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Building from Scrap: Computational Design and Robotic Fabrication Strategies for Spatial Reciprocal Structures from Plate-shaped Wooden Production Waste

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Abstract

This paper describes an innovative methodology allowing upcycling production waste into legitimate construction material for spatial structures, with minimal change to elements` shape. The system is based on interlocking joints between the boards. The plates are organized around nodes, creating a three-dimensional reciprocal system guaranteeing the stability of the entire structure, without any fasteners. We use an inversed, data-driven design process, in which unique components are defining the form of the structure. The design-to-production workflow consists of measuring and labeling of the elements, creating a data file, data-driven generation of the structure with a custom form-finding algorithm, structural optimization of the form, robotic processing of the scraps and manual assembly. The proposed methodology was tested in public spaces as a temporary pavilion and three wood-clay composite sitting elements, thus practically demonstrating the feasibility of our approach.

Keywords: *Circular economy in construction, data-driven design, design based on availability, robotic fabrication, spatial reciprocal structures.*

Atık Kullanarak İnşa Etmek: Levha Şeklindeki Ahşap Üretim Atıklarından Üretilmiş Uzaysal Mütekabil Strüktürler İçin Hesaplamalı Tasarım ve Robotik İmalat Stratejileri

Öz

Bu makale, üretim atıklarının, minimum biçim değişikliği ile mekansal yapılar için meşru inşaat malzemesine dönüştürülmesine izin veren yenilikçi bir metodolojiyi açıklamaktadır. Sistem, levhalar arasındaki geçme bağlantılara dayanmaktadır. Plakalar, herhangi bir bağlantı elemanı olmadan tüm yapının stabilitesini garanti eden üç boyutlu bir karşılıklı sistem oluşturarak düğümler etrafında düzenlenmiştir. Benzersiz bileşenlerin yapının biçimini tanımladığı tersine çevrilmiş, veriye dayalı bir tasarım süreci kullanılmıştır. Tasarımdan üretime iş akışı, öğelerin ölçülmesi ve etiketlenmesi, bir veri dosyası oluşturulması, özel bir form bulma algoritmasıyla yapının veriye dayalı olarak oluşturulması, formun yapısal optimizasyonu, hurdaların robotik işlenmesi ve manuel montajdan oluşmaktadır. Önerilen metodoloji, kamusal alanlarda geçici pavyon ve üç ahşap-kil kompozit oturma elemanı olarak test edilmiştir, böylece yaklaşımımızın uygulanabilirliği pratik olarak gösterilmiştir.

Anahtar Kelimeler*: İnşaatta döngüsel ekonomi, veri odaklı tasarım, mevcudiyete dayalı tasarım, robotik imalat, mekânsal karşılıklı yapılar.*

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1. Introduction

Ecology and circular economy are becoming major topics in the architectural discourse. This comes as no surprise, as a significant part of the environmental impact of human activities arises from construction (Hughes, 2019). The climatic crisis and new globally applied environmental strategies are forcing construction to change its approach towards more suitable solutions. Such strategies can involve the reuse of existing buildings by refurbishing them, as was outlined by Pehlivan (2018). Other approaches include the use environmentally friendly raw materials like earth (Özgünler, 2017), or wood, which is also generally considered a sustainable building material. To the authors' knowledge, however, the use of waste streams emerging from construction has not yet been sufficiently investigated in the literature. This paper presents a novel methodology for using wooden production scrap as a legitimate building material.

Timber construction companies order wood in standardized dimensions and cut it to final shapes defined by the current design practice. The remaining cut-offs, irregular in size and properties, cannot be used in standard buildings and are usually downcycled or burned, which causes significant losses for the manufacturer and environment. Although the problem concerns roughly 10% of ordered material, it is mostly neglected, as it is difficult to tackle with available traditional techniques and approaches. Poor digitization of the construction sector is one of the factors hindering better exploitation of production waste and opportunities in circular economies (Durmisevic et al., 2021). To this end, new digital working methods have been defined, in which available materials are considered as a source of ideas, following the principle: reuse, re-invent and give life again.

Building with heterogeneous elements requires a paradigm change in architectural aesthetics, design, manufacturing, structural optimization, and assembly. We believe that one of the greatest potentials of growing digitalization is shifting the construction industry towards more circular solutions. Data-driven design strategies and robotic fabrication can help in repurposing production waste into form-found functional structural shapes and lead to smarter and more sustainable cities.

