



Digitising Waste: Teaching Circular Construction Through Computational Workflows and Digital Fabrication

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Abstract. The transition toward a circular built environment requires not only technical innovation but a fundamental shift in engineering pedagogy. While theoretical models of circular economy are well-established, the practical application of reusing waste materials in structural design remains a complex challenge due to material variability and non-standard geometries. This paper presents the pedagogical framework and outcomes of a graduate-level course at Politecnico di Milano, designed to bridge the gap between theoretical circularity and digital fabrication. The methodology follows a “waste-to-resource” workflow, guiding building engineering students through three distinct phases: Urban Mining and Digitization, Computational Design, and Advanced Fabrication. The cohort was tasked with sourcing waste materials from the urban context, which were then catalogued and digitized. Leveraging a suite of computational design tools within the Grasshopper environment - including evolutionary solvers for optimization, nesting algorithms for material efficiency, and specific plugins for timber joinery - students developed parametric models capable of adapting to the irregularities of reclaimed materials. The course culminated in the fabrication of five large-scale architectural structures, utilising advanced manufacturing techniques including milling and 3D printing, specifically focusing on creating bespoke interfaces and connections that facilitate dry assembly and future disassembly. This paper discusses the successes and challenges of this pedagogical model, analysing how digital tools serve as essential enabler for scaling circular practices. By treating waste as a variable input for algorithmic design, the course demonstrates that digital fluency is a prerequisite for the next generation of engineers to effectively operationalize circular economy in construction.

Keywords: Circular Pedagogy · Urban Mining · Computational Design · Digital Fabrication · Design for Disassembly

1 Introduction

The construction sector is a primary consumer of raw materials and a major generator of waste, operating largely within a linear “take-make-dispose” model [1]. Transitioning to a Circular Economy (CE) requires moving towards reduction, reuse, and recycling of

materials. To implement those, a paradigm shift is necessary, where existing building stock and demolition waste are viewed as material banks [2]. However, a significant gap exists in current engineering education: while students are taught the theory of circularity, they often lack the practical skills to handle the unpredictability of secondary resources. Unlike standard construction materials with certified properties and dimensions, waste is irregular, variable, and often contaminated.

This paper addresses the “Linear vs. Circular” gap by proposing a pedagogical framework that treats waste not as a problem, but as a “data-rich” resource. We argue that computational workflows are the key to unlocking the reuse potential of these materials. By digitizing waste - creating a “Digital Twin” of irregular scraps - designers can use parametric tools to adapt their structures to the material, rather than forcing the material to fit a standardized design. In this work we show that the design, becomes an iterative process, in which materials constraints inform the design development process, as well as the re-manufacturing processes inform the design in order to reuse existing materials. To demonstrate this thesis, the outcomes of a graduate course at Politecnico di Milano is presented, where students moved from theoretical “Urban Mining” to the physical fabrication of full-scale reversible structures. The course aimed to demonstrate the circularity of design to remanufacturing processes and to validate that digital fluency allows for the structural reuse of “junk,” turning unpredictability into a design driver through computational logic.

2 Methods

The course was structured around a rigorous “Waste-to-Resource” workflow, divided into three interconnected phases, comprising urban mining and digital cataloguing, computational design based on stock-constraints, and hybrid re-manufacturing. This structure forced students to abandon traditional linear design processes (Design → Material selection) in favour of a circular approach (Resource Mapping → Design adaptation).

2.1 Phase 1: Urban Mining and Digitization

The first phase challenged students to identify, collect, and catalogue waste materials from the local urban context. This process went beyond simple scavenging. Students identified waste material coming from deconstruction of furniture, construction components, and other waste streams (Fig. 1). They used photography and physical measurement to capture the geometry of found objects (e.g., discarded timber in various forms and composition, pallets, polycarbonate panels, and plastic based components).

A comprehensive *Material Catalogue* was structured to develop a rigorous ID-based list that tracked the dimensions, material quality, and probable origin of every piece of collected material and component. As far as feasible, this was expanded into a “Digital Material Passport” concept, ensuring that the history and properties of the waste were embedded in the digital model from the start, effectively creating a simplified “Digital Twin” of the physical stock, that was shared among the students, to allow them to reserve quantities of the available materials for planning their design and then re-manufacturing for prototyping.



