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Abstract	Spatial systems like shells, arches and shelters can often be used as temporary structures to accommodate short to medium expositions, events, or emergencies. This has historically allowed them to be designed for multiple uses. Recent advancements in computer graphics, algorithmic design, and advanced manufacturing have accelerated their development and opened new scope for applications, by exploiting new capabilities and opportunities for material-efficient designs and constructions. The authors aim to develop combined systems approaches to the design of resilient, de-constructible constructions for the built environment. This work presents the recent advancements in the development of discrete shell systems developed at the AS_Lab between the Politecnico di Milan and the University of Leeds, using biogenic materials such as wood which are inherently sustainable. Coupling geometry design and segmentation with ad-hoc connection systems, demountable systems have been developed, which are materially efficient, digitally designed, and fabricated, and can, in some instances, be robotically assembled. The study presents the conceptual design and fabrication of three prototypes, which have been realized to accelerate the transition to industry 4.0 while posing the focus on a circular future.
Keywords (separated by '-')	Circular economy - design for deconstruction - computational design - Digital fabrication - lightweight structures - robotic assembly

Design for Deconstruction Through Digital Fabrication of Thin Spatial Systems

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Abstract. Spatial systems like shells, arches and shelters can often be used as temporary structures to accommodate short to medium expositions, events, or emergencies. This has historically allowed them to be designed for multiple uses. Recent advancements in computer graphics, algorithmic design, and advanced manufacturing have accelerated their development and opened new scope for applications, by exploiting new capabilities and opportunities for material-efficient designs and constructions. The authors aim to develop combined systems approaches to the design of resilient, de-constructible constructions for the built environment. This work presents the recent advancements in the development of discrete shell systems developed at the AS_Lab between the Politecnico di Milan and the University of Leeds, using biogenic materials such as wood which are inherently sustainable. Coupling geometry design and segmentation with ad-hoc connection systems, demountable systems have been developed, which are materially efficient, digitally designed, and fabricated, and can, in some instances, be robotically assembled. The study presents the conceptual design and fabrication of three prototypes, which have been realized to accelerate the transition to industry 4.0 while posing the focus on a circular future. AQ1

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1 Introduction

The continued increase of material resources' environmental and economic costs has brought attention to improving the reuse of our built environment. In this context, circular economy principles have been developed. Cities can lessen the detrimental effects of the urban built environment by using circular principles, which guarantee that materials and components are preserved and retained at their best value over multiple life cycles.

Computational design and fabrication methods, with special regard to additive and subtractive manufacturing, and robotic assembling are technologies that can be used to improve the circularity of the built environment. A large body of knowledge is under development to demonstrate this, and this paper, indeed, builds on this evidence. This paper demonstrates how digital design, advanced manufacturing, and robotic assembly

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can facilitate the development of de-constructible systems for curved surfaces, looking at three prototypes developed by Iuorio's group, in response to international collective exhibitions.

2 Methodology

The current study is intended to demonstrate the scope of design for disassembly in lightweight structural systems, particularly thin timber structures. By collecting a selection of our recent developments in this field, we exhibit some advancements in computational design, digital fabrication and assembly processes. These additions to the state of the art are shown to have potential to decrease material waste production, and allow for non-adhesive reversible connections which benefit the return of materials to construction stocks.

To demonstrate these contributions, Sect. 3 presents 3 case studies in the computational design of the ECHO shell, the ECHO arch, and the "Set in transition" prototype. Section 4 describes the use of digital fabrication technologies to manufacture elements of these designs, and the benefits of using these technologies. Section 5 describes some advancement in the use of robotic assembly for the construction of these new structural designs. Finally, conclusions are made highlighting the contributions, and how they bridge the gap between circular economy theory and practical applications.