This paper describes working methods to design and fabricate spatial structures out of irregular production scraps. This includes the following: a description of structural principle of a spatial reciprocal system consisting of non-uniform rectangular boards, data-driven design, robotic fabrication and sequencing and assembly of complex structures. Finally, it shows the implementation of this process in two constructed demonstrators: a temporary pavilion for ArchitekturWoche Basel (Figure 1a) and 3 wood-clay sitting elements constructed for the TouchWood exhibition in Museum ZAZ Bellerive in Zurich (Figure 1b).

a) b)

Figure 1. Constructed pavilions: a) a temporary pavilion for ArchitekturWoche in Basel, b) wood-clay sitting elements at TouchWood exhibition in Museum ZAZ Bellerive in Zurich (Photos courtesy of ARCHIBATCH)

1.1 State of the Art

1.1.1. Circular strategies for working with wood waste

Wood is a renewable resource, but not an infinite one. Across Europe, the construction sector accumulates 70.5 million tons of wood waste annually, of which only a third is currently recycled (WoodCircus, 2019). A significant amount is incinerated, which means the stored CO_2 is re-emitted into the atmosphere (Rüter & Diederichs, 2012). In this context, several European research projects have emerged with the prerequisite of establishing a circular economy setting to extend the service life of wood (WoodCircus (2019) and CaReWood (Risse & Richter, 2018)). One solution is cascading of wood (Hughes, 2019), meaning that the material goes through usage cycles through consecutive downcycling to maximize the duration of its availability in construction. An alternative approach is reusing material, which can further reduce the environmental impact of a building, as less energy is used for reprocessing (Kromoser et al., 2022). Designing within the constraints of non-standard components, however, requires changing conventional design and manufacturing processes (Moussavi et al., 2022), as explored by various research projects (Malé-Alemany et al., 2022, Circulating Matters, 2022). Most projects that deal with the circular economy in construction focus on working with elements reclaimed from demolished buildings. The problem of manufacturing waste, although significant, is not adequately addressed. These scraps are either downcycled (as biomass, panel board or animal bedding) or burned. This calls for developing new strategies to return the production waste to the construction cycle.

1.1.2. Data-driven approaches in architectural planning

In the face of growing complexity in the building industry (Kolarevic, 2009) and its low efficiency (McKinsey, 2016), new data-driven design approaches have recently been introduced, replacing the traditional, linear, and sequential project workflow (Alvarez et al., 2019). As stated by Brown and Mueller (2017), despite the widespread belief that architecture depends on human intuition, reasoning and creativity, data can complement or enhance human activities, for example, by helping to make informed decisions and to solve complex problems (Wei, Yuan & Liu, 2020). This method is used in multi-objective design processes, where an architect is guided by simulations that describe several aspects of building performance (Brown & Mueller, 2017). This data can be either used as guidelines in the next design decisions, without a direct impact on the generation of the geometry (Deutsch, 2015) or, as shown in the recent studies (Brown & Mueller, 2017, Bianconi & Filippucci ,2019), can be connected to the form-finding algorithms. In this case, data-driven design can effectively support the designer in problem-solving by comparing different generated design solutions. However, it requires constant human feedback and is still marked by computer performance problems.

Data-driven computational strategies have been also applied in production-aware design practice (Wei, Yuan & Liu, 2020, Figliola & Battisti, 2019). In these projects, data collected during manufacturing guide the architects in optimizing the design to improve the adaptability of products to the manufacturing environment. This approach is particularly beneficial when working with irregular materials (such as non-engineered wood) and when combined with structural goals, as shown in the Wood Chip Barn project (Mollica & Self, 2016). Here, the data-driven design, along with advanced computation fabrication techniques led to the construction of a stable truss with minimal processing of the original wooden trunks.

Only a few projects have attempted to generate building form by analyzing the shape of the available material (Monier, Bignon & Duchanois, 2013). One example is `Mine the scrap` by Nolte et al., (2016). The authors developed an algorithmic tool that scans scrap elements from demolished buildings and rearranges them into new architectural envelopes using pattern recognition, classification and machine learning. These forms defined by non-uniform stocks of material are characterized by a new architectural vocabulary. The challenge in these constructions remains, however, assembly and structural performance.

2. Materials and Methods

The proposed methodology enables the flexible design of structures from components with predefined dimensions and properties and facilitates their production and assembly. It is based on the concept of digital craftsmanship (Augustynowicz et al., 2021), manifesting itself in application of custom digital design tools and hybrid manufacturing system that intelligently combines automated and manual production to achieve economic feasibility and high aesthetic quality. The process consists of several prototypical digital and manual processes, which were developed independently and can be used in various configurations depending on the design task (Figure 2). All computational tools were written in the Grasshopper plugin for Rhinoceros with custom Python components. The robotic fabrication tool additionally uses KUKA|Prc plugin for planning of robotic paths.

