Teaching Architectural Design from Stock

A course-based framework for material reuse leveraging digital design and fabrication

Ornella Iuorio[1], Bruno Figueiredo[2], Sam Wilcock[3]
[1,3]Politecnico di Milano, [2]University of Minho
[1]ornella.iuorio@polimi.it, [2]bfigueiredo@eaad.uminho.pt, [3] sam.wilcock@polimi.it

Abstract. *The urgency of circular construction requires architectural and engineering education to move beyond abstract sustainability principles toward direct engagement with material reuse and non-standard design conditions. This paper presents a pedagogical framework that integrates computational design, material stock management, and digital fabrication within a graduate-level curriculum. The methodology is structured around four interconnected domain processes: Urban Mining, Design for Circularity, Fabrication, and Assembly. Through these modules, students transformed reclaimed timber, plastics, and industrial waste into data-rich resources via digital inventorying and photogrammetry. Computational workflows - including parametric modelling, structural optimisation, and algorithmic nesting - enabled students to navigate the constraints of fixed material stocks, moving from unconstrained to stock-constrained design. A central component of the course was the iterative production of prototypes. These projects utilised bespoke 3D-printed joints and CNC-machined connections to facilitate Design for Disassembly (DfD). By analysing the course structure and student outcomes, the paper argues that digitally enabled, prototype-driven frameworks are essential for operationalising circular construction practices. This approach equips future practitioners with the technical competencies to manage material uncertainty and bridge the gap between digital optimisation and physical materialisation.*
Keywords. *Circular Pedagogy, Design-Based Learning, Computational Design, Material Reuse, Digital Prototyping, Design for Disassembly.*

INTRODUCTION

Scarcity of resources and the high environmental impact of the construction sector have, in the last ten years starting from the Circular Economy Action Plan, led to a rethinking of the way we build. The European Union is strongly advocating for a more responsible use of resources, with particular emphasis on reuse, recovery and recycling of construction material and products. From a design perspective this means reconsidering the way we start the design process, which should no longer account for an infinite amount of material from which to design new systems, but should rather aim as much is possible and feasible to integrate material and components reclaimed from the urban environment. This shift will not be feasible until architects and engineers are able to shift their design thinking. In order to progress in this direction, this work presents a pedagogical approach that integrates circular design principles with digital design and fabrication tools and approaches. Indeed, while computational design and digital fabrication have been widely integrated into architectural pedagogy (Celani, 2012; Jenny et al., 2022) and approaches to embedding circular economy principles in education are increasingly discussed, their integration within coherent, prototype-driven frameworks for reuse-oriented design remains limited. This work presents the development and analysis of a pedagogical framework structured around the intersection of three complementary domains (Figure 1): domain processes, design objectives, and computational and fabrication tools. Rather than being addressed independently, these domains were intentionally interwoven to support the integration of circular construction principles within the design process. The efficacy of the approach is here validated through five designed and prototyped spatial structures.

METHODS

The pedagogical framework is articulated around four domain processes (Iuorio et al. 2026): Urban Mining, Design for Circularity, Fabrication, and Assembly (Figure 1). These processes define the operational context in which students engage with reclaimed materials, develop design proposals, and materialise them through physical prototypes. Rather than functioning as isolated stages, these domain processes are interconnected through iterative feedback loops to design and fabrication objectives, and tools (Figure 2). Each process is directly aligned with specific design objectives, ranging from the creation of a material database and waste use analysis during Urban Mining, to form-finding, optimisation, and connection design within Design for Circularity, and finally nesting strategies and robotic/digital fabrication during Fabrication and Assembly.

To support this alignment between processes and objectives, a set of computational design and digital fabrication tools was progressively introduced throughout the course, not as isolated technical skills, but as operative instruments

