project, 19-mm thick Douglas Fir plywood was chosen for its lightweight nature and potential availability as reclaimed material from deconstruction projects in the USA. Students were asked to create an optimized and versatile kit of parts, with few component types to serve as both roof and vertical supports. While reciprocal systems have traditionally involved the use of beams or rods, the decision to use plywood instead of lumber or linear wood products necessitated a departure from conventional design approaches. This shift encouraged the exploration of polygonal shapes for the planar members, considering a few exemplary precedents [32]. The width of the elements also opened new connection design possibilities, enabling the use of surfaces.

To streamline fabrication, all components were required to be cut using a CNC router bit perpendicular to the panel surfaces, pushing the projects towards 4-fold rotational patterns which have orthogonal rather than angled connections. An investigation was conducted into how 4-fold rotational patterns could create curvatures across multiple connections by offsetting notch endpoints on elements. Experiments with notched elements, specifically deep half-laps, identified optimal notch profiles for enabling rotational attachments. The half-lap notches were advantageous as they provided higher tolerances compared to other wood-to-wood joints.

Examples of components developed during the initial design iterations, along with their jointing systems, are illustrated in Fig. 6. One proposal that emerged for further development was based on a project by Kengo Kuma Associated Architects for the Kyushu Geibun Kan Museum [47], in which the roof consists of a planar reciprocal frame made up of notched triangular cedar members.

Following the construction of a small-scale model using a modified hexagonal grid, the triangular members were adapted to a 90-degree planning pattern that incorporated 4-fold rotational symmetry, facilitating easier cutting and assembly. For enhanced module stability, the joint notches were placed on the flat top edges of the triangular pieces,

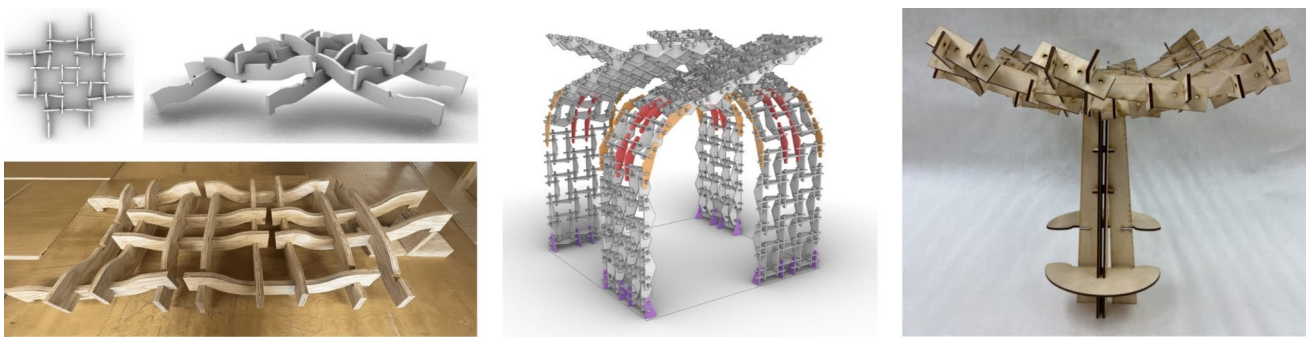

Fig. 6 Initial projects experimented with creating curvature via component shape

allowing individual elements to rest on the symmetrical corners of the isosceles triangles. Details were iteratively refined through both digital and physical testing of alternatives.

Structural analysis was conducted throughout the design process and at various scales to inform design decisions. This analysis revealed that notches weakened the elements, with some depths exceeding the recommended ratio based on their placement (as shown in Fig. 7). Additionally, the partially constructed system resting on triangular corners lacked stability, gaining stiffness only as the network expanded. This instability was exacerbated by each piece having only two slot connections; systems with more connections per member can prevent destabilizing rotations by incorporating a third connection point. Furthermore, the analysis highlighted potential challenges related to wind uplift (illustrated in Fig. 8).