Figure 2. Proposed design, fabrication and assembly process in steps

2.1. Structural Principle

The main objective for developing the structural concept was to ensure the overall stability of the system, built out of irregular plates. The authors wanted to avoid generating more waste by cutting the scraps to specific dimensions. It was also crucial that the components return to the construction cycle after the project's lifespan by avoiding the use of additional adhesives or metal fasteners. An interlocking plate-based spatial reciprocal system was chosen as the best answer to these prerequisites.

Reciprocal Frame Structures (RF) are spatial configurations consisting of load-bearing elements, where each one supports, and in turn is supported by, all the others (Larsen 2014), with no clear structural hierarchy (Pugnale et al., 2011). The advantage of RF lies in the fact that they can cover large spans with small and lightweight components (Araullo & Haeusler, 2017) so that the assembly can be performed by people with little construction expertise and without the need for sophisticated machinery. Although most research focuses on exploring surface-based linear RF (Larsen, 2014, Thönnissen, 2014), planar components can also be arranged in a reciprocal arrangement, which has been applied in furniture design (Baverel & Pugnale, 2013) and has been explored recently in various projects (Araullo & Haeusler, 2017, Plate Pavilion, 2014). There are several approaches to working with planar RF (Baverel & Pugnale, 2013). The design principle chosen for this project is based on the solution developed for the Kodama Pavilion (Kuma et al., 2019). In this project the solid larch slabs of uniform size were organized in an interlocking manner around nodes (Figure 3a).

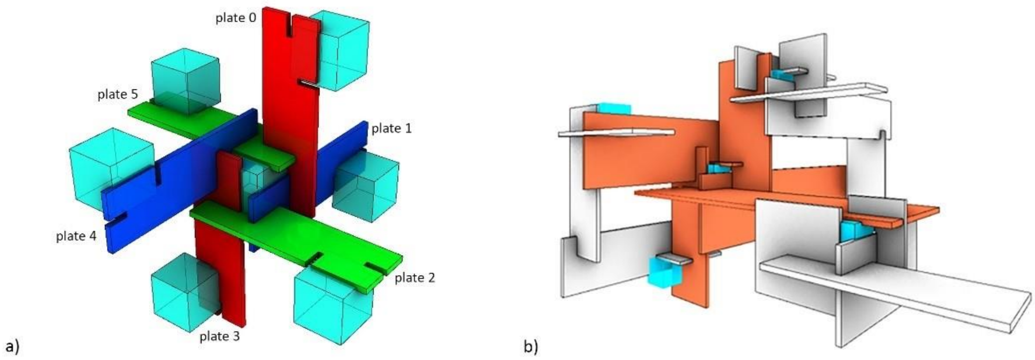

Figure 3. Connection principle. Each node is built out of 6 interlocking plates in 6 directions. a) a single node with uniform interlocking plates (Kodama pavilion). Cyan blocks symbolize the nodes around which the plates are organized. b) the second generation of structure with irregular plates

Every plate has two nodes in diagonal corners, where each is a starting point for the subsequent aggregation. To ensure stability, every member must have at least two and optimally four connections to neighbouring elements through a system of notches. In the project described here, the individual components were of a non-repetitive size, which posed a challenge in providing each board with sufficient intersections while avoiding unwanted overlaps (Figure 3b). Therefore, an advanced data-driven algorithmic approach for aggregation of plates has been developed.

2.2. Material

During the project, the authors collaborated with a local wood construction company, which provided waste panels from its production accumulated over a month: 1.5 tons of heterogeneous cut-offs both in dimensions (length:50-100cm, width:20-70cm, depth:1.8-4.2cm) and properties (OSB and layered panels) (Figure 4).

Figure 4. Material used in the project: 1.5 tons of cut-offs irregular in dimensions and properties, received from a local wood construction company, ERNE AG Holzbau

Roughly half of the available plates were measured manually and logged in a CSV file. Out of the 350 measured plates, over 90% were OSB and the remaining plates were three-layer panels. A statistical overview of the material dimensions is provided in Figure 5. The available material resources were very heterogeneous. Plates with a width of around 250-300 mm were particularly common, while the lengths were relatively evenly distributed between 300 and 1000 mm. The distribution of thickness reflects plate types commonly used in construction. It is noteworthy that the authors were dealing with aspect ratios that were from close to square up to long strips that were almost four times as long as they were wide.

