Green Building & Construction Economics
https://ojs.wiserpub.com/index.php/GBCE/

UNIVERSAL WISER
PUBLISHER

Conference Proceeding
Paper presented at Sustainability GEN-4 Post COP 27 Conference 2023, October University for Modern Sciences and Arts (MSA), Egypt

# Carbon Sequestration in Lumber Columns: Facilitating the Reuse of Lumber Waste for Prefabrication through Computational Design and Augmented Fabrication

**Bastian Wibranek**
School of Architecture and Planning, University of Texas at San Antonio, Texas, USA
E-mail: bastian.wibranek@utsa.edu

**Received:** 5 January 2023; **Revised:** 8 February 2023; **Accepted:** 7 March 2023

**Abstract:** Industrial prefabrication brings benefits such as higher productivity and reduced waste production. However, waste, cut-offs, and failures cannot be prevented even in a prefabrication setting. Yet, most processes for utilizing scrap materials promote downgrading. This research presents a construction framework to facilitate the reuse and salvaging of lumber waste from a lumber construction company using a computational design (CD) and augmented reality (AR) setup. Specifically, we explore the design of columns based on an inventory of scrap materials and propose a high level of automation (LoA) prefabrication for reusing lumber waste for structural parts. The design and AR framework support the extension of the matching skillset through the integration of existing materials and the automation of creating an assembly plan for AR, improving the reusability of cut-off lumber blocks. It features a design tool for placing existing lumber scrap blocks and an integrated AR application for assembling these blocks into wood columns. The setup is demonstrated through column prototypes, resulting in six columns, each 10 feet high. The proposed methods extend the opportunities for designers to reuse lumber scraps for prefabrication and simplify assembly instructions for craftspeople, providing valuable tools to enable a resource-efficient workflow for lumber scrap.

***Keywords*:** augmented reality, computational design, reuse, design for reuse, prefabrication, carbon sequestration

## 1. Introduction

The reuse of salvaged lumber blocks, which are wood products that have been salvaged from the waste stream in fabrication, demolished, or decommissioned buildings and structures, has the potential to reduce the environmental impact of the building sector significantly. The reuse of lumber can significantly impact the idea of buildings as a global carbon sink, as it can potentially reduce the demand for new building materials and the associated emissions from their production [1]. The carbon absorbed by the trees during their lifetimes remains stored in the reclaimed lumber within buildings and structures rather than being released back into the atmosphere through combustion or derogation as landfill, as well as the process of creating and transporting new lumber into cities [2].

For instance, the production of one ton of Douglas fir lumber is associated with significant carbon dioxide ($CO_2$) emissions due to the energy and resources required to grow, harvest, and process the trees. The exact amount of $CO_2$ emissions will depend on various factors, including the location and management of the forest, the efficiency


DOI: https://doi.org/10.37256/gbce.4120232309

of the milling and processing operations, and the transportation and distribution of the finished product. In general, however, producing one ton of Douglas fir lumber is estimated to release around 1.5 to 2.0 metric tons of $CO_2$ into the atmosphere. On the other hand, it is worth noting that Douglas fir and other trees absorb and store $CO_2$ as they grow, which helps to offset some of the emissions associated with their production. It is estimated that a mature Douglas fir tree can sequester around 50 pounds of $CO_2$ per year and that a single tree can sequester a total of approximately 1 ton of $CO_2$ over its lifetime. Douglas fir dry wood density averages 0.45 tons per $m^3$, equating to 0.78 tons of $CO_2$ per $m^3$ [3]. These estimates are based on several factors, including the size and age of the tree, the location and climate in which it is growing, and the overall health and productivity of the forest ecosystem [4-6].

The reuse of lumber in construction has a long history, dating back to ancient times [7-9]. However, the amount of lumber waste the industry generates has become a growing concern, with significant environmental and economic implications [10]. Lumber waste has been a concern in the construction industry for many decades. It was estimated that up to 40% of the wood used in construction was wasted due to inefficient cutting and processing methods [11]. In response to this problem, the industry has developed various strategies for reducing waste, such as improved cutting techniques and better utilization of wood byproducts [12].

In recent years, one of the most significant developments has been the growing emphasis on reusing and repurposing lumber waste in new construction projects. The approach involves salvaging wood from demolished buildings and other sources and using it to create new products and structures [13]. The reuse of wood has become increasingly popular in recent years due to its environmental and economic benefits, which include reducing the demand for new lumber, reducing waste and landfill use, and lowering the cost of construction materials [14].

Additionally, there is a need to develop more efficient and effective methods for processing and utilizing reclaimed wood in new construction projects. The growing emphasis on wood reclamation and other sustainable practices offers promise for reducing waste and promoting a more environmentally and economically sustainable construction industry. However, repurposing salvaged lumber blocks today requires significant manual labor and expertise, which can be time-consuming and costly.

Two approaches for overcoming these challenges and increasing the likelihood of reusing lumber waste products are computational design (CD) and augmented reality (AR) fabrication due to their adaptability and possible automation. Projects in academia have focused on various issues, including the capabilities and limitations of AR and CD for repurposing salvaged building materials, the potential for integrating these technologies with traditional building practices, and the impact of these technologies on the sustainability and efficiency of the building sector.

CD is a methodology that employs computer-aided tools and algorithms to optimize the design and construction of buildings and other structures [15]. In the context of lumber reuse, CD can be used to develop custom solutions for repurposing lumber in construction projects [16]. Designers can create sophisticated designs incorporating reclaimed lumber by leveraging digital tools such as three-dimensional (3D) modeling software, parametric design platforms, and structural analysis programs.