Recognizing the existing design's instability and the critical role of edge conditions for stabilization led to a reevaluation of the connection system. To address these issues, notched connections were replaced with more stable mortise and tenon joints. A precedent for this approach was found in the 2005 Serpentine Pavilion by Siza-Souta de Moura-Balmond [48], which utilized mortise and tenon joints for sturdy, reversible connections. At the pattern edge, where only partial modules could fit, these joints locked components in place, thus stabilizing the entire system (Fig. 9).

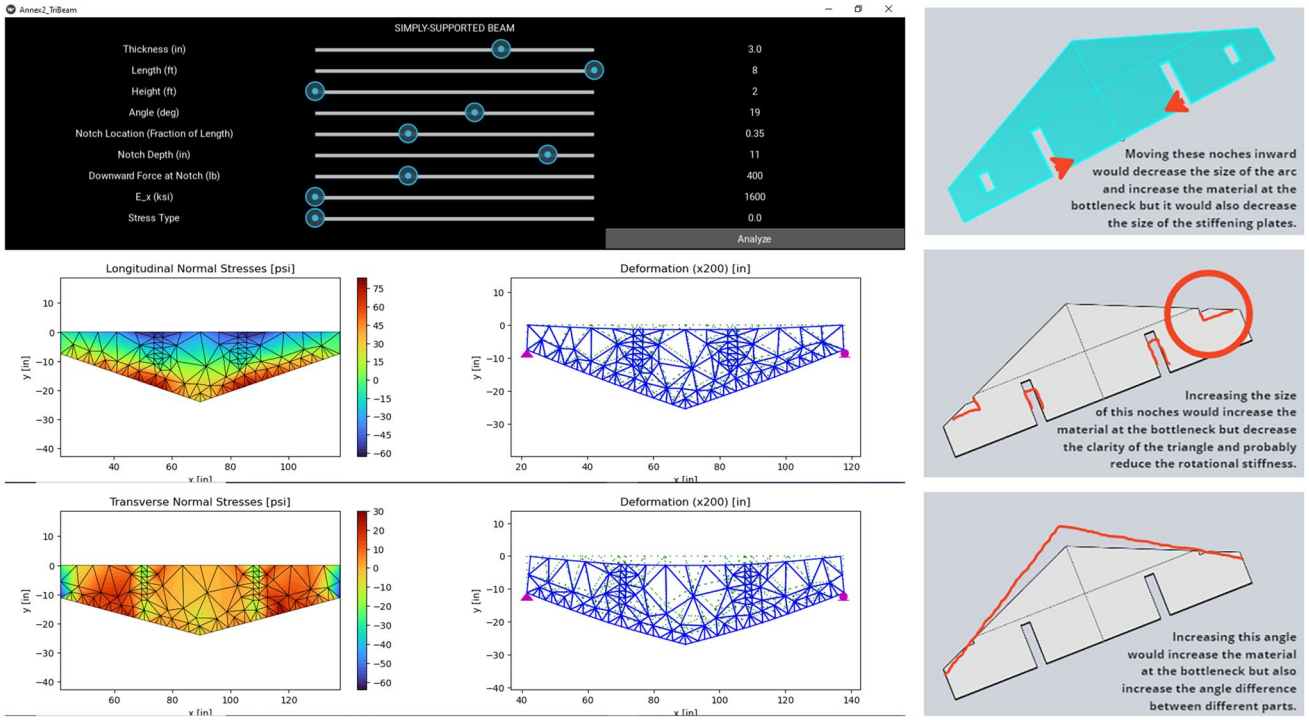

Fig. 7 Structural analysis and recommendations for notched components (Courtesy N. Thielsen)