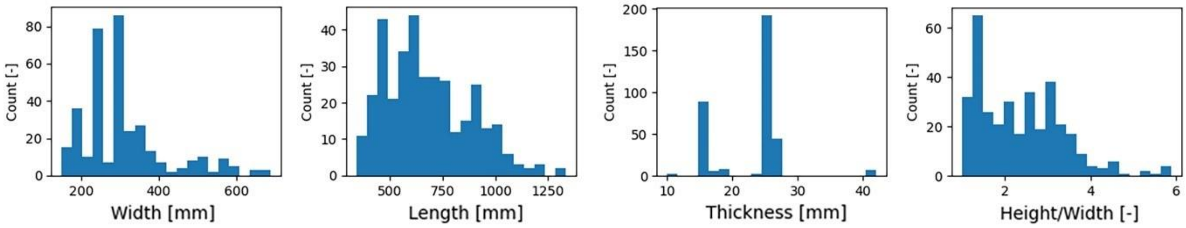

Figure 5. Distributions of the dimensions and aspect ratios of the material used in the project

2.3. Data-driven design approach

This data collected from board measurements was then fed into an algorithm, which organized the scraps into user-defined boundary volumes according to the structural principle described earlier (Figure 6).

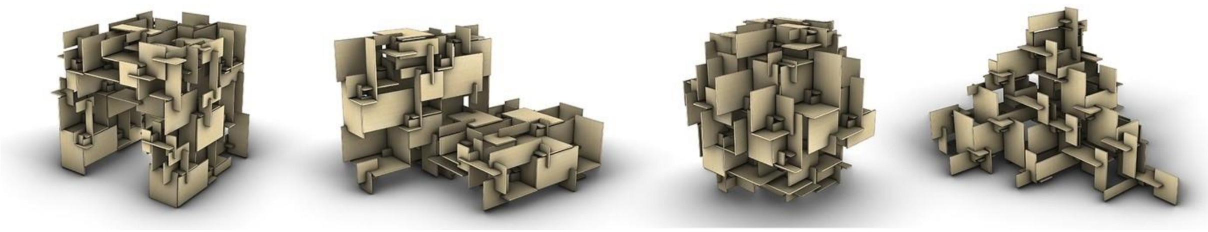

Figure 6. Results of the plate aggregation algorithm for different, user-defined, boundary volumes

Users can indirectly influence the placement of plates in the volume by parametrically adjusting the weights assigned to their width, length, or depth, which define the order of elements in the database and prioritize their selection in subsequent iterations of the program. The proportion of employed elements and the porosity of the structure are controlled by several numerical parameters: the node size, the distances between plates and the depth of the notches. The optimum node size should allow for sufficient intersection length between plates and correlate with the dimensions of available material (Figure 7).

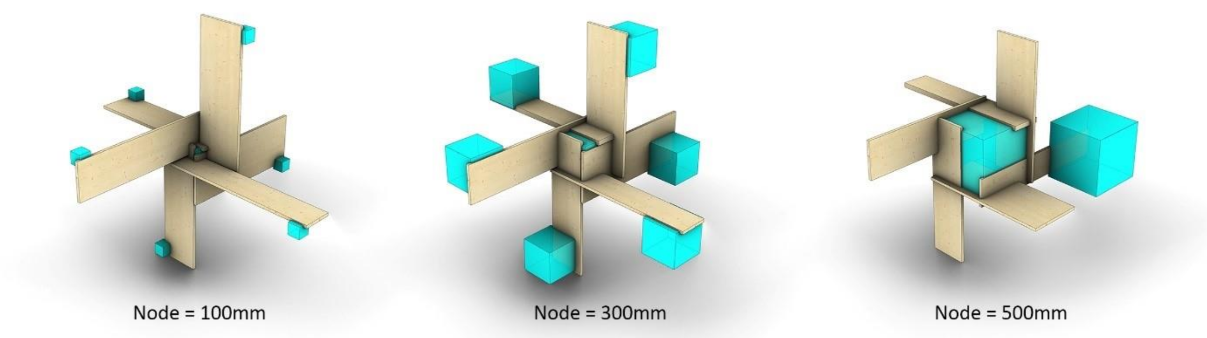

Figure 7. Influence of the node size on the interconnection between the plates. The size of the nodes should be adjusted to the dimensions of the available plates in the set. In the depicted example node = 100mm would not ensure enough of intersection surface, whereas node = 500mm is too big for the given set and would stop the aggregation in the second iteration