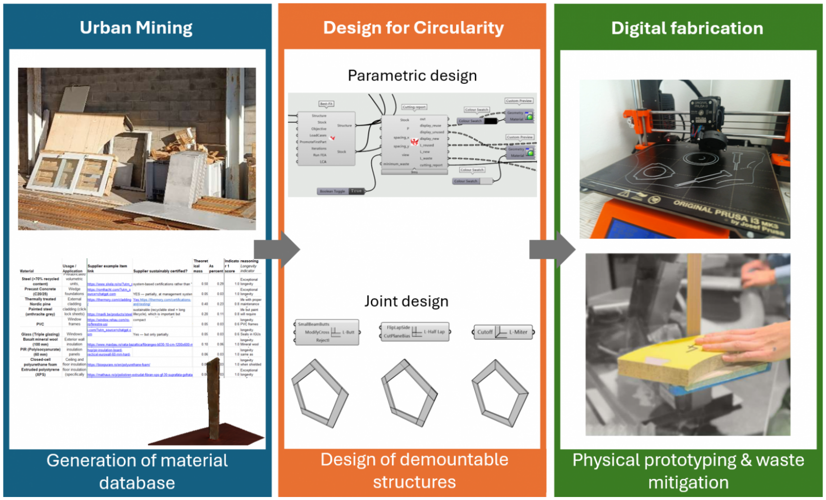
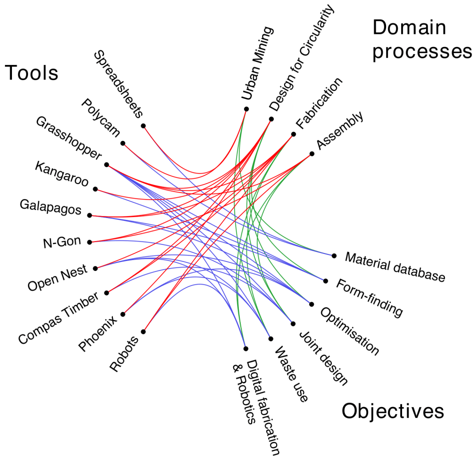


Figure 1
Overall methodology

Figure 2
Interconnections between the different domain processes, tools and objectives



embedded within each domain process (Celani 2012; Jenny et al. 2022). The teaching strategy followed a cumulative approach, where tools were first presented in relation to specific objectives and then expanded into more complex, integrated workflows.

In the early stages, software such as spreadsheets and Polycam photogrammetry were used to support material cataloguing and digitisation, enabling the construction of a shared material database and the analysis of available resources. As students moved into the Design for Circularity phase, parametric modelling environments, primarily Grasshopper, became the central interface through which material data, geometric logic, and design intent were connected. Within this environment, tools such as Kangaroo and Galapagos were introduced to support form-finding and optimisation processes, allowing students to explore structurally informed and resource-aware design solutions. Additional tools, including NGon (Vestartas and Rad 2021) and Phoenix3D (Warmuth et al. 2021), enabled the rationalisation of geometry and the implementation of stock-constrained design strategies. This allowed students to directly link computational modelling to material availability, utilising digital tools to navigate the specific challenges of salvaged material reuse (Zboinska and Göbel 2025).

In the fabrication-oriented stages, tools such as OpenNest (Vestartas 2021) were introduced to address nesting and material efficiency, while Compas Timber (Apolinarska et al. 2022) supported the development of connection logic adapted to irregular geometries. Digital fabrication technologies, including robotic systems and additive manufacturing processes, were integrated as extensions of the computational workflow, requiring students to translate design models into fabrication-ready data and to consider constraints related to production, tolerances, and assembly.

Through this progression, tools were not only learned but actively combined into customised workflows, enabling students to navigate the relationships between material constraints, design objectives, and fabrication processes. This approach reinforces the role of computational design and digital fabrication as mediators between domain processes and objectives, allowing circular construction principles to be operationalised through a coherent and integrated design-to-production system.

TEACHING

This section reflects on the teaching contents articulated to guide 15 students in 5 groups through material sourcing and mapping, as well as the digital tools and exercises prepared to allow them to engage with reclaimed components as active design constraints, which directly informed the development of adaptable systems derived from a predefined material stock.

Material database

As an initial stage in the teaching module, students sourced reclaimed materials through urban mining at university waste points, demolition sites, and plastic factory offcut stockpiles. This foundational step was designed to reframe their perception of waste by introducing them to the practicalities of the circular economy. Students created a communal inventory, cataloguing the materials by quantity, dimension, and perceived condition. Representative photographs and 3D scans, generated using free mobile photogrammetry software, such as Polycam, were also included.

This digitisation process, embedding data regarding material quality, dimensions, and origin into a shared catalogue, transformed passive waste into an active, data-rich resource. While the students did not construct a fully-fledged digital material passport, this detailed inventory served as a practical pedagogical proxy. It provided a tangible foundation for teaching the broader concepts of Digital Twins and material passports, specifically illustrating how digitised physical stock links to Building Information Modelling (BIM) to directly inform successive design decisions. Further, the shared catalogue fostered collaboration and allowed students to reserve specific items, establishing the core constraints of stock-aware design from the outset. Before progressing to computational modelling, students undertook initial hands-on explorations through dry assembly and prototyping to understand the physical capabilities and limitations of their materials. The final inventory consisted predominantly of timber struts and sheets, alongside large quantities of clear polycarbonate panels, providing a diverse palette for the design explorations that followed.