AR in construction involves using digital information and virtual objects overlaid onto the physical environment through a device such as a smartphone or an AR headset. AR technology allows construction professionals to view 3D models of building designs in real-world settings, providing a more immersive and interactive experience than traditional two-dimensional (2D) drawings. The potential of AR in the construction sector has been highlighted in recent projects [17, 18]. In 2019, Hughes et al. [19] conducted an experiment using the HoloLens, an AR headset, to guide users through the assembly. In this regard, recent research developments have investigated AR applications with a user interface for synchronizing the construction progress via user-specific content visualization for topologically interlocking lumber modules [20] and assembling unstructured rocks based on a superimposed holographic model [21]. In addition, a growing number of research efforts have recently highlighted the possibilities of using AR to enhance production processes in construction. For instance, AR has been used to fabricate bespoke wood elements via steam bending via holographic 3D models superimposed over the actual materials [22] or to provide instructions for arranging bricks with highly accurate pose estimation to form 3D curved walls [23]. Other areas of research have focused on the economic, social, and environmental implications of using AR and CD to facilitate the reuse of salvaged building materials [24] and on how these technologies can support the development of more sustainable and efficient building practices [25]. The relevance of the initial material stock for the designer as a starting point has been discussed as a critical input factor [26]. Moreover, the utility of a mobile application for data acquisition via an AR-guided measurement tool of a building needs to be deconstructed based on a future design [27]. Recently, the project HoloWall explored the benefits of reclaimed lumber construction using a mixed-reality setup [28].

Overall, the existing research suggests that CD and AR have the potential to improve the process of repurposing salvaged building materials significantly and contribute to the development of more sustainable and efficient building practices. However, more research is needed to fully understand these technologies' capabilities and limitations and identify the most effective and efficient approaches for leveraging them in the reuse of salvaged lumber blocks.

Therefore, this research explores the potential of emerging technologies such as digital data acquisition, CD, and AR for fabrication to facilitate the reuse of salvaged lumber blocks. The goal was to develop an understanding of the fabrication of lumber columns as $CO_2$ storage. Prefabrication of columns based on reclaimed lumber blocks involves taking salvaged lumber and fabricating it into usable building components, such as lumber posts (Figure 1). This process typically involves cutting the lumber into the desired shape and size, then sanding and finishing the surface by examining the capabilities and limitations of computational technologies and design approaches and the potential for their integration with digital building practices. Overall, this research seeks to identify the most promising and effective approaches for leveraging these technologies to repurpose salvaged lumber blocks to maximize environmental impact.

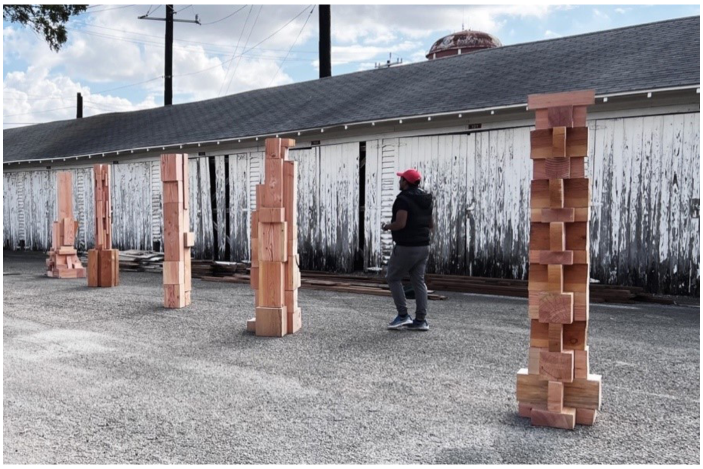

**Figure 1.** Columns made from reclaimed lumber

## 2. Methods and materials

The methods applied in this study focused on identifying tools and approaches for automation for using reclaimed lumber waste. The research follows the case study approach set out to illuminate qualities and possible protocols. Therefore, various approaches were tested for their feasibility within the three main processes of fabrication with reclaimed materials: data acquisition of the materials, CD development, and augmented fabrication.

### 2.1 *Data acquisition for reclaimed lumber*

Acquiring data on reclaimed lumber blocks for designs based on availability and reuse can involve several different steps, depending on the specific goals and needs of the project. To acquire reclaimed lumber blocks for novel design, it is first necessary to identify the sources of the material. This might include identifying suppliers of reclaimed lumber, such as salvage yards, wood reclaimers, or deconstruction contractors. This study's material came from a lumber construction company focusing on medium- to large-scale post and beam constructions. The company provided cut-off pieces of solid lumber from dimensional posts and beams. The reclaimed pieces were mainly green wood from Douglas fir species and some cider, pine, and oak. The dimensions of the blocks ranged from smaller triangles with edge lengths of around 20 cm to larger blocks of approximately 40 × 40 × 100 cm. The blocks were picked up regularly at the end of the week using a pickup truck and stored at a wood shop (Figure 2).

(a) (b) (c)

**Figure 2.** The acquisition process of the lumber blocks: (a) picking up from the cutting station, (b) loading onto a pickup truck, and (c) storage

Before incorporating reclaimed lumber into a design project, it is crucial to assess the availability and quality of the material. This evaluation process may involve reviewing inventory lists and conducting physical inspections of the lumber to determine its suitability for the intended purpose. Assessing the availability and quality of reclaimed lumber is essential in ensuring the material is suitable for the project.