A Python-based custom algorithm carried out the distribution of plates and initial optimization of the structure. It stores data tree for nodes, a nested list containing six items for each plate orientation relative to a given node, and another one with meshes defining a collision-free zone for each element. The aggregation process is iterative, where the number of iterations influences the density of the structure. In each loop, the algorithm distributes plates around the available nodes from the data tree in such a way as to allow intersections with already placed elements at the neighboring nodes and simultaneously reach the limits of the boundary volume. Each added plate introduces another node into the data set, located at its opposite end. The optimal number of iterations enables sufficient intersections between the scraps while keeping the number of elements within a reasonable range (Figure 8).

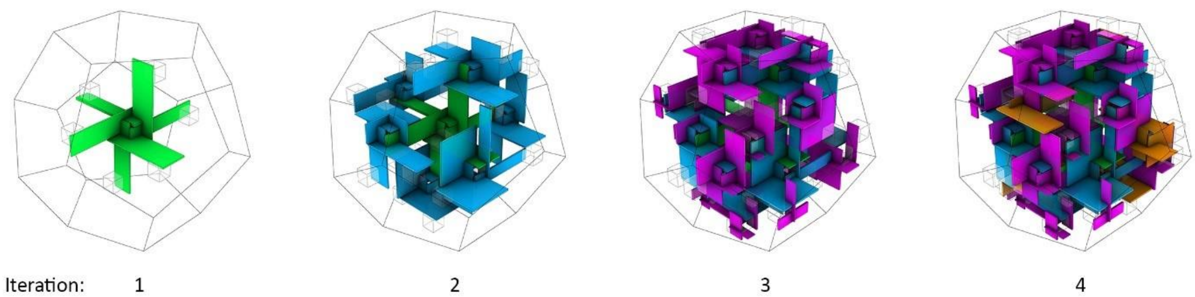

Figure 8. The iterative process of generation of the plates within the predefined boundary volume. The nodes mark the position of the next iteration

However, as the dimensions of elements are diverse, the program's biggest challenge is providing each board with at least two connection points while avoiding joints impossible to assemble. Several means have been introduced to address this issue. After each iteration, the script performs self-checking and automatically removes those boards with insufficient support points. In addition, the geometry is post-rationalized after it is generated when the user manually removes those elements that overlap or adds additional supports to ensure sufficient connections to the base. For this purpose, another script was written to find the best-fitting item in a given location from the data file, excluding already used elements.

Notches between the plates are automatically generated based on their respective geometries and assumed tolerances for fabrication and assembly.

The current implementation of the generating algorithm does not perform any checks regarding the integrity and static properties of the finished structure. Therefore, the design was exported to RFEM software for finite element analysis (FEA). Material properties and joint stiffnesses were approximated, thus no quantitative results on stresses and deformations were obtained. However, this analysis allowed us to identify areas of concern, which were then supported with additional plates from the material catalogue (Figure 9). Based on this analysis, 4 plates were added to stiffen the structure.

