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DIGITAL ARTISAN: AUGMENTED REALITY AIDED UPCYCLING FOR RECLAIMED TIMBER BOARDS

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ABSTRACT: This research employs augmented reality (AR) to assist artisans in upcycling reclaimed timber boards into free-form structures. It proposes a tailored AR-aided workflow that prioritizes human judgment and creativity in construction processes by evaluating different scenarios. This cyclical workflow iterates through surveying, nesting, cutting, and assembling, which bypasses the need for extensive inventory management and labeling processes by surveying a limited part of the material stock in each iteration. With the assistance of AR, artisans can make intuitive decisions on material nesting and get precise instructions for cutting and assembling. The AR application involves visualization, model processing, user interface design, and algorithm development, fostering an environment that values human input alongside technological advancements. It visualizes nesting boundaries and material efficiency, documents nesting patterns, updates cutting lines, and designates assembly locations, thus ensuring a seamless integration of digital feedback into the physical construction process. Overall, the proposed workflow facilitates the integration of digital and physical processes, revealing the potential of AR technology in advancing circular construction practices.

KEYWORDS: augmented reality, timber upcycle, digital fabrication, circularity, computational design

1 – INTRODUCTION

Reclaimed timber boards are often sourced from cutoffs in the timber industry and demolition sites. Upcycling or reusing them offers a sustainable approach to resource management, but it has inherent challenges that complicate its practical implementation [1]. A primary issue is the nonuniformity and uncertain quantity of these remnants. Unlike standardized materials, reclaimed materials often vary in dimensions and quality, which makes integrating them into new projects challenging without screening, precise measurements, and extra processing [2]. Each piece may need a unique cutting or joining strategy that fits its shape, making it less economically viable than cutting desired shapes from new materials. This irregularity also poses design constraints that require a matching process to effectively utilize the material, potentially restricting the design flexibility and target form [3].

Integrating digital technologies for upcycling reclaimed timber boards can improve efficiency and feasibility [5]. Computational design tools provide a risk-free experiment to explore a spectrum of design solutions [6] and list their trade-offs among different optimization objectives [7]. However, these tools typically require detailed material information, complex inventory management, and customized materialization, optimizing material usage but potentially compromising fabrication efficiency [8]. The classification and storage of these reclaimed materials present logistical difficulties, as scanning, labeling, storing, and retrieving them can be challenging [4]. Artisans may experience a steep learning curve when scanning reclaimed objects or implementing intricate digital representations into physical objects [9]. Preparing data and interpreting outputs can be labor-intensive and time-consuming, especially when human intuition and creativity are undervalued.

Augmented Reality (AR) can be a solution to bridge the gap between digital designs and physical reclaimed parts [10]. This technology allows designers and artisans to overlay digital models onto actual materials, offering an immediate understanding of how a design could interact with the available resources [11] and enabling direct communication between the digital and physical worlds [12, 13]. However, the current AR-aided fabrication workflow usually relies on ready-to-fabricate design solutions or prefabricated and labeled materials (Figure 1a), requiring much preparation time [14]. Most research on material upcycling neglects human intuitions, using AR tools only as a strict 3D guidebook [15]. Thus, this research aims to amplify the intuitive decision-making of artisans by providing real-time visual feedback in an AR environment, allowing them to adjust their creations on

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upcycling offcuts more tangibly. By offering a tailored AR-aided design to fabrication workflow, this research answered the following questions:

1. How to integrate human intuition with AR for upcycling reclaimed timber boards?
2. How to reconfigure the material on hand to achieve free-form structures?
3. How to balance material efficiency and fabrication efficiency?

2 – PROJECT DESCRIPTION

2.1 AR-AIDED DESIGN-TO-FABRICATION LOOP

This research introduces an artisan-oriented AR workflow that balances material efficiency with fabrication efficiency in upcycling waste timber boards. Typical designer-oriented workflows for upcycling involve surveying and documenting all reclaimed materials and nesting them into a target design for optimized model matching or material efficiency, as shown in Figure 1a. After nesting, this process requires identifying the selected objects, cutting and labeling each piece, then storing and assembling them. During Assembly, the AR environment usually displays piece locations following predefined sequences. The operator needs to identify the labeled piece and then locate it accordingly. This workflow may achieve global optimal for material nesting but sacrifice time in inventory management and virtual model preparation.

In contrast, the proposed workflow integrates AR as a dynamic tool within a design-to-fabrication loop, serving as a digital marker that provides real-time feedback. By breaking down the global nesting into a per-layer local nesting process, artisans can use their expertise to make intuitive decisions without needing information about the entire stock. This nesting logic enables a smooth iteration between the surveying, nesting, cutting, and assembling processes layer by layer (Figure 1b). The consistency directly links selected objects to customization and assembly, thus eliminating the need for labeling, storing, and identifying. This AR setup assists the artisans in managing a limited number of objects at a time, gradually constructing the target design.

2.2 TAILORED NESTING LOGIC FOR FREE-FORM BOUNDARIES

The cyclical workflow is rooted in a tailored nesting logic, where a given 3D shape is sliced into 2D nesting boundaries. These boundaries are then nested with reclaimed timber boards and stacked together to configure the target shape. Unlike the prevailing trend in current research for reusing or upcycling planar materials, which focuses on nesting complex shapes into one rectangular boundary [16-18] (Figure 2a), this study explores transforming the most common leftover shape—rectangular—into freeform boundaries (Figure 2b). This nesting logic places rectangular pieces to cover a free-form 2D boundary partially, preserving the boundary consistency and maintaining proper spacing between pieces. Nesting free-form boundaries enables the creation of varied 3D forms by stacking, offering design flexibility and fabrication convenience. The strategic inclusion of gaps reduces the massiveness of the structure and minimizes cutting effort. However, these gaps must be covered in subsequent layers to maintain stability. Thus, AR is employed to record and visualize gaps from previous layers during the nesting process to ensure effective stacking.

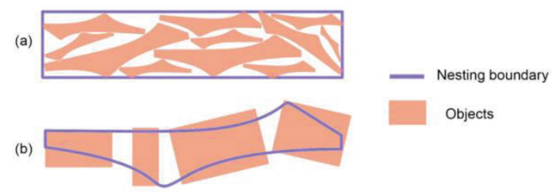

Figure 2. Comparison of two nesting logics for upcycling waste materials.

3 –EXPERIMENTAL SETUP

The study investigates the repurposing of reclaimed timber boards, ranging from 0.3 to 0.6 meters in length and 0.3 to 1.2 meters in width (Figure 3), to construct a free-form parametric wall. An artisan with a VR headset strategically distributes