Gathering data on the material's properties and characteristics is essential to incorporate reclaimed lumber blocks into a novel design. The data collected may include measurements of strength, stiffness, density, moisture content, and any other relevant properties. This information is crucial in determining the material's performance and how it may be integrated into the design. In addition, accurate data collection is vital in ensuring that the reclaimed lumber is appropriately utilized, reducing waste, and minimizing the need for additional materials.

The measurement of block dimensions and their translation into 3D blocks in a computer-aided design (CAD) environment is a necessary process for the reuse of lumber blocks in design tasks. Initially, the block dimensions are recorded in a spreadsheet, which is then used to generate an accurate 3D model of each block in CAD software, such as Rhino 3D and Grasshopper. This process allows the lumber blocks to be accurately represented in a digital environment, improving reuse efficiency and design capabilities. Two approaches for capturing dimensions were tested to ensure accurate measurements and effective use of the reclaimed lumber in the design process.

The salvaged blocks were measured and stored in an online digital repository, testing two approaches. The first method was simple manual measurements by one person and translating them into an online Google sheet with XYZ dimensions and a sequential number system (e.g., A-001) by a second person. The second method was based on Light Detection and Ranging (LiDAR) 3D scanning with the iOS application Polycam, providing 3D meshes of the blocks (Figure 3). Finally, the generated meshes of multiple blocks were algorithmically converted into 3D blocks and imported into the design environment Rhino 3D to give an estimate of the available materials (Figure 4).

**Figure 3.** A 3D scan of a set of salvaged blocks with a detail of the mesh resolution

**Figure 4.** The 176 reclaimed lumber blocks are organized by height

Once the reclaimed lumber blocks have been identified and the necessary data has been collected, the next step is to source the material and incorporate it into the design.

## 2.2 *CD development*

The design development was started in parallel with the collection of lumber blocks and their digitalization. This process required some flexibility during the design as the final dimensions of the blocks were unknown. Six different designs were developed for diversification purposes, exploring the design potential of the acquired blocks. The designs were supposed to explore various fabrication techniques, such as interlocking or gluing for connecting the blocks. They were designed on a spectrum from no processing of the blocks to complex cuts for interlocking purposes.

The design task started with analyzing the data of the already analyzed lumber blocks. Based on these blocks, preliminary designs were developed (Figures 5-7). Therefore, the blocks were modeled in Rhino 3D and assembled into a column that measures 40 cm in cross-section and is 300 cm in height. The specific modeling procedures were captured in diagrams to be translated into a design algorithm. The purpose of this algorithm is to automate the aggregation of blocks into a column based on any input lumber blocks. As a programming environment, the Grasshopper Plugin for Rhino 3D was chosen, as it is a visual programming language well suited for prototyping such algorithms.

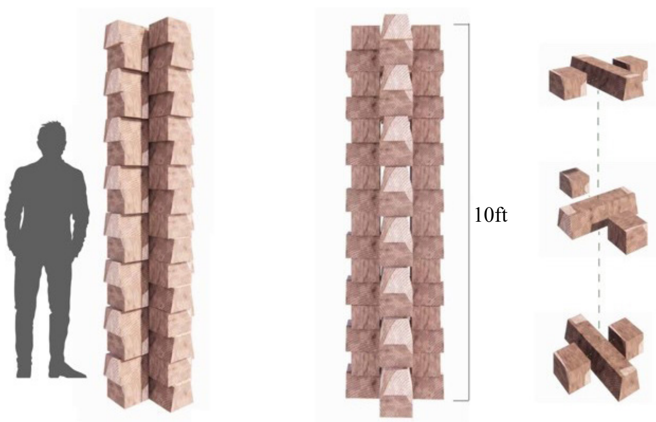


**Figure 5.** Design drawing and assembly sequence of cut lumber blocks

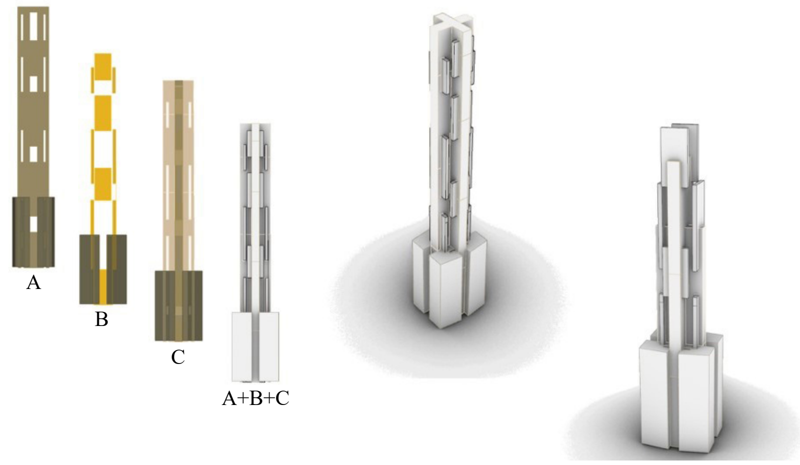


**Figure 6.** Interlocking parts laid out flat, their assembly logic, and the complete

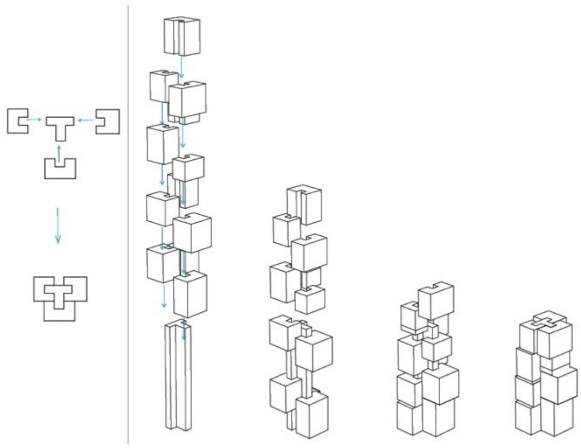

**Figure 7.** Assembly logic of blocks along a T-shaped centerpiece

First, a tool was implemented to automatically translate the block dimensions from an online Google sheet into 3D geometry. The resulting boxes were organized based on their volume and dimensions. Then, based on these generated boxes, aggregation algorithms were implemented to create different arrangements.