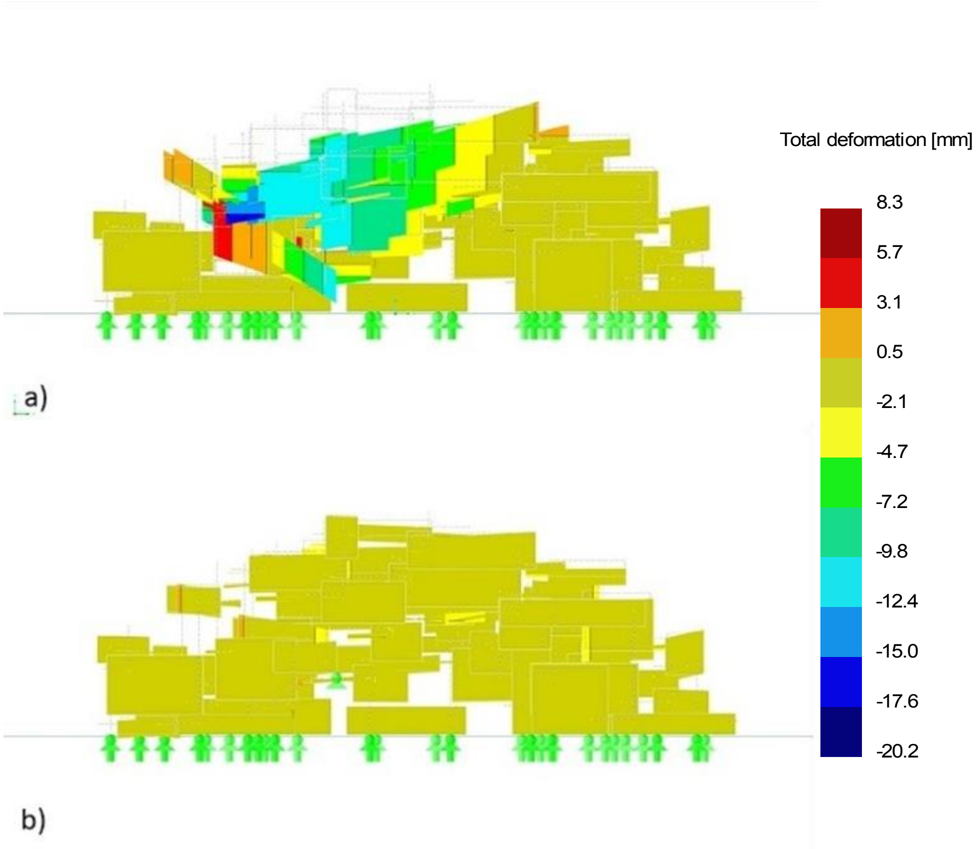

Figure 9. Finite Element Analysis of the structure: a) deformation of the structure in the original form, large deflections can be seen in the centre left of the structure. b) reduced overall deformation after adding additional support

2.4. Fabrication

In order to compare a manual and an automated process, roughly half of the plates were processed using conventional hand tools (Figure 10a). The other half was milled on an industrial robot (KUKA KR 60 HA, Figure 10b) equipped with an HSD E919 spindle. All milling was performed with an 8 mm 2 flute roughing carbide endmill. Plates thinner than 25 mm were milled in a single pass, while thicker plates were milled in two passes. We used a feed rate of 100 mm/s at 24000 RPM. For work holding, we used the Schmalz Innospan vacuum clamping system on a 1200 x 800 mm raster table. The vacuum cups had to be repositioned for almost every board – this process was facilitated by printing 2D plans of every workpiece. The boards were positioned by aligning two edges with a laser cross projected on the raster table.

Robotic path planning was performed directly in Rhino/Grasshopper using the KUKA|PRC plugin. This custom script translated a Brep geometry of the plates to fabrication data. The fabrication relevant attributes are bit size, location of the notches and thickness of the plates, which define the number of milling steps. The generated KRL code was exported and transferred to the robot controller, where the appropriate program for each board was executed.


a) b)

Figure 10. Manual cutting (a) versus robotic milling (b) of the notches.

2.5. Sequencing and assembly

The complex nature of the structure required the development of an algorithm to categorize the plates according to their assembly sequences. The basic logic is as follows - since the notches between the plates are always orthogonal (X, Y or Z), the structure is divided into layers in which all elements are connected horizontally (X and Y). Thus, the connection between consecutive layers has only one vertical direction. This is necessary for simultaneous connecting multiple plates in sliding motion (Figure 11). However, due to the irregular geometry of the components, the order of assembly had to be further adjusted by hand in more complex layouts.

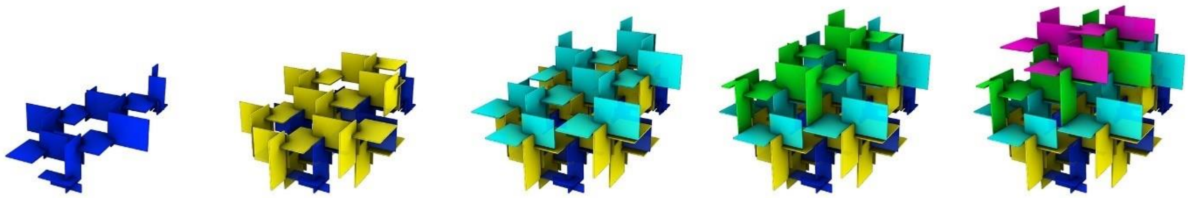

Figure 11. Clustering of a structure into construction layers. To ensure that the design can be assembled, all panels within a layer are joined together horizontally (in X or Y direction). The segments must then be connected vertically

Both constructed demonstrators were manually assembled by students with carpentry backgrounds on-site in a collaborative effort. As far as a digital model with tags and separated construction sequences proved essential to the process, the need to look at the screen to place the individual members in the correct location was suboptimal (Figure 12a). To address that problem, during the workshops, the students tested a Microsoft HoloLens system with software provided by Tecslot. It was concluded, however, that the technology failed in the case of multi-agent collaboration, where immediate communication and feedback are necessary (Figure 12b).