Fig. 1. Material stock

2.2 Phase 2: Computational Design

With the physical waste digitized into a database of 3D assets, students moved to the computational environment. The primary challenge was to design structures that could adapt to the fixed, irregular constraints of the reclaimed materials.

Students were introduced to a set of algorithms that could be employed to: design based on stock-constrained members, such as *Phoenix* [3]; model structures based on adaptive algorithms, such as *Kangaroo 2* [4], which is based on physics-based form-finding, and simulates forces, constraints, and material behaviour in real time, so that the structure adapts automatically to loads, tension, compression, or minimal surface, or *Galapagos* [5], based on evolutionary optimization, that allow changing design variables iteratively to meet goals like minimizing material, stress, or waste. As well as algorithms that can guide in the reduction of waste, from a given set of components, such as *Open Nest* [6], which can be used for 2D nesting optimization, to automatically arrange shapes inside a given area to minimize material waste, and can be particularly useful in manufacturing processes where parts must be cut from sheets of material; or *NGon* [7], which excels at converting complex meshes into NGon-based topologies, and can be highly effective for panelization as it supports rationalization of panels, enabling, therefore better segmentation for fabrication, ultimately improving material usage. Finally, *Compas Timber* [8] was introduced to manage complex timber joinery logic, allowing to automate the generation of cutting paths for materials with non-standard cross-sections.

2.3 Phase 3: Advanced Fabrication and Design for Disassembly (DfD)

The final phase focused on materializing the digital models using advanced manufacturing techniques. Based on the material, selected from the digital waste catalogue, students had to elaborate strategies for the remanufacturing of the material/components to fabricate their physical prototypes within 3 weeks of the course. The re-manufacturing/fabrication processes, therefore, together with the given constrained stock of materials, informed the design choices. Moreover, a core requirement was that

the structures had to be designed for disassembly (DfD) to ensure the materials could return to the cycle after their temporary use.

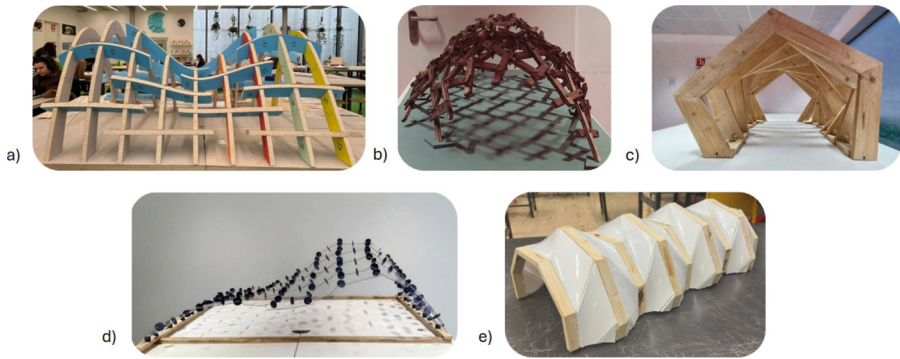


Fig. 2. Prototypes: a. The Skeleton; b. The Interlace; c. The twisting frame; d. the Polyhex; e. The Formilatte

3 Results

3.1 Structures

The course resulted in five full-scale structures (Fig. 2), each demonstrating a distinct strategy for operationalising waste.

The Skeleton addressed the challenge of “Material Agency.” Dealing with moisture-swelled wooden panels that defied standard dimensions, they used the *Galapagos* evolutionary solver to optimize the nesting and placement of elements. Their script adapted the overall form of the pavilion to minimize cuts and waste, effectively letting the material dictate the design.

The Interlace built on applying reverse engineering to prototype a reciprocal shell. By initially overlapping and connecting a sample of carpenter’s excess architectural moldings, the curvature that they produced was found and developed in repeating patterns to create a digital plan. By assigning lengths to cut from each section of stock using bin packing, minimal offcut waste was ensured.

The Twisting frame proved the value of data. This project relied on a rigorous ID-based catalogue that tracked quality and dimensions of wooden linear members, effectively turning a series of debris into a searchable “Temporary Material Bank.” By combining *Phoenix* with *Compas Timber*, they could instantly query this bank to find the optimal piece for each structural member, minimizing cutting waste.