## 2.3 *AR tool for fabrication*

The fabrication of the column designs was conducted in a wood shop at the School of Architecture and Planning at the University of Texas at San Antonio. The tools used included a bandsaw, and a table saw (Figure 8). As a glue, polyvinyl acetate (PVA) was used, a liquid chemical compound derived from petroleum, resulting in a clear, viscous liquid that can be easily applied to surfaces and cured to form a robust and flexible bond.

**Figure 8.** Process of cutting dowel into lumber block using a table saw

To overcome the matching of non-standard blocks with the assembly task, an AR tool for mobile devices and the Microsoft HoloLens were programmed using Fologram and Grasshopper. The application was used by different participants using up to three smartphones connected to a private wireless fidelity (Wi-Fi) network to enable data transfer to and from the design environment. The implemented AR tool can display all possible assembly stages with a color gradient indicating the stage (Figure 9). It projects a holographic full-scale 3D model based on a manually set position or using a quick response (QR) marker. The user can change the range of the displayed blocks via two sliders, one for the lower and one for the upper bound of the blocks (Figure 10).

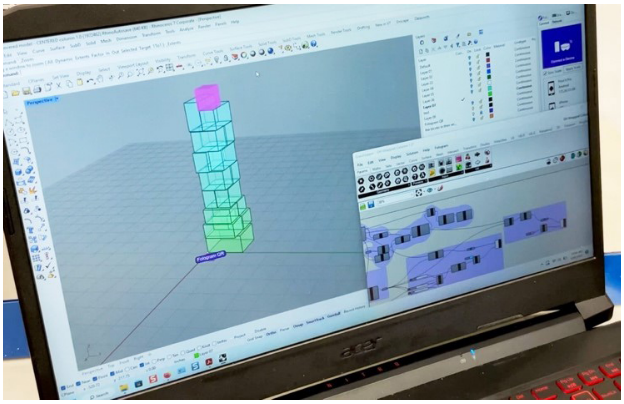

**Figure 9.** The Rhino-Grasshopper interface for the color-coded assembly elements is added to their sequential

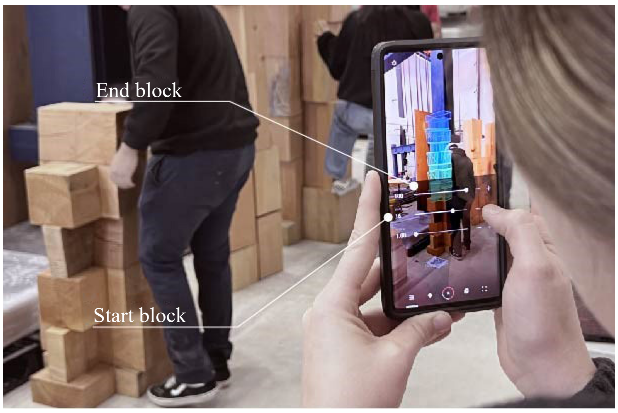


**Figure 10.** AR application with sliders for monitoring the assembly steps

## 3. Results

The columns in this study were designed and fabricated using various methods and materials. Column 1 was constructed using only interlocking parts and was completely dry-stacked, resulting in the need for a significant amount of cutting. Column 2, on the other hand, was a hybrid construction method that involved both gluing and dry stacking. Each layer of Column 2 was made using only two cuts. In contrast, Columns 3 and 4 were glued using a dove-tail insert made from new wood, which required cutting on one side of each block. Column 3 consisted of two aligned blocks in cross-section, while Column 4 used three blocks. Column 5 was constructed using complete gluing, except for the large top block, which was left unglued and held in place by the adjacent blocks. Finally, Column 6 was made using dry-stacked blocks that were neither cut nor treated and were held together only by shrink wrap. Figure 11 shows the spectrum of the used connection techniques on a scale based on labor input.

(1) (2) (3) (4) (5) (6)

**Figure 11.** The six different column prototypes organized the amount of cutting from extensive on the left to no cutting on the right (numbered from one to six)

### 3.1 *Material stock data*

The simple measuring and transcribing into a Google sheet were the most feasible of the tested methods to acquire and store the relevant information of the salvaged blocks. The LiDAR 3D scan for the blocks shown in Figure 3 was captured in 2 minutes and transferred into the design environment in 3 minutes. It is worth noting that the arrangement of the blocks is a time-consuming process, if necessary. The 3D scan contained 87 lumber blocks as a 3D mesh. The blocks required manual remodeling to generate proper 3D surfaces for modeling with them due to tolerances and inaccuracies within the mesh geometry.

Nevertheless, this method was feasible to give designers a useful overview and rough estimate of the range of available lumber blocks. In addition, the manual method of providing measurements in a Google sheet was enhanced by the automated translation of the numbers into 3D geometry. Compared to the first method, this takes around half a minute per lumber block, so around 90 minutes for all 176 blocks.