3 Case Studies in the Design of Thin Spatial Systems

3.1 The ECHO Shell

The ECHO shell is a lightweight segmented shell system comprising of hexagonal wooden panels joined together with location-specific 3D printed connections [1]. The design of the ECHO shell revolved around dimensional constraints of the constructed prototype, imposed by a competition organized for the 60th Anniversary Symposium of the International Association for Shell and Spatial Structures in 2019 in Barcelona. However, the most critical limitations were practical ones and were imposed by manufacturing and shipping considerations e.g. limit on the maximum size of panels for manufacturing purposes, weight of the structure for shipping purposes, and the necessity to assemble and disassembling it.

The labour-intensive nature of shell construction and assembly was a starting point of consideration in the development of the ECHO shell. The goal was to design a structure that can be assembled and most importantly safely disassembled by a team of 2 to 4 people in a few hours. The shell was designed to support self-weight-induced internal forces. A 6 mm poplar plywood material was shown to be suitably lightweight and structurally sufficient to withstand the expected forces while fulfilling manufacturing requirements i.e. being suitable for laser cutting.

The entire design was contained in one parametric definition, which helped streamline the eventual changes in later stages. Starting with a simple concept of a hemispherical synclastic shape, that represents a portion of a soundwave, which inspired the name ECHO. Then moving into a segmentation process or "Tessellation" that generates the hexagonal panels on the curved surface (Fig. 1). And finally generating a planarized version of each individual panel in a process called "Planarization" that converts the original surface into a continuous curved poly-surface of planar panels, while maintaining the original properties of a shell that converts the external forces into membrane actions [3].

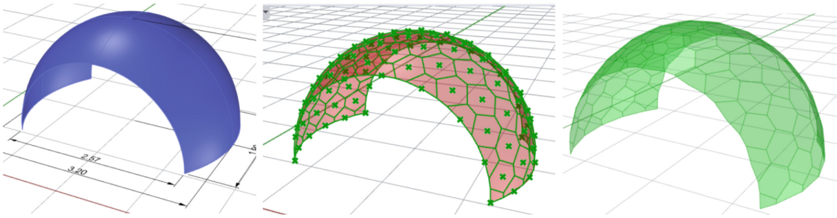

Fig. 1. Concept, tessellation, and planarization of the ECHO shell made with Grasshopper environment [2].

A multitude of steps follow; generating finger joints between the panels that help with assembly and positioning, generating final features of the panels that create slots for the 3D printed connection, panel numbering, and generating and exporing manufacturable panels.

Fig. 2. The ECHO shell during construction. The panels require some external support during assembly, to counteract bending moments; however, support can be removed after assembly.

The design achieved its purposes not only by producing a stable structure, but most importantly by resulting in a structure that has - so far - been assembled and disassembled three times for testing, presenting, and educational purposes, the last of which was for the Leeds International Summer School in 2022 where a group of students managed to reassemble the structure under supervision (Fig. 2). The design has also shown to be durable with very few maintenance requirements or inappropriate storage conditions, while maintaining the same level of structural stability and having minimal need for support in the construction and deconstruction stages.

3.2 The ECHO Arch

Since the original ECHO shell concept, developing anticlastic surfaces was deemed to complete the sound echo waves blend with shell curvature. Hence, to demonstrate the capacity of the conceived system, an arch was designed to follow the same principal design and fabrication methodology of the shell, while relying more on the catenary load-resisting mechanism. The arch was assembled, in his final configuration at the Material Eco-Systems symposium, organized by Iuorio for the Venice Biennale of Architecture, Italy in 2023 (Fig. 3). The assembly, disassembly requirements and being flat packed for shipping were essential in this design.

Fig. 3. The ECHO arch as displayed at the "Material Ecosystem Symposium" within the Collateral Event at the Venice Biennale of Architecture 2023.

The design starts with a catenary arch as a starting surface; however, the planarization process results in a poly-surface that deviates from the original. The original surface is - by design - a catenary arch, but the final surface, combined with the very thin panels, results in forces that do not follow the optimal flow path of forces of a catenary. This introduces bending moments that are most pronounced in the nodes of the panels, in other words, in the connections.