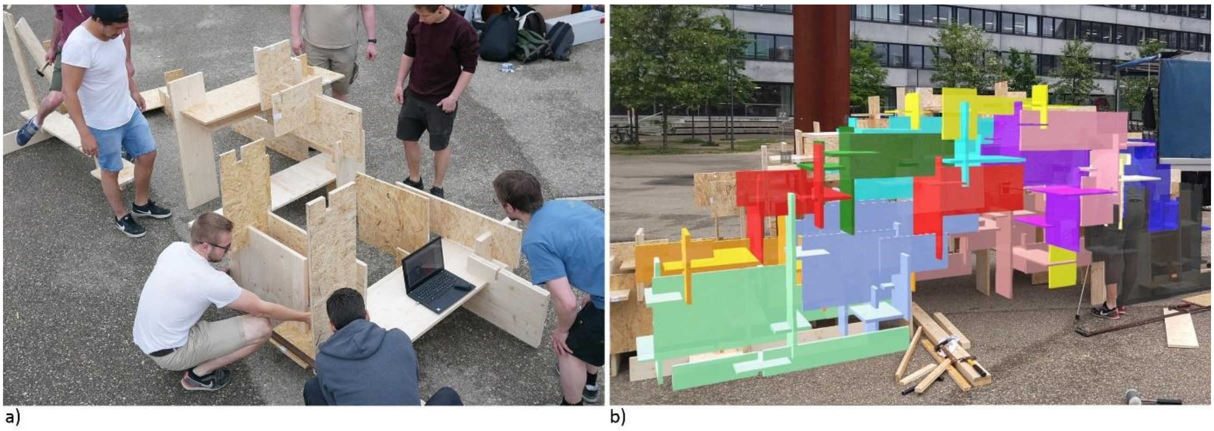

Figure 12. Manual assembly of the structure. a) collaboration between multiple builders, during which the position of the plates was checked on a monitor screen. b) Unsuccessful test of using Microsoft HoloLens during assembly

3. Findings and Discussion

3.1. `Structure from Scraps`: temporary pavilion for the ArchitekturWoche Basel, 2022

The first application of the described methods was a temporary pavilion designed and constructed by 13 bachelor students from Bern University of Applied Science within a 1-week long workshop for the ArchitekturWoche in Basel. The workshop task was to construct the possibly largest structure with a maximum of 150 plates. The final pavilion had a form of a quarter of an ellipsoid of dimensions 5.7mx2.4mx2m, with a spherical void in the centre and consisted of 142 plates (Figure 13).

Figure 13. Temporary pavilion constructed during week-long workshops with bachelor students from BFH for Architektur Woche Basel. (Photos courtesy of ARCHIBATCH)

This design resulted in a very porous space, where most of the components had only 2 points of support. The structure was divided into 13 construction segments, consisting of 5 to 20 elements (Figure 14), which were partially preassembled before the transportation to the final location. On-site the structure was assembled within just 2 hours. The efficiency achieved during the workshop in design, fabrication and assembly exceeded the authors' expectations.

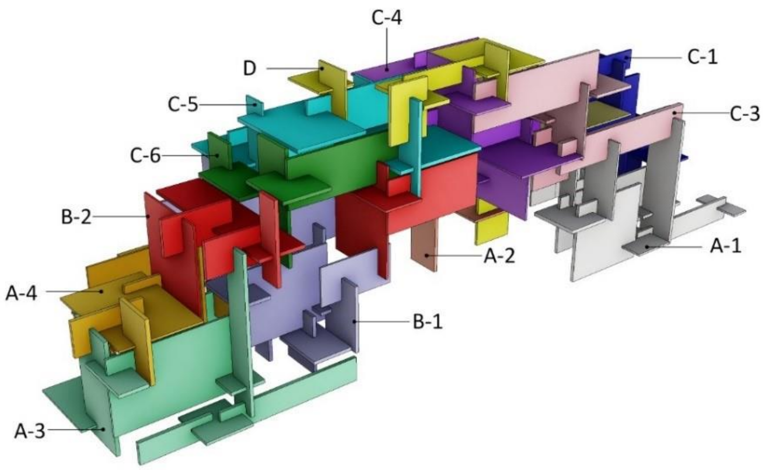

Figure 14. Division into 13 construction segments of pavilion in Basel, each consisting of 5 to 20 individual elements