### 3.2 *Design automation*

The designs were successfully translated into design algorithms that automatically distribute and assemble the available blocks from the available stock. The design algorithm increased the speed of block arrangement drastically. For example, while the distribution of blocks along the 10 feet took between 5 and 20 minutes in a manual setup, the algorithm can provide feasible solutions within milliseconds. However, these algorithmic designs still needed a check by a human to validate the proposed result. Figures 12 and 13 show automated designs with a limited stock of lumber blocks.

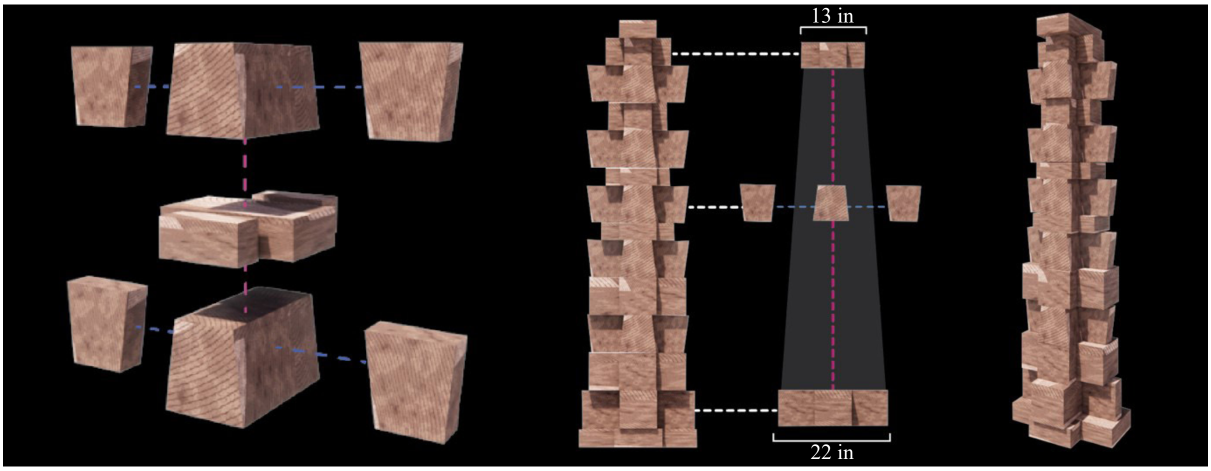


**Figure 12.** Explanation of the cutting steps and positioning based on block sizes

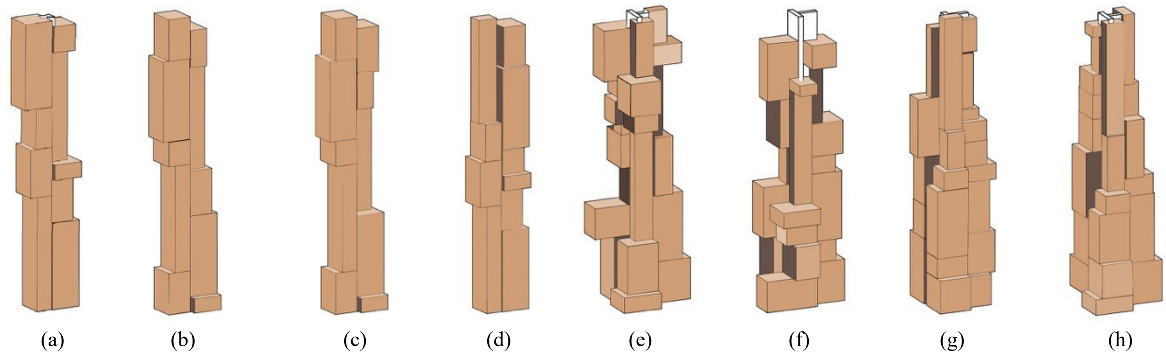


**Figure 13.** Design iterations for two different approaches: (a, b, c, and d) columns with two aligned strips of blocks, and (e, f, g, and h) four columns with three aligned strips of blocks

## 3.3 *Augmented fabrication*

The columns were assembled and disassembled in three locations: the wood shop, an outdoor site, and a large-scale testing facility. The mobile application was a supportive tool in augmenting the assembly task with real-scale instructions. The AR-guided fabrication systems provided immediate visual validation and feedback, especially when identifying the next assembly block based on visual cues like geometry and size (Figure 14). While the mobile app-enabled assistance or supervision by a coworker, the same approach can be utilized on an AR headset (Figure 15).