Form-finding

Panelled shell structures were introduced early in the computational design curriculum to teach 3D form-finding through physically-based optimization. Using the Kangaroo physics engine (Piker 2013), students discretized planar boundaries into quadrangular meshes and defined energy goals such as edge lengths, anchor points, and vertical thrust to generate shell geometries. The solver's interactivity allowed students to manipulate anchor points and mesh topology in real-time, observing how shifts (e.g., from quadrangular to triangular remeshing) affected structural behaviour. To bridge the gap to fabrication, students applied panelling and planarisation techniques.

Building upon these form-finding exercises, the course also explored the design of reciprocal frame structures. Such structures are defined by mutually supporting struts connected at engagement windows (Douthe and Baverel 2009), formed by translating, rotating and extending mesh lengths systematically (Figure 3). Plugin NGon (Vestartas and Rad 2021) contains some tools specifically built to make these required rotations about vertices. By rotating edges of a mesh about an average vector, the rotation operation can be defined in both 2 and 3 dimensions. Initial exercises demonstrated this basic concept using 2D geometry as shown below, and then were extended to 3D based gridshells.

While the use of this tool allows the development of base reciprocal geometries in the form of curves, they lack some key points that allow rationalisation into real structures, namely consideration of modelling realistic material thicknesses, and of how the members can be joined. The initial assumption for design of a reciprocal structure was that struts were of consistent cross-section area, and that intersection of struts was not possible (to minimise potential CNC machining requirements). The first issue, of adding material thickness, can be simply resolved by orienting planes with Z axes pointing along the curves,

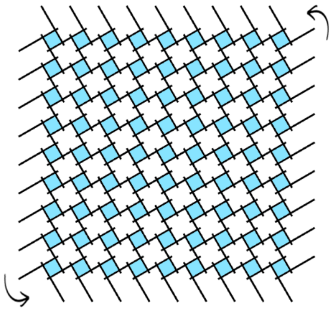


Figure 3
A simple 2D reciprocal form, formed by extension and rotation of mesh edges 30° about vertex average planes. Coloured regions mark the forming engagement windows.

a perpendicular axis aligned with the panel face, and orienting rectangular cross-sections to the endpoints of these generated lines before extruding them into volumetric structural beams.

To address the second issue - how the members can be joined without complex physical intersections - the workflow focused on creating controlled overlaps at the engagement windows. Students learned to reorient the curves away from the original vertices and angle the members between the top and bottom layers of the shell framework. Finally, to facilitate dry, reversible assembly, students automated the generation of bolt holes. This was achieved by drawing computational lines through the overlapping beam ends, thickening these lines into cylindrical pipes, and executing a Boolean subtraction to carve the required voids directly out of the timber elements.

Joints design

The exploration of connection logic for assembly and disassembly of demountable systems was facilitated through an interactive workshop focused on the COMPAS Timber library (Apolinarska et al. 2022), a project actively developed by the COMPAS Association at Gramazio Kohler. Taught directly by the software's developers, this session enabled students to progress from designing abstract geometric intersections to generating robust, fabrication-ready details. This progression addressed one of the most critical technical challenges in circular construction: the necessity of designing bespoke interfaces capable of accommodating the inherent dimensional variability of reclaimed timber. During the workshop, students learned to automate the generation of traditional joinery, including tenon-and-mortise, lap, and birdsmouth joints, and dynamically adapt these connections to the non-standard cross-sections identified during their initial urban mining phase.

Beyond internal joints, the cohort also explored the parametric design of bespoke external edge and vertex connections. This approach was particularly crucial for panelled shell structures, where irregular geometries required custom digital "structural adapters" to resolve non-standard intersection angles. Utilising Grasshopper's native geometry and Boolean operations, students developed adaptable nodes capable of bridging these unpredictable reclaimed elements, building upon previously established workflows for bespoke node generation (Korkis and Iuorio 2025).

To bridge the gap between these complex digital models and physical construction, the workflow required students to generate fully resolved, machine-readable geometry. Students were instructed on how to properly detail structural nodes for bolt holes to create reversible fixtures, ensuring their computational models were primed for direct data transfer to automated manufacturing tools. Ultimately, cultivating this technical fluency in joint generation reinforced the foundational principles of dry assembly and disassembly (DfD).