The arch demonstrates that even deviating from the optimal shape of a catenary, the arch, realized with thin and flexible materials, could withstand static and dynamic loading. The deviation from catenary and the consequent resulting forces could be counteracted by creating more rigid structures and, hence, requiring more material usage. However, an appropriate design of a connecting system can resist bending moments while maintaining the structural stability of the structure, avoiding increased material usage, and minimizing the supports needed in the construction stages, as demonstrated by this prototype.

3.3 Set in Transition Leaf

In addition to using external joints to constrain panels, other research within the group has focused on the design of self-supporting shell structures with integral joints. Such designs have made use of dovetail inspired joints cut from the panel material, using geometric Boolean operations to remove and add matching joints and slots through a design (see Fig. 4). Such designs are driven by traditional joinery and depend on friction-based interference fitting. The use of integrally attached joints has the benefit of reducing internal stress on panels at interfaces, due to bending moments that may arise. The use of the joints additionally allows for dry stacking assembly, that is, without adhesives or external fixings, making deconstruction trivial.

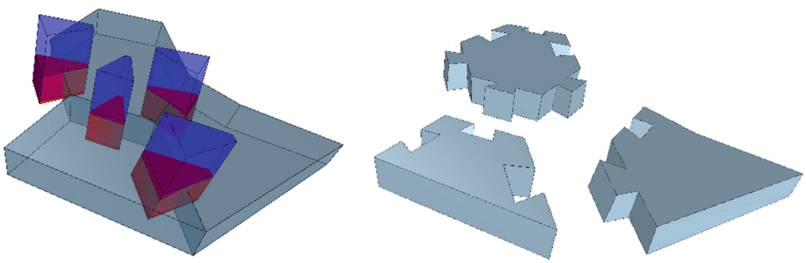

Fig. 4. A selection of three neighbouring panels, showing the boolean addition (red) and subtraction (blue) of dovetail wedges from pairs of panels, giving panels with integral mating joints. Wedges are extruded along the perpendicular vector of the planar panels.

An additional key driver of this work was to develop a system that could be self-supporting not only once assembled but also during assembly. Formwork makes up a large percentage of construction waste for shell structures, estimated by some to be as high as 45% of carbon emissions in constructing a shell [4]. By designing assemblies that can support themselves during construction, this formwork waste can be mitigated, providing a more sustainable construction approach.

In order to model structural stability during assembly, the coupled rigid block analysis was utilized. Using scale 3D printed models, and assuming that the shell can be treated as a set of rigid panels, the use of the analysis was validated by comparing to replica models, demonstrating the use of stability tools other than FEA for rapid, early stage design feedback [5]. It was shown that with suitably low tolerance on dovetail joints, long cantilevered sections could be constructed, unsupported, depending on friction effects on joints to maintain stability throughout assembly.

We received an invitation to propose a physical model to be displayed at the Students as Researchers exhibit for the Biennale di Architettura in Venice 2023, which aimed to discuss how schools of architecture and architectural engineering are responding to the global challenges brought by climate change and social needs. For this, a protype titled "Set in Transition" was developed. The prototype aimed to demonstrate the necessity of reducing our built environment footprint by developing systems using geometry and advanced static to reduce material use in the final product and during construction, that can be adopted over multiple cycles. A maple leaf inspired design was specified and hand drawn before being converted into a computer graphics representation, and form-finding was applied to the free-form drawing, by anchoring the base artificially and using energy goals to pull regions of the geometry around, whilst maintaining a funicular form which is dominated by membrane loading. The surface was segmented, and planarized using the variational tangent plane intersection method [6]. Using the CRA technique, the leaf was designed to be stable throughout assembly at a full scale of $2 \times 2 \times 1$ m; for the purpose of the exhibition, a scale version was manufactured to fit within a $0.7 \times 0.7 \times 0.35$ m envelope (Fig. 5).

Fig. 5. The "Set in Transition" interlocking leaf structure. Each panel element is inserted along the vector perpendicular to its own plane.