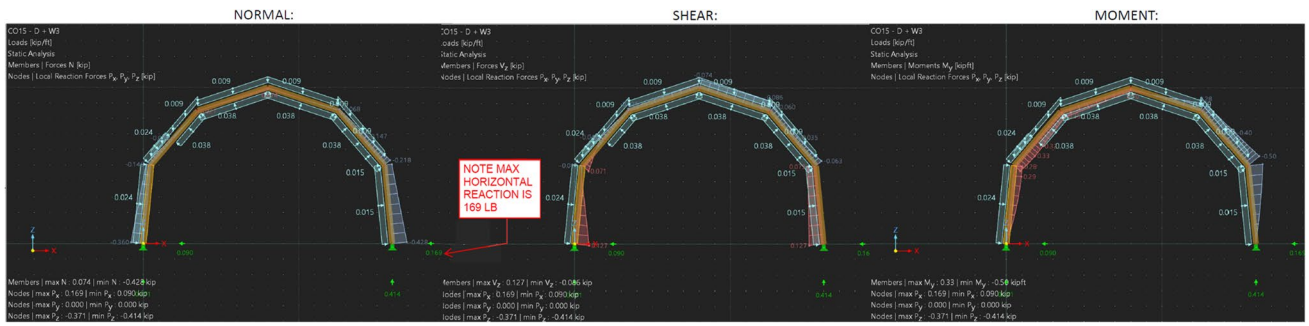

Fig. 8 Stresses caused by self-weight and wind (courtesy N. Thielsen)

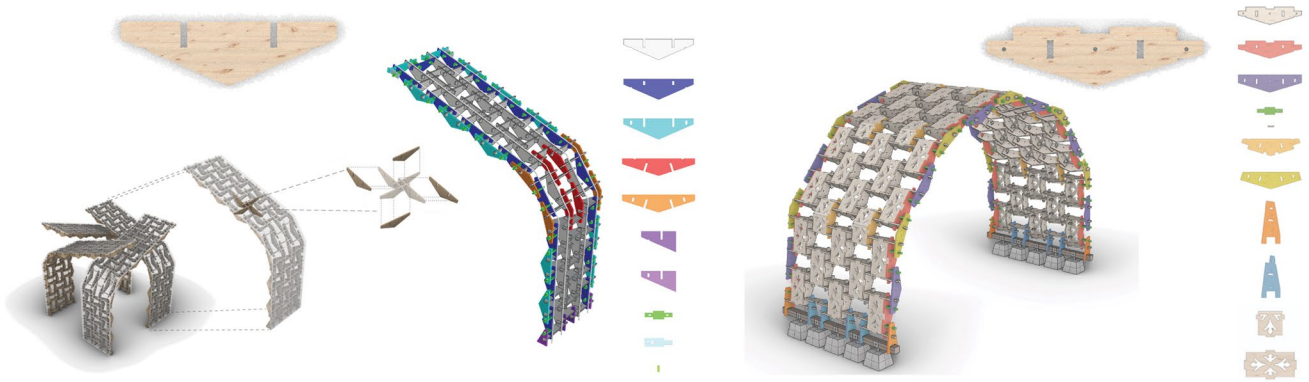

Fig. 9 Initial design with half-lap notches (left) and revised mortise and tenons (right)

Ultimately, the modular triangular elements were adopted to create a segmented arch that could effectively address the site's directional needs. In addition to the basic reciprocal frame structure, other components were used to reinforce the design. Concrete blocks acted as removable connections to the ground, preventing uplift and minimizing movement of the footings. Perforated, plywood stiffening plates enhanced rigidity, maintaining square spacing between nodes and reducing twisting and torsional forces at the joints. Additional elements designed for moisture protection were omitted for the prototype indoor installation.

During the construction of the arch, several phenomena were observed, including joint rotation, structural settlement, and imperfect supports after shoring removal. Joint rotation led to loose connections during sectional assembly, a problem that could be addressed by enhancing element detailing, sizing, and tolerances based on the accuracy of the CNC equipment used (Fig. 10). After allowing the arch to stand for a few days, measurements were taken to demonstrate the deformation occurring between the linear arch segments, which were then compared to a 3D Karamba model. This analysis indicated that the stiffest load path in the as-built arch under self-weight resembled an "X" stretching across its line segments, resulting in alternating inward and upward deflections of the external and central sections from the crown to the foot (Fig. 11).