Material use and waste management

Initial exercises introduced the shift from unconstrained to stock-constrained design. Students first performed a manual 2D packing task using paper strips representing reclaimed and new timber, to cover a truss while minimising waste (Figure 3). This tactile exercise was then reconstructed computationally using the Phoenix3D plugin (Warmuth et al. 2021). By optimising cutting assignments from a material database, students saw how algorithmic workflows reduce waste and ensure design feasibility based on real-world material availability.

To further develop these computational skills, a secondary design exercise was introduced involving Voronoi tilings projected onto a semi-sphere Students learned to use mathematical components to derive a custom utilisation metric that calculated the percentage of reused material stock. This metric then functioned as the fitness criteria for the Galapagos evolutionary solver (Rutten 2013), which allowed iterative generation of thousands

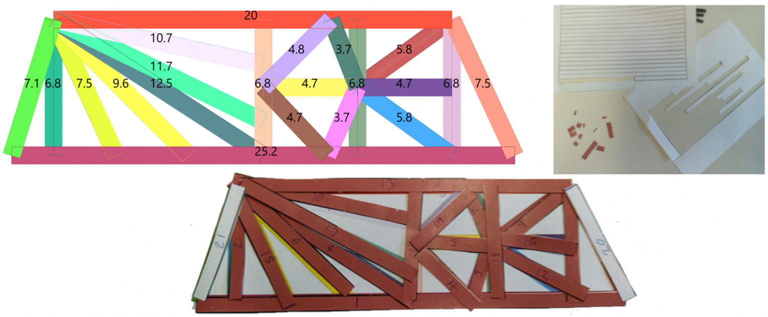


Figure 4
2D packing exercise, comprising of a printed out predefined structure, a set of lengths of “reclaimed material” to be cut out from a sheet, and additional lengths representing unlimited newly procured material. Red struts indicate “reclaimed” material, while white indicates newly procured material.

of design permutations to automatically drive parameters towards maximum material reuse and minimal offcut waste. The animated nature of Galapagos' optimisation allowed students to observe in real-time how parametric adjustments to a global form could drastically alter the utilisation rate of a specific material stock.

Beyond frame structures, the curriculum also addressed the specific challenges of planar geometry, to account for the large amounts of sheet material available. While Phoenix3D effectively manages 1D strut lengths, the reuse of sheet materials (such as the reclaimed polycarbonate and timber panels identified in the students' urban mining inventory) benefits from 2D packing. Students were introduced to OpenNest (Vestartas 2021) , a Grasshopper plugin specifically designed for optimising nesting. By automatically iterating through various translations and rotations, the algorithm determines the tightest possible arrangement of these components within a predefined boundary curve, which represents the physical dimensions of the available stock sheets. This exercise allowed students to visually quantify cutting waste prior to fabrication, demonstrating how algorithmic nesting directly translates to increased material efficiency in subtractive manufacturing processes, such as CNC routing and laser cutting.

Digital fabrication and robotics

The final teaching segment integrated automated fabrication as a necessary bridge between digital optimisation and physical materialisation. Before transitioning to the fabrication lab, students were introduced to the fundamental principles of robotic assembly, focusing on the kinematics of multi-axis robotic arms and toolpath generation using plugin Robots (Soler 2025). A core component of this theoretical teaching was the early assessment of robotic constructability (Zargar et al. 2024). Rather than treating fabrication as an afterthought, students learned to simulate the robotic assembly process directly within their computational workflows. By evaluating parameters such as robot reachability and kinematic constraints in the CAD environment, students could verify whether their stock-constrained designs were physically constructible before any real-world execution. This simulation-first approach was then validated during live lab demonstrations, where students observed how robotic precision could manage the physical manipulation and assembly of a spatial structure (Figure 5).

Parallel to robotic assembly, the course covered subtractive and additive manufacturing techniques tailored to handle the irregularities of reclaimed waste. For subtractive processes, students learned to export BTLx machining codes directly from their COMPAS Timber models to drive CNC milling