4 Technological Advancements in Digital Fabrication

4.1 Additive Manufacturing

Advancements in 3D printing technologies and the availability of 3D printers have made creating custom parts with very specific dimensions and features more accessible than ever. A novel connection system was created for the ECHO shell that relies on pins on location-specific connections that pair in a friction-fit manner with slots in the panels (Fig. 6). Each connection consists of two components joint together by a small fastener. The two components of the connection join three adjacent panels for the shell system, and then adapted to join two panels for the ECHO Arch.

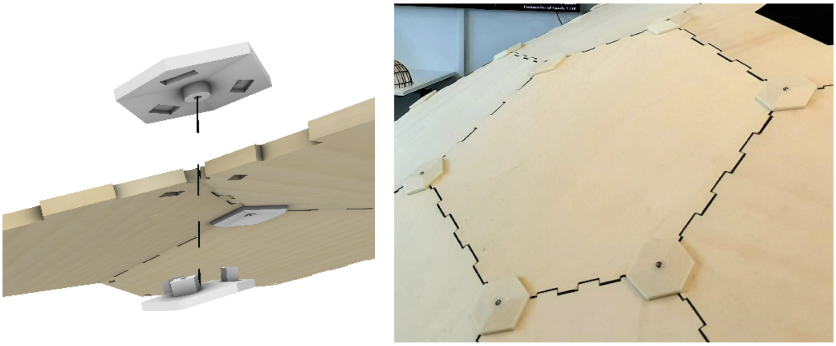

Fig. 6. Parametrically designed, 3D printed connections for the ECHO shell and arch. Printed from PLA plastic, the top and bottom parts are fastened together to constrain the 6 mm thick plywood panels.

4.2 Laser Cutting

Laser cutting is a subtractive manufacturing technique that can be very efficient in material use if the sections to be manufactured were optimized to the size of the sheets of raw material used. Laser cutting was used to manufacture the panels for all of the reviewed projects. Laser cutting integrates well with the design to manufacturing methodology followed, because as a Computer Numerical Control (CNC) manufacturing method, it uses vector images that can be very easily extracted from the design.

4.3 Approximating Complexity: Stacked Contour Method

While laser cutting can be utilised to manufacture single layer panels, it can also be used for the creation of thicker, more complex geometries. The construction elements within the Set in Transition leaf, along with other panels being tested within our lab, use a combination of positive and negative gradients on their interface surfaces to create the required cantilevering and joining effect. Initially, 5-axis CNC milling was considered for the manufacture of these components, however the cost proved to be inhibitive.

By instead slicing panels into layers within parametric design software Grasshopper [2], it is possible to approximate them by laser cutting them as laminar layers which can then be reconstructed (Fig. 7). Some details are lost on the edges due to the approximation, although this effect can be reduced by using thinner layers of sheet material.

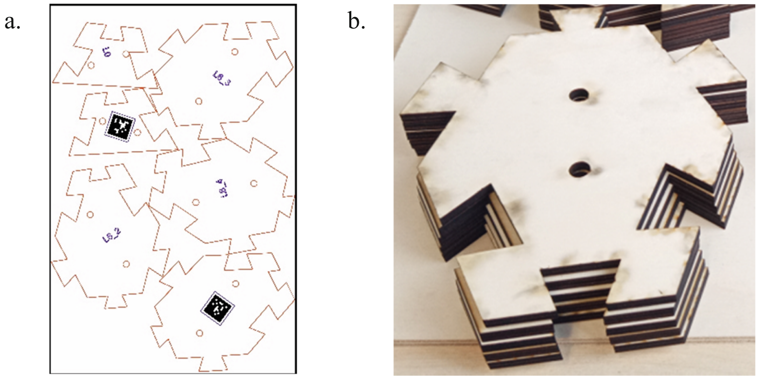

Fig. 7. The method of stacked contours used with laser cut sheets. a) A laser cutting sheet for a selection of panel layers. b) A single panel, made of 6 mm timber sheets.