A few weeks after its initial installation, the full-scale arched pavilion was taken apart into modular components and stored in a sheltered outdoor area for several months before being reassembled in a new location. The arch was installed using telescoping struts, ladders, and a scissors lift for the keystone. During deconstruction, mallets were employed to remove the tenons from the mortises at the joints. However, this method occasionally resulted in localized damage, such as crushing the tenon ends or causing small areas of plywood delamination. It was observed that pre-assembling the reciprocal frame into modular sections not only streamlined construction and disassembly but also enhanced reusability, allowing disassembly to occur primarily at the joints between modules. This strategy effectively minimized material damage. The components of the prototype were successfully reused after the second installation



Fig. 10 Initial construction (left and center) and second installation of the pavilion (right)

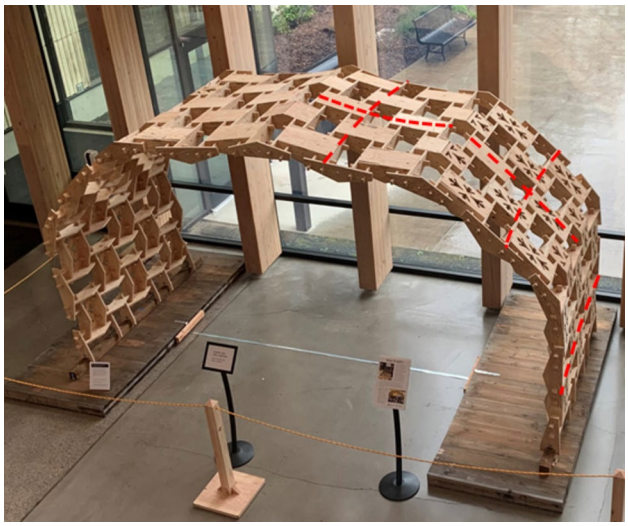

Fig. 11 Reciprocal frame after settlement. Red dashed lines show deformations in different directions

of the full pavilion to create a sculptural wall and a portable exhibit stand (Fig. 12).

Discussion

The integration of circular design approaches into construction is still far from mainstream and suffers from a lack of standardized procedures for assessing the structural integrity and safety of reclaimed wood. While some initial steps have been taken to develop standards and regulations to facilitate its application, there is a clear gap in methodologies for re-grading the strength properties of reclaimed wood and determining its level of toxicity, both of which are critical to ensuring that reused materials meet safety and durability requirements. Without established protocols, their use on a larger scale remains limited due to liability and insurance concerns. Even in small-scale applications such as pavilions, these issues cannot be overlooked. In Case 1, uncertainty about the mechanical properties of reclaimed wood and need for expert calculation required for the 3-dimensional trusses using short-length timbers resulted in a complete redesign of the structural solution, requiring a slightly different raw material supply, which was fortunately available from one of the project partners.

Thus, another bottleneck to the upscaling of recovered wood in the material-based Design from Reuse approach is the availability of recovered wood. The viability of a reclaimed timber market is highly dependent on the ability of companies to engage in selective demolition or deconstruction, which involves more labor-intensive processes and thus increases operational time and costs. However, the literature also revealed the critical role that the regulatory landscape of a country or region can play in the establishment of an industry for reclaimed wood, as in the case of Portland, Oregon. In addition, Case 1 demonstrated the importance of matching design and construction expectations with the local availability of reclaimed wood. Not only does this limit the uncertainty of what is possible at the time of construction, but it can also help reduce the logistical challenges of storage, reprocessing, and transportation.