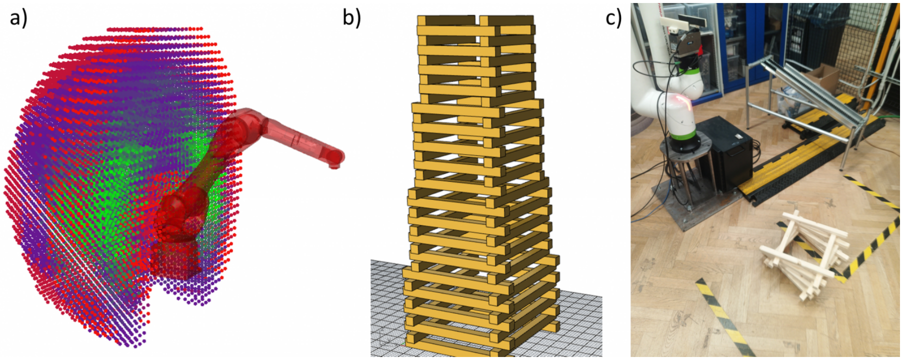


Figure 5
Robotic assembly . The students used Robots plugin to a) assess kinematic capabilities of the provided manipulator arm, b) design a structure and plan assembly sequence, and c) export paths for testing on a real arm.

machines. This workflow allowed for the automated fabrication of complex, high-precision timber joinery - such as custom tenon-and-mortise joints - directly onto the non-standard cross-sections of the sourced wood. Additionally, to address the need for bespoke structural interfaces, particularly where unpredictable geometries or materials (like polycarbonate offcuts) met at non-standard angles, additive manufacturing was also introduced. Students were taught how to prepare their digital joint models using Ultimaker Cura. By introducing slicing parameters, structural infill densities, and support generation in Cura, and teaching on the export process to convert designs from CAD to GCODE, they successfully 3D-printed custom group logos using bio-based PLA. This provided the students with the tools required to manufacture bespoke structural components, to "fill in" the gaps for potentially complex geometries which were more difficult to manufacture from the material inventory.

STUDENT EXPLORATIONS AND STRUCTURAL OUTPUTS

Students explored the taught tools, through the development of five distinct morphological design principles, defined based on the available material stock and in dialogue with the professors. The selected typologies were a sequence of rotating pentagonal portal frames (Group A), an interlocking freeform demountable shell (Group B), a reciprocal double curvature shell (Group C), a panellised shell structure rationalised from a free-form surface (Group D), a double curvature torsional shell (Group E).

Physical prototyping studies

An iterative approach was central to most students design and fabrication projects. Among them, Group C applied a reverse engineering approach for development of the reciprocal structure. A set of 4 struts was assembled with different sized engagement windows and different overlapping configurations, until the foreseen curvatures were reached in the physical prototype. Some degree of tolerance was introduced into the system by oversizing the bolt holes, allowing some degree of variation into curvature. Through observation of the curvature arising from this, and from attaching to further similar repeated units, behaviour of the real manufacturable repeating units could be brought back into the parametric model. A doubly curved shell was designed using a standard Kangaroo workflow (Figure 6). By feeding the results of the Kangaroo form-finding into the NGon reciprocal mesh adjustment node, and checking both structural feasibility (with physically touching struts) and curvature feasibility compared to the physical experiments, the structure could be

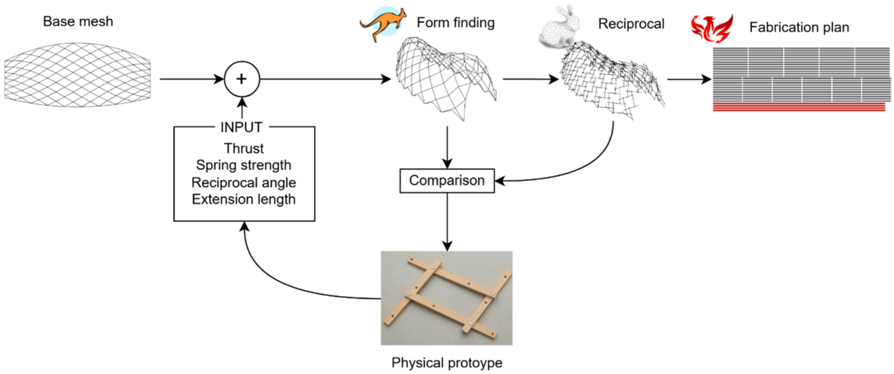


Figure 6
Initial experimental assembly of overlapping reciprocal timber struts allowed feedback into the design process.

designed within the physical constraints. Parameter control of the Kangaroo energies were adjusted, alongside reciprocation angle, to correctly match the tested configuration. Finally, cutting lengths could be assigned to different stock using Phoenix3D.