The Polyhex gave a completely unpredictable root to the waste generated during the production of polycarbonate panels. Four discarded panels were re-elaborated in hexagonal components connected through ad-3D printed bespoke PLA joints that fit perfectly, to allow spacing the hexagonal panels in a freeform configuration.

The Formilatte found a stream for the reuse of unconventional material coming from polypropylene cheese containers. Double-curved repeating surfaces were desired

as panels to fit across a frame structure, and so experimental molds were created from both cement and ABS. Using these molds, and a custom adaptation of a vacuum forming machine, large planar sections of the polypropylene containers could be re-formed into panels of higher geometric complexity.

Table 1. Likert graded survey questions.

Section	#	Question
Circularity & resource mapping	1.	I can now clearly distinguish between simple recycling and circular strategies (reuse/re-manufacturing).
	2.	I feel confident in performing “Digital Mapping” and cataloguing non-standard urban resources.
	3.	The course improved my ability to critically evaluate the reuse potential of discarded components.
	4.	I understand how to design for “Dry Assembly” and total reversibility of building components.
Digital design & advanced manufacture	5.	Computational tools were essential for adapting my design to the actual dimensions of the waste found.
	6.	3D printing was a critical enabler for solving complex interfaces between irregular materials.
	7.	Designing within the constraints of “available waste” led to more creative solutions than “free” design.
	8.	I can effectively bridge the gap between a digital model and physical fabrication (CNC/Robotics/3D Printing).
Pedagogical & professional outcomes	9.	Working in a multidisciplinary team helped me integrate different engineering and design perspectives.
	10.	Developing a physical prototype was essential to validating the digital and circular theories learned.
	11.	I believe “Digital Fluency” (computational skill) is a prerequisite for circular engineering.

3.2 Post Course Survey: Quantitative Feedback

To investigate the efficiency of the developed pedagogical framework a survey was developed that included Likert graded questions (on a scale of 1-5), as shown in Table 1. Figure 3 shows the results. Student responses indicated a significant increase in capability regarding the handling of non-standard resources. Students reported high confidence in performing digital mapping (Q2 avg.: 4.3) and strongly agreed that designing within the constraints of available waste led to more creative solutions (Q10 avg.: 3.7) than an unconstrained “blank slate” approach. Notably, there was a strong consensus that “Digital Fluency” is a prerequisite for circular engineering (Q8 avg. 4.4, Q11 avg.: 4.0), validating the course’s heavy emphasis on computational skills (Grasshopper/Rhino) as a primary enabler of circularity. The lowest score was in Q8, suggesting the need to further develop skills in CNC and digital fabrication practice in future classes.

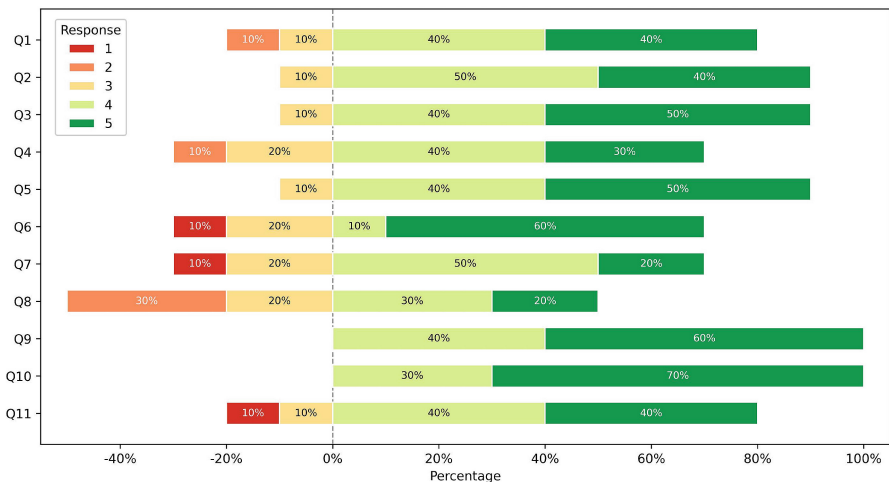


Fig. 3. Diverging stacked Likert chart of survey responses

Correlation between question scores were also calculated using Spearman’s rank correlation coefficient. The highest correlation coefficients were Q6 vs. Q9 ($\rho = 0.964$), suggesting that technical challenges of 3D printing and adapting designs to best work alongside waste required technically varied teams; Q3 vs. Q11 ($\rho = 0.868$), indicating that those who felt they got better at seeing value in pre-used material stocks strongly believe that you need high-level computational skills to actually make that waste useful; and Q1 vs. Q4 ($\rho = 0.783$), suggesting that participants who grasped the conceptual difference between downcycling and circularity were significantly more likely to understand the technical benefits of reversible “dry” joints.