3.2. Three wood-clay sitting elements for Touch Wood Exhibition, Zurich, 2022

The second demonstrator was three wood-clay sitting elements, produced in June 2022 in collaboration with ERNE AG Holzbau for the TouchWood Exhibition in Museum ZAZ Bellerive in Zurich (Figure 15). This project focused on exploring the potential of hybrid material, where both components stem from a renewable origin, with digital design and fabrication tools. The clay plinths were construction waste from the production of the new office building of ERNE AG Holzbau. They were fabricated robotically at the newly established facility of the company (Figure 16a). Each of these massive blocks measured 2.26mx0.35mx0.85m, weighed around 900kg, and was transported on-site with a crane. Due to the delicate nature of the material and uneven ground, the top surface of the blocks had to be manually levelled after positioning them in the final location (Figure 16b).

Figure 15. Wood-clay sitting elements for the Touch Wood exhibition in museum ZAZ Bellerive in Zurich

a) b)

Figure 16. a) Robotic production of clay blocks at ERNE AG Holzbau; b) manual levelling of the top surface of the clay plinths before the assembly of the wood plates

The 68 pieces of 3-layered boards of uniform depth (27mm) and varied width (0.2m-0.9m) and length (0.3m-1.65m) were arranged around the blocks in such a manner that they protected their top surfaces from rain while the clay plinths provided support for the wooden plates. The design process required increased manual control, so each node was generated separately in just one, maximum of two iterations. Due to the structural requirements, each plate had, on average, four points of support, which resulted in a much denser structure and complicated sequencing. The wooden elements were assembled on-site within seven hours by three workers. Although the plates did not need any foundations, their bottom had to be adjusted to the correct height to compensate for the sloping, uneven terrain during assembly.

3.3. Discussion

The built demonstrators represent a successful validation of the proposed methodology for building from manufacturing waste of irregular size and properties. Both structures were received very positively by the visitors at these events. Its irregular shape encouraged people of all ages to playful spatial explorations (Figure 17). The algorithmic design organized the heterogeneous components in an optimal manner but required significant manual adjustments to guarantee stability and assembly of the structure. While the reuse of waste materials for construction has been explored in literature (e. g. Bolden et al., 2013, Purchase et al., 2022) and shown to be ecologically and economically viable, mostly the reprocessing of bulk materials has been investigated so far. This approach often involves significant processing to produce materials for the use with technologies like large scale 3D printing (Dey et al., 2022, Patti et al., 2022). Our approach is new in that it attempts to make use of the materials' shape with minimal changes.

A comparison of automated and manual notch fabrication favored the robotic approach. Although it took significant time to prepare, it outperformed the manual process in terms of processing speed and, more importantly, precision. The manual assembly of the structures was very efficient, partially due to the workers' high level of carpentry knowledge. The current process requires coordination between installers and validation of each component's position in the 3D model, which leaves room for improvement. The tested AR assembly with Microsoft HoloLens was too slow and inaccurate. Since the students only worked with one device, group collaboration was impossible, which was of great importance in the case of the pavilion. We thus faced some of the issues as outlined by Daling & Schlittmeier (2022), we do, however, expect the technology to advance in the future to become more viable for our purposes.

Figure 17. Usage of the project demonstrators. This type of structure enhances people of all ages to explore them in various playful ways. Left: Temporary pavilion in Basel, right: Wood-Clay sitting element in Zurich

4. Conclusion and Suggestions

The project is the first step in a longer study focusing on data-driven design, manufacturing and assembly strategies for reusing wood waste. The study found that the challenges of working with non-standard building elements create complexity not yet encountered. This requires more integral planning from the early stages of the project and more advanced design and fabrication strategies to deal with the induced complexity. It is interesting to note, however, that while the design approach heavily relies on digital tools, fabrication and assembly can also be performed manually. Therefore, it is concluded that this approach has an exceptionally high potential for use in lower-income areas without access to expensive machinery and new resources.

Future research steps will test assisted assembly strategies that allow for greater collaboration between builders, automated, image-based techniques for measuring the elements and hybrid material systems. Another potential improvement will be advancing the algorithmic design process to create more interactive and structurally informed assemblies without requiring manual adjustments. There are plans to publish the software as open source, opening up the potential of using it in areas where such an approach would enable construction of functional structures. In terms of design, an additional investigation must ensure the structure's safety and durability for long-term public usage.

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The article complies with national and international research and publication ethics. Ethics Committee approval was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

Author's contribution: 1st author: 75%, 2nd author: 25%. There is no conflict of interest.

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