Group E's project, "The Formilatte," provided a focused case study in the reuse of low-value, single-use plastic as an architectural material. The group sourced discarded polypropylene (PP) cheese containers and industrial wood scraps, and their work exemplified a highly experimental and resourceful approach to circular design. Their objective was to create doubly-curved panels, but the irregular nature of the source material required a multi-stage process of transformation. Because of the trays' packaging structure, only the flat bases could be utilised to produce the doubly-curved panels of the shell via an experimental thermoforming workflow.

Their prototyping workflow was designed to transform flimsy plastic into stiff, structural panels whose performance depended primarily on their new geometry. This required a bespoke mould-making strategy that underwent significant iteration. Initial 3D-printed PLA moulds melted and warped under the 60°C heat of the vacuum-forming machine. Subsequent attempts using cast cement and plaster (Figure 7) proved too fragile and brittle for repeated use. Ultimately, the group succeeded by 3D-printing a positive mould out of ABS, which withstood the thermal stress and successfully formed approximately parts from 20 trays without significant degradation. By additionally drilling holes into the deepest areas of the mould, they allowed the vacuum machine to properly extract air, ensuring the plastic fully adopted the intended shape.

Figure 7
a) Negative mould creation in PLA; b) Positive mould forming through cement casting; c) Vacuum forming of the reused tubs around the ABS mould.

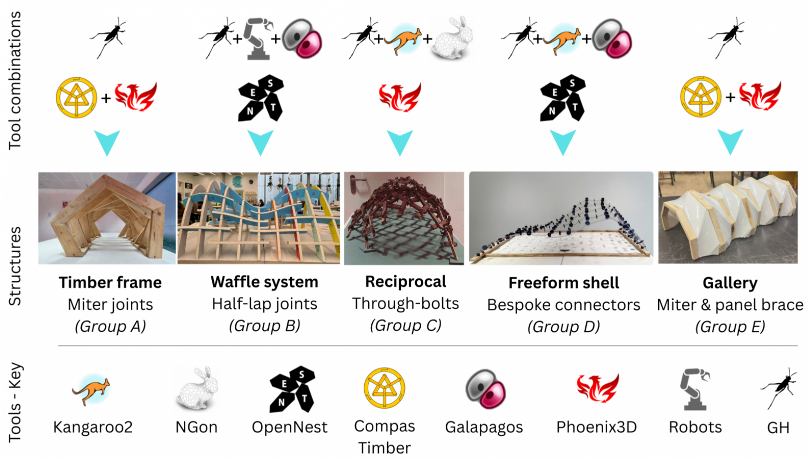


Figure 8
How different taught tools fed into the design of the finished structures. The first row of the tools describes plugins used in parallel in geometric generation, whilst the second row describes plugins used in a sequential step for manufacturing preparation or material optimisation stages.

Final structures

After the initial Urban Mining phase, students applied taught computational workflows to develop the final structures (Figure 8). Group A addressed material constraints by bespoke joint generation with Compas Timber and stock optimisation using Phoenix3D. Group B focused on sheet-material reuse through OpenNest nesting strategies and Robots plugin to verify assembly. Group C combined Kangaroo form-finding, NGon reciprocal geometry generation, and Phoenix3D stock assessment within an iterative reverse-engineering process. Group D integrated Kangaroo and Galapagos to optimise material use by modifying shell support and length constraint strengths, managing Fabrication and Assembly by resolving sheet material layouts with OpenNest. Finally, Group E addressed 1D and planar constraints through Compas Timber and Phoenix3D, complemented by additive manufacturing for custom connectors.

DISCUSSION

This work presents a pedagogical framework that integrates circular design principles with computational design and digital fabrication through the structured interaction of domain processes, design objectives, and tools. Quantitative and qualitative feedback were taken from the 15 students involved in the coursework. They reported high confidence in performing digital mapping and strongly agreed that designing within the constraints of available waste led to more creative solutions. They noted that the objectives are deliberately balanced, reflecting a holistic approach in which material databases, form-finding, joint design, waste use, and robotic fabrication are all interdependent. Optimisation emerges as a key integrative mechanism, linking performance, resource efficiency and design decision-making. Grasshopper functions as a central platform due to its interoperability and capacity to integrate multiple plugins, such as Galapagos for optimisation and OpenNest for material efficiency, enabling a continuous workflow from design to fabrication. Reverse engineering of physical models, particularly in exploring reciprocal structures and vacuum forming, strengthens the feedback loop between digital and physical domains. The methodology demonstrates how a prototype-driven, digitally mediated approach can support circularity and sustainability in architectural pedagogy by aligning processes, objectives, and tools within a coherent and iterative framework.

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