When it comes to circular design and construction strategies, both material-based Design from Reuse (using pieces from the past) vs. forward-looking Design for future Reuse (reusing pieces in the future) approaches offer advantages. The first approach is driven by the availability of reclaimed materials, which typically results in the use of smaller, non-standard wood pieces to construct elements such as trusses and reciprocal frames. In these cases, lightweight construction methods are generally more suitable for working with linear members. In Case 1, a Design from Reuse approach was used and short-length pieces were splined together with screws to construct an A-frame structure. This approach offers the advantage of allowing non-standard pieces to be used to create one frame, which can then be reused in similar applications. When working with reclaimed planar members,



Fig. 12 Re-used components were connected with new corner pieces featuring sharper angles

the construction of composite panels leading to shell structures is a more common practice. Case 2 illustrates a kit-of-parts strategy focused on Design for Reuse with a tradeoff between the number of component types, form and flexible reuse. Few component types repeated many times simplify fabrication, construction logistics and training, while limiting the number of components constrains possible overall geometric configurations. Edge, support and corner conditions typically require special consideration. The many customized components needed to create non-standard geometries can limit how components can be repurposed. Small components require multiple coordinated connections, each introducing potential fit and stability issues.

The use of reversible joints and connectors is crucial for promoting reuse and designing for disassembly, ensuring that structures built today can achieve a high level of circularity in the future. Digital fabrication can streamline wood-to-wood connections; however, the accuracy of tools and tolerances can greatly influence the fit of notches and the system's rigidity. Furthermore, both immediate settlement and long-term deformation may impair the original reversibility of the joint.

After the completion of a project, a significant knowledge gap remains in the objective verification and measurement of circularity claims. Currently, the tools and methodologies designed to assess circularity in construction are still in their early stages of development and remain largely non-standardized. This inconsistency among tools and frameworks limits their widespread adoption and hampers the ability to compare circularity outcomes across different design strategies and projects.

Finally, the two case studies were self-evaluated using an abbreviated adaptation of the ReBuilding index [20] up to the principle level (see Table 1) not as an objective measure but as a way to better understand strengths and shortcomings. Each principle was scored on a scale from 0 to 4, defined as follows: 0 = Not implemented; 1 = Implemented at a low level; 2 = Implemented at a medium level; 3 = Implemented at a high level; and 4 = Fully implemented. An arithmetic average was calculated for each principle, and the results were plotted in a radar diagram (Fig. 13). Finally, the overall score for each case was determined by averaging the scores across the five strategies, resulting in a final score of 2.86 for Case 1 and 2.91 for Case 2.

Figure 13 shows that both cases scored relatively high in the Disassembly Design category, indicating that design efforts in both projects successfully emphasized this aspect. Case 1 also presents a high average in the Construction Design category. A likely explanation is that the course's low-tech approach encourages principles such as simplicity, standardization, and accessibility as an inherent part of the design process. Additionally, it exhibits a high Circularity score due to the utilization of reclaimed materials, designed with natural materials for straightforward recycling in the future, also avoiding the use of heterogeneous material assemblies. However, the emphasis on hands-on learning sometimes results in a strong focus on the making process, with comparatively less attention to documentation, which received the lowest score of all five categories. Case 2 scores highly in the "circularity" category due to its design's flexibility and adaptability. The kit's parts can be reused in their current form, and their modular nature allows, to a certain extent, for modification and upgrades to