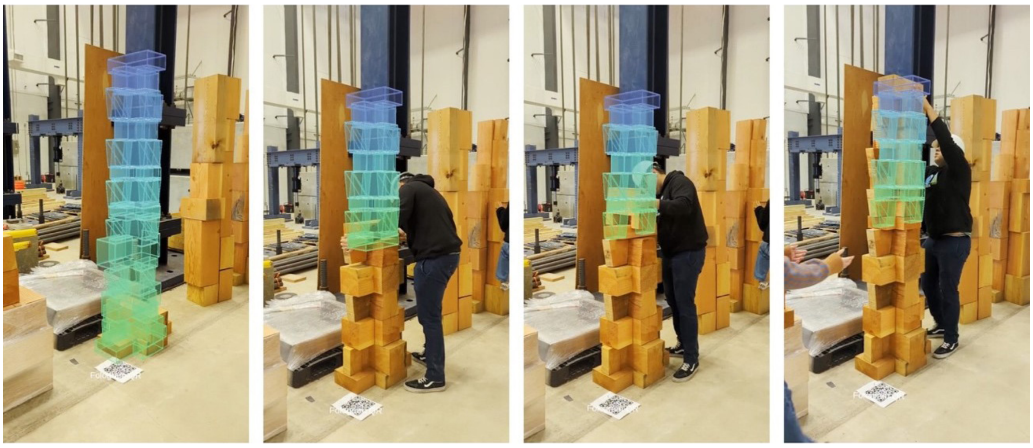

**Figure 14.** The sequential assembly of one column with AR support

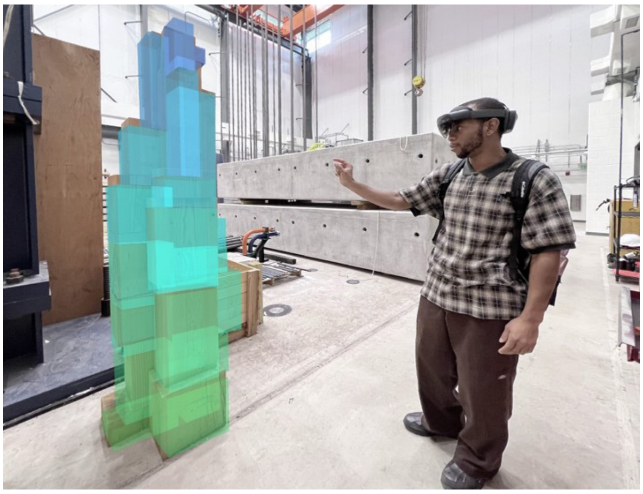

**Figure 15.** Illustration of the superimposed geometry visible through the HoloLens

During the nine-week project, 176 wooden blocks were recovered and repurposed, with 113 used to create six lumber columns. Based on the volume and density of the reclaimed wood, it is estimated that a total of 1,493 cubic meters of wood were saved, equivalent to approximately 1,165 tons of $CO_2$. The data provided in Table 1 shows the details of each column, including the amount of reclaimed lumber used, the stored $CO_2$, the number of cuts made, and the time required for cutting, preparation, assembly, and disassembly. The type of adhesive used for each column is also noted. It was observed that the number of cuts and the cutting time are correlated, and a reduction in cuts results in shorter fabrication times. For instance, Column 1 required 252 cuts and 420 minutes of cutting time while only storing 0.165 $m^3$. In contrast, Columns 2, 3, and 4 required the cutting and gluing of all parts but could be assembled in under 20 minutes, with total fabrication and assembly times ranging from 122 to 165 minutes. The highest amount of $CO_2$ was stored in Columns 5 and 6, which utilized uncut lumber blocks, resulting in longer preparation times. For Column 5, most of the preparation time was spent on gluing and clamping the blocks, while for Column 6, wrapping the parts as a subassembly and during the final assembly required the most time.

**Table 1.** Column comparison

| Column number | 1 | 2 | 3 | 4 | 5 | 6 | Total |
|---|---|---|---|---|---|---|---|
| Wood volume (cubic meters) | 0.165 | 0.206 | 0.203 | 0.290 | 0.294 | 0.335 | 1.493 |
| Stored $CO_2$ (tons) | 0.129 | 0.161 | 0.158 | 0.226 | 0.229 | 0.261 | 1.165 |
| Used lumber blocks | 22 | 12 | 10 | 21 | 26 | 22 | 113 |
| Number of cuts | 252 | 24 | 10 | 21 | 0 | 0 | 307 |
| Cutting time (minutes) | 420 | 75 | 65 | 85 | 0 | 0 | 645 |
| Preparation time (minutes) | 65 | 80 | 45 | 30 | 110 | 80 | 375 |
| Assembly time (minutes) | 10 | 10 | 12 | 18 | 5 | 20 | 85 |
| Total time (minutes) | 495 | 165 | 122 | 133 | 115 | 100 | 1,130 |
| Adhesives | - | Wood glue | Wood glue | Wood glue | Wood glue | Stretch wrap | - |

## 4. Discussion

By providing tools and knowledge for working with non-standard lumber parts, this research provides approaches to include waste products from prefab factories that could also be translated into reusing building materials from deconstructions. The data acquisition methods need to be understood in two separate stages: one of quickly assessing available materials via a LiDAR 3D scan, and the second as a precise and valid measurement.

The six columns enabled the prototypical validation of the CD and fabrication approaches. The spectrum of design iterations highlights the variability of approaches and the shift in thinking toward building components as carbon sinks. For example, while the first attempt focused on elaborate connection details for dry joined interlocking of the blocks, it had the issue of introducing many cuts and creating much waste. The later prototypes focus on attempts to minimize and avoid all cuts. The choice of testing the approach of the building as a carbon sink with columns might sound counterintuitive, as a column makes such a tiny portion of an architectural structure; however, we were able to show that by reducing cutting, we can almost double the $CO_2$ storage in a single column.

The proposed designs challenge the dominant notion in the CD of material efficiency and instead emphasize the storage of $CO_2$ within building elements. These saved $CO_2$ emissions are approximately equivalent to emissions from heating a home for a year with natural gas, burning approximately 220 gallons of gasoline, or manufacturing approximately 700 pounds of cement [29].

The AR application and its custom-developed functionalities, such as scrolling through the assembly stages, provide an immersive and interactive experience during the fabrication. Most of the current research on AR tools focuses on the efficiency of construction techniques; however, the direct interaction with physical blocks overlayed with a full-scale holographic model seemed to increase the understanding of the assembly task while removing a mental translation task from a conventional abstract plan into an assembly instruction. This supports earlier findings that reported a motivating interaction and immersion through an AR setup for constructing a pavilion [20]. Moreover, the AR tool can benefit the arrangement of non-standard elements, such as the lumber blocks, specifically due to the superimposition, validating instructions, and correct positioning at the same time via visual feedback.