The use of sheet material allows for reduction of material waste by finding tight nesting of panel borders within a sheet. Assessing the no-fit polygon criteria [7] to find feasible, non-overlapping configurations of panel boundaries, different layouts of panels can be found in an attempt to minimise the offcut area. For the example sheet of Fig. 7, with dimensions 40 × 60 cm, an area of 1,030 cm^2 is offcut representing 43% material wastage; this can be further reduced by having a larger selection of panels to place to fill spaces. It should be noted that this is still a significantly lower level of waste than produced by CNC milling, particularly as the offcuts can be reused as compared to milled material. Panels can also be disassembled by removing their reference dowels, allowing them to be reintroduced to the material stock with a small amount of sanding to post-process.

5 Robotic Assembly

The use of robots in construction of the built environment will likely continue to grow and disrupt the AEC industry, with 81% of firms planning to introduce robotics in the next 10 years according to a survey by robotics company ABB [8]. While digital fabrication can aid the reduction of material usage, innovative assembly systems can additionally reduce the dependence on human operatives, improving safety in construction. Further, the use of digitally controlled assembly agents and sensing can allow for better recording of process data for construction monitoring, giving live feedback on the assembly.

Our lab has explored the use of a robot manipulator arm for the assembly of the thicker, stacked contour panel system. Making use of custom-made gripper fingers, the arm can hold onto the dowel referencing rods securely. QR code style Apriltags [9] are used to monitor the construction environment and inform the robot where to pick and place panels, shown in the center of panels in Fig. 8, while the panel placement is informed by the reach envelope of the particular robot.

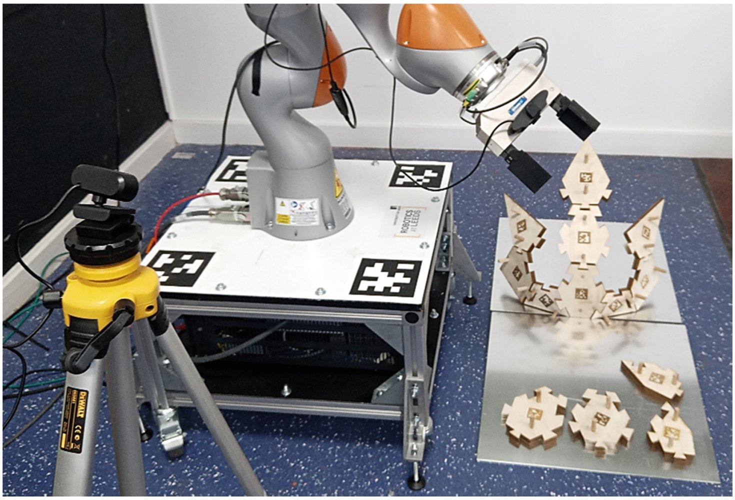

Fig. 8. Robotic assembly of the leaf panels.

The use of robot arms for assembly additionally requires encoding the relative insertion directions by which panels can be connected to each other, which a human operative would implicitly understand. Using custom Grasshopper C# components, structures can be represented as a tree structure, where nodes represent panels, and edges represent the liaisons between them and their relative insertion vectors [10], found from the mating geometry. We demonstrated that, through such a representation of a structure, potential assembly sequences could be found algorithmically, finding multiple potential assembly sequences which can then be checked to find the most structurally stable sequence, and by extension, a suitable stable sequence for disassembly. This area could certainly be extended for better planning of disassembly in end-of-life decommissioning of buildings, where BIM or CAD data is available.

6 Conclusions

Digital techniques can be of support in the transition to circular future. Material and component passports, digitally driven geometries for efficient use of material, scanning technologies for construction tracking, and advanced manufacturing with subtracting and additive manufacturing to build only what needed where needed can be implemented to develop de-constructible systems. The research presented in this paper, using as case study shell design and fabrication, demonstrates how the development of discrete systems with ad-hoc connections, can facilitate the reusability of components and full systems. It also demonstrates the importance of considering the construction and future de-construction process in the initial stages of the design process, to reduce the amount of material, and increase the amount that can be recovered. It finally builds on the idea that strength can be achieved through geometrical efficiency, and in this sense digital manufacturing techniques can drastically facilitate that. These results open the way to large scale experiments, that will integrate materials and components retrieved from existing buildings.

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Chapter 24

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