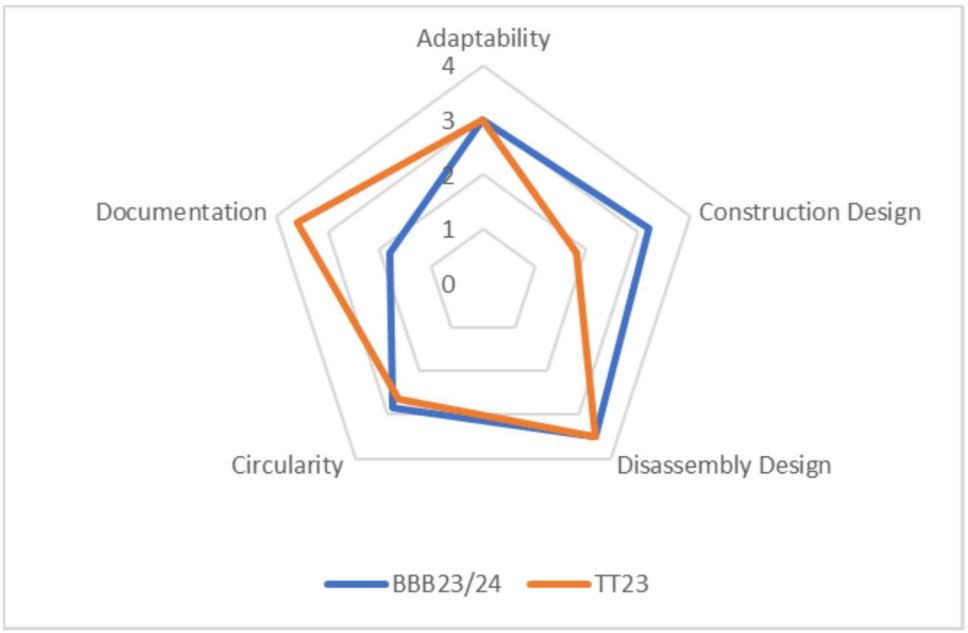

Fig. 13 Evaluation of the two cases using the ReBuilding index developed by [20]

meet alternative design requirements. However, settlements in service and local embedment at the notches can limit multiple use cycles, requiring attention for future implementations. Specifically, addressing digital fabrication, construction tolerances, and controlling the stiffness of the joints will be essential. While reclaimed material wasn't utilized in this project, the choice of materials and design approach encourages the potential use of plywood sourced from manufacturing and construction waste. Nevertheless, the actual feasibility of creating a complete kit-of-parts with reclaimed plywood should be tested. Documentation was another key strength and essential feature of the project, enabling effective communication and collaboration among student teams working synergistically on various tasks. This approach proved critical to the project's success and highlights a necessary shift in both practice and education toward integrated design approaches.

Conclusions and next steps

In recent years, the need to design for increased circularity has been recognized as essential for the transition from a linear to a circular economy, with renewable, bio-based materials like wood at the forefront. However, achieving circularity requires a rethinking of how products and buildings are designed, used, and (re)processed at the end of their lifecycle. The integration of design for circularity into academic curricula plays a crucial role in advancing this transition. This paper evaluated key practical challenges and barriers to the broader adoption of DfC practices through the analysis of two Design/Build educational projects involving wood, comparing them with the latest literature on the subject. The findings revealed five key guidelines for enhancing the future circularity of construction practices, which are as follows:

1. **Standardization and Safety**: The development of standardized procedures for re-grading the structural integrity and toxicity of reclaimed wood is crucial and lacking. Establishing these standards will enable the wider adoption of reclaimed wood in construction by ensuring safety, durability, and compliance with regulations, thus reducing liability concerns.
2. **Market and Regulation**: The establishment of a market for reclaimed wood products is heavily dependent on regulatory frameworks that promote selective demolition and deconstruction processes in lieu of conventional demolition. Those frameworks can offer financial support to the more labor-intensive processes associated, which is essential to making reclaimed wood economically viable and matching local supply with demand, minimizing logistical challenges.
3. **Design Approaches**: Circular design strategies have to be chosen on a case-by-case basis, depending on material availability and project scale to confer the most benefits associated with each other. Material-based Design from Reuse approaches, using non-standard and smaller timber pieces, benefit from lightweight methods, as these materials can be used for less heavily loaded elements in redundant framing systems. Design for future reuse approaches can suit larger elements such as glulam and CLT panels, preparing and facilitating their future salvage and efficient redeployment. Reversible connectors and joints are critical in both approaches to enable future disassembly and reuse, minimizing material losses and properties decay.
4. **Measurement and Verification of Circularity**: Despite its recent growing body of knowledge, there is still a significant knowledge gap and consensus regarding the tools and methodologies for objectively measuring circularity. The development of standardized assessment frameworks is essential for enabling consistent comparisons of circularity across projects and for promoting best practices in circular wood construction. Prioritizing key design attributes such as accessibility, exchangeability, adaptability, and durability is vital to ensuring the longevity and reusability of structural components.
5. **Education and Training**: To implement circular economy principles in the construction industry effectively, AEC education and training methods must shift towards hands-on, interdisciplinary, and systems-based learning. Project-based learning, where students design, build, and reuse prototypes, can provide practical experience with circular design principles. Collaborative courses involving architecture, engineering, and construction management students would mirror real-world teamwork across the supply chain. Enhancing digital literacy in design modeling, analysis, prototyping, and fabrication would better align students' skills with industry needs. Additionally, partnerships with industry on pilot projects could expose students to real circular practices, creating a workforce equipped to drive sustainable innovation in the AEC field.

In conclusion, advancing circularity in wood construction will require a multidisciplinary approach, beginning with educational efforts and encompassing the entire supply chain to achieve technical standardization, regulatory support, and innovative yet tailored design strategies. By addressing these needs, the critical challenges currently experienced in practice can be overcome, guiding the construction industry toward more circular practices. Furthermore, ongoing efforts to develop standardized tools for measuring circularity will be essential to ensure that future projects adhere to best practices and can objectively demonstrate their circularity performance. Through these measures, wood construction

holds significant potential to contribute to the transition to a more circular and resource-efficient built environment.

Acknowledgements R. Passarelli, P. Winkels and E. Knapen would like to acknowledge the students of the 23-24 Postgraduate certificate Building Beyond Borders of Hasselt University and the others members of the staff team, Nicolas Coeckelberghs, Liesbeth Huybrechts, John Silvertand, and Jasper Van der Linden. The project was supported by the Municipality Houthalen-Helchteren, De Werkvennootschap, Friends of the Pastorie and Deholi and funded by Faculty of Architecture and Arts of Hasselt University and The Living Lab Circular Economy "Application of Earth Blocks in Practice" (http://www.livinglabearthblocks.be), funded by VLAIO, the Flemish Agency for Innovation and Entrepreneurship, and the NextGenerationEU fund of the European Commission.

M. Riggio and N. Cheng would like to acknowledge all the students of the Fall 2023 Timber Tectonics in the Digital Age class and teaching assistants, Alireza Yari and Grayson Wright. Their effort was partially supported by a grant from the U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS), Agreement N. 58-0204-2-143, and by the 2023 UO Sustainable City Year Program. Roseburg Forest Products donated materials to build the demonstration project. TallWood Design Institute and Tom Coates assisted with the CNC fabrication and installation.

Author contributions R.N.P.: Conceptualization; Methodology; Formal analysis; Investigation; Writing - Original Draft; Writing - Review &; Editing.

M.P.: Investigation; Formal analysis; Writing - Review &; Editing; Project administration; Funding acquisition.

N.C.: Investigation; Formal analysis; Writing - Review &; Editing; Project administration; Funding acquisition.

P.W.: Investigation; Writing - Review &; Editing; Project administration; Funding acquisition.

E.K.: Investigation; Writing - Review &; Editing; Project administration; Funding acquisition.

Funding This study was funded by VLAIO, the Flemish Agency for Innovation and Entrepreneurship, NextGenerationEU fund of the European Commission, U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS, N. 58-0204-2-143), and by the 2023 UO Sustainable City Year Program.

Data availability No datasets were generated or analysed during the current study.

Declarations

Ethical approval Not applicable.

Competing interests The authors declare no competing interests.

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