Future comparison between six lumber columns made from reclaimed materials could involve evaluating the physical and mechanical properties of each of the columns, as well as their aesthetic characteristics. This could include testing each column’s strength, stiffness, and durability, as well as any other relevant performance criteria such as fire resistance, moisture resistance, and reusability. In addition to these quantitative measures, it would also be essential to consider the aesthetic qualities of each column, such as its appearance, texture, and proportions. It would also be helpful to consider the environmental impacts of each processing method, including the energy and resources required to produce the columns, as well as any waste or emissions generated during the material acquisition and production. Finally, through the evaluation of the performance and sustainability of each column, it would be possible to identify the trade-offs involved in using reclaimed materials and determine the most effective and efficient approaches for repurposing these materials in construction.

## 5. Conclusions

In conclusion, this research sheds light on the impact of design choices on waste reduction and carbon storage in the built environment. By utilizing computational tools, the study identifies strategies for repurposing unstructured lumber waste into meaningful lumber columns. Furthermore, the research presents data collection approaches that can be implemented at various factories, with the potential for automation. The paper also discusses attempts to automate design and assembly planning, including digital fabrication strategies incorporating AR through a mobile phone or AR headset.

As crucial stakeholders in sustainable project development, designers can leverage their strategic position to create awareness and aesthetic solutions that contribute to the effort of waste prevention and $CO_2$ emissions reduction in the built environment. The proposed shift towards designing for carbon sequestration in our built environment presents opportunities for designers and fabricators to embrace these concepts, benefiting both the environment and their practice. Overall, this research contributes to the ongoing conversation about sustainable design practices and their potential impact on mitigating climate change.

## Acknowledgments

The author would like to express sincere appreciation to the students from the Digital Design and Fabrication class, ARC 4123, during the fall semester of 2023 at the School of Architecture and Planning at UTSA. Their invaluable contributions to this research project through their enthusiastic participation in data collection and their insightful feedback on the methodology greatly enhanced the quality of this work. Thanks to the students Gerardo A. Aguilar, Evan Al Saadi, Victor Alvarado, Andrea E. Bernal Jara, Joshua I. Forney, Elsa K. Leiva, Nixon I. Maldonado Hernandez, Elizabet Medellin, Ayah B. Milbes, Claudia C. Ortiz, Yaire O. Padilla, Fabian R. Perea, Ana I. Sanchez, Jameel Shaheer, Kyndal M. Thompson, Mauro A. Zuniga, and teaching assistant Kameron Hover for their efforts in this research project. Thanks to Patrick Page-Sutter for his support and guidance during the project when working with lumber.

The author is also grateful to the Timberlyne Group for their generous donation of lumber blocks and their ongoing support throughout the development of this project. The invaluable feedback and advice on material and design-related issues provided by Alex Arrunada and Eric J. Arnold played a crucial role in achieving our research goals.

Furthermore, this research work was sponsored by the City of San Antonio Office of Historic Preservation and funded by the City of San Antonio Office of Innovation. The author is thankful for their generous support in bringing this project to fruition.

## Conflict of interest

There is no conflict of interest in this study.

## References

[1] Churkina G, Organschi A, Reyer CPO, Ruff A, Vinke K, Liu Z, et al. Buildings as a global carbon sink. *Nature Sustainability*. 2020; 3: 269-276. https://doi.org/10.1038/s41893-019-0462-4

[2] Dodoo A, Gustavsson L, Sathre R. Recycling of lumber. In: Worrell E, Reuter MA. (eds.) *Handbook of Recycling: State-of-the-Art for Practitioners, Analysts, and Scientists.* Waltham, United States: Elsevier; 2014. p.151-163. https://doi.org/10.1016/B978-0-12-396459-5.00011-8

[3] Bastien J-C. Douglas-fir biomass production and carbon sequestration. In: Spiecker H, Lindner M, Schuler J. (eds.) *Douglas-fir – An Option for Europe*. What Science Can Tell Us, vol 9. Joensuu, Finland: European Forest Institute; 2019. p.84-88. https://hal.inrae.fr/hal-02791000

[4] Koddenberg T. Handbook of wood chemistry and wood composites. *Journal of Cleaner Production*. 2016; 110: 193. https://doi.org/10.1016/j.jclepro.2015.07.070

[5] Pettersen RC. The chemical composition of wood. In: Rowell R. (ed.) *The Chemistry of Solid Wood*. Advances