3.3 Post Course Survey: Qualitative Feedback

Additional open questions were also provided for each of the three sections, encouraging reflection on change in perspectives on material use, challenges in using digitised waste,

and the three-phase workflow of the pedagogy as an approach to prioritising circular material practices.

Open-ended responses highlighted a profound shift in perspective from linear consumption to circular adaptation. One student noted, *“I stopped seeing materials as infinite products to buy and started considering them as precious resources already present in the territory.”** Another described the workflow as an inversion of the traditional design hierarchy: *“It is no longer the material that must satisfy a predefined form, but the design that adapts intelligently to the available resources.”** However, the transition was not without friction; some students noted that strict adherence to “stock availability” could initially feel *“limiting”** compared to traditional design freedom, highlighting the pedagogical need to frame constraints as creative drivers.

3.4 Case Studies: The Waste-to-Resource Matrix

The student reports for the structures were assessed to compare their material usage optimisation efforts. In the Skeleton, they noted that design utilised optimisation of nesting to adjust cutting patterns to best fit into the envelope of the cabinet boards they reused, leaving 38% offcut waste. In the Interlace, it was found using *Phoenix3D* and a custom evaluation component that a lower percentage of 15% of the architectural molding was left as offcuts. This groups use of metal fixtures was noted as a difficult item to source in the material catalogue, however the fixtures could enter the catalogue if and when the structure was assembled. Similar to the Interlace, the Twisting Frame utilised the same custom evaluation, leaving 33% of material as offcuts yet still with a high percentage of lengths which may be reasonably considered reusable.

With the Polyhex shell, moderate nesting of panels in the source material was applied but with a relatively high offcut waste of 59%, which could potentially have been improved through adjustment of the nesting parameters. The group additionally noted that the bespoke 3D printed connection components would be difficult to repurpose, although this was balanced somewhat by the biomaterial aspect of the PLA used. Finally, with Formilatte, they noted that 70% of the plastic trays used were effectively destroyed in the initial experimental prototyping stages, yet that now that the vacuum forming and molding process is honed future inefficiencies would be greatly reduced. For all of the groups, the initial setup of the communal material catalogue and the high use of dry assembly ensures that many parts of the structure, and the material stock offcuts, can be returned to the inventory for following cohorts.

4 Discussion

The results confirm that the barrier to reuse is often information, not material quality. By digitizing the waste (Phase 1), it becomes a “predictable” entity in the computational environment (Phase 2). This “Digital Twin” of the waste allows for high-precision fabrication (Phase 3) that would be impossible with manual methods. A key question remains regarding the scalability of this “Bespoke” approach. As one student noted, the shift from “Standard Catalogues” to “Urban Mining” is primarily a data management challenge. By developing robust scripts (like Group 05’s *Compas* workflow), the “cost”

of dealing with irregularity drops significantly, making circular construction a viable alternative to the convenience of the linear model.

A recurring theme was the difficulty of “listening to the material.” Traditional engineering creates a form and specifies a material to match. Circular engineering demands the reverse. The survey revealed that while students found this technically challenging (specifically managing tolerances), it was the key factor in changing their mindset. The “Informed” nature of the design - where the 3D scan data drives the geometry - ensures that the final structure is constructible despite the variability of the input.

4.1 Conclusion

This paper presented a “Waste-to-Resource” pedagogical framework that validates the use of computational workflows to bridge the gap between circular economy theory and construction practice. We demonstrated that Urban Mining combined with Computational Design transforms waste from a liability into a high-value asset. The successful fabrication of five reversible structures proves that when waste is digitized, it can be re-engineered with the same precision as virgin material. We conclude that Digital Fluency is not merely an optional skill but a fundamental prerequisite for the next generation of engineers tasked with building a regenerative future.

Acknowledgments. This work was developed at the AS_Lab of DABC in Politecnico di Milano, and was partially supported by the Multiannual Funding of Lab2PT/UM, Ref. UID/04509, financed by PIDDAC - FCT/MCTES.

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