in Chemistry, vol 207. Washington, United States: American Chemical Society; 1984. p.57-126 https://doi.org/10.1021/ba-1984-0207.ch002
[6] Ramage MH, Burridge H, Busse-Wicher M, Fereday G, Reynolds T, Shah DU, et al. The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews*. 2017; 68(1): 333-359. https://doi.org/10.1016/j.rser.2016.09.107
[7] Creasman PP. Ship timber and the reuse of wood in ancient Egypt. *Journal of Egyptian History.* 2014; 6(2): 152-176. https://doi.org/10.1163/18741665-12340007
[8] Woodard AC, Milner HR. Sustainability of timber and wood in construction. In: Khatib JM. (ed.) *Sustainability of Construction Materials*. 2nd ed. Woodhead Publishing Series in Civil and Structural Engineering, vol 70. Duxford, United Kingdom: Woodhead Publishing; 2016. p.129-157. https://doi.org/10.1016/B978-0-08-100370-1.00007-X
[9] Sands R. Life beyond life: Repair, reuse, and recycle—the many lives of wooden objects and the mutability of trees. *Archaeometry*. 2022; 64(S1): 168-186. https://doi.org/10.1111/arcm.12708
[10] Jahan I, Zhang G, Bhuiyan M, Navaratnam S. Circular economy of construction and demolition wood waste–A theoretical framework approach. *Sustainability.* 2022; 14(7): 10478. https://doi.org/10.3390/su141710478
[11] United States Environmental Protection Agency. *Advancing Sustainable Materials Management: Facts and Figures Report*. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management [Accessed 1st March 2023].
[12] Sathre R, Gustavsson L. Energy and carbon balances of wood cascade chains. *Resources, Conservation and Recycling.* 2006; 47(4): 332-355. https://doi.org/10.1016/j.resconrec.2005.12.008
[13] Ormondroyd GA, Spear MJ, Skinner C. The opportunities and challenges for re-use and recycling of timber and wood products within the construction sector. In: Kutnar A, Muthu SS. (eds.) *Environmental Impacts of Traditional and Innovative Forest-based Bioproducts*. Environmental Footprints and Eco-Design of Products and Processes. Singapore: Springer; 2016. p.45-103. https://doi.org/10.1007/978-981-10-0655-5_3
[14] Pitti AR, Espinoza O, Smith R. The case for urban and reclaimed wood in the circular economy. *BioResources*. 2020; 15(3): 5226-5245. https://doi.org/10.15376/biores.15.3.5226-5245
[15] Knippers J, Kropp C, Menges A, Sawodny O, Weiskopf D. Integrative computational design and construction: Rethinking architecture digitally. *Civil Engineering Design*. 2021; 3(4): 123-135. https://doi.org/10.1002/cend.202100027
[16] Satterfield B, Swackhamer M. Material custodies: Embracing loss, failure, and death as opportunities in wood construction. *Journal of Architectural Education*. 2021; 75(1): 121-128. https://doi.org/10.1080/10464883.2021.1859896
[17] Song Y, Koeck R, Luo S. Review and analysis of augmented reality (AR) literature for digital fabrication in architecture. *Automation in Construction*. 2021; 128: 103762. https://doi.org/10.1016/j.autcon.2021.103762
[18] Fologram. *Holographic Handcraft: ACADIA 2018 Workshop*. [Video] 2018. https://vimeo.com/302387497?embedded=true&source=vimeo_logo&owner=67686853 [Accessed 1st March 2023].
[19] Hughes R, Osterlund T, Larsen NM. Integrated design-for-manufacturing and AR-aided-assembly workflows for lightweight reciprocal frame timber structures. *Construction Robotics*. 2021; 5: 147-157. https://doi.org/10.1007/s41693-020-00048-3
[20] Atanasova L, Saral B, Krakovská E, Schmuck J, Dietrich S, Furrer F, et al. Collective AR-assisted assembly of interlocking structures. In: Gengnagel C, Baverel O, Betti G, Popescu M, Thomsen MR, Wurm J. (eds.) *Design Modelling Symposium Berlin 2022: Towards Radical Regeneration*. Cham, Switzerland: Springer; 2023. p.175-187. https://doi.org/10.1007/978-3-031-13249-0_15
[21] Wibranek B, Tessmann O. Compression-only structures with irregular rock and 3D printed connectors. In: *International Association for Shell and Spatial Structures (IASS) Annual Symposium 2019 – Structural Membranes 2019: Form and Force*. Barcelona, Spain: IASS; 2019. http://congress.cimne.com/Formandforce2019/admin/files/fileabstract/a666.pdf
[22] Jahn G, Wit AJ, Pazzi J. [BENT] Holographic handcraft in large-scale steam-bent timber structures. In: Bieg K, Briscoe D, Odom C. (eds.) *Paper Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) 2019: Ubiquity and Autonomy.* Austin, Texas, United States: The University of Texas at Austin School of Architecture; 2019. p.438-447. https://doi.org/10.52842/conf.acadia.2019.438
[23] Mitterberger D, Dörfler K, Sandy T, Salveridou F, Hutter M, Gramazio F, et al. Augmented bricklaying. *Construction Robotics*. 2020; 4: 151-161. https://doi.org/10.1007/s41693-020-00035-8
[24] Fivet C, Brütting J. Nothing is lost, nothing is created, is reused: structural design for a circular economy. *The Structural Engineer*. 2020; 98(1): 74-81. https://doi.org/10.56330/LXAH1188

[25] De Wolf C, Hoxha E, Fivet C. Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society*. 2020; 61: 102322. https://doi.org/10.1016/j.scs.2020.102322
[26] Brütting J, Senatore G, Fivet C. Form follows availability - Designing structures through reuse. *Journal of the International Association for Shell and Spatial Structures.* 2019; 60(4): 257-265(9). https://doi.org/10.20898/j.iass.2019.202.033
[27] Wibranek B, Tessmann O. Augmented reuse. In: Gengnagel C, Baverel O, Betti G, Popescu M, Thomsen MR, Wurm J. (eds.) *Design Modelling Symposium Berlin 2022: Towards Radical Regeneration.* Cham, Switzerland: Springer; 2023. p.411-423. https://doi.org/10.1007/978-3-031-13249-0_33
[28] Dean J. *Arts Quad installation upcycles wood with mixed reality*. https://news.cornell.edu/stories/2021/12/arts-quad-installation-upcycles-wood-mixed-reality [Accessed 1st March 2023].
[29] United States Environmental Protection Agency. *Greenhouse Gas Equivalencies Calculator.* https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results [Accessed 15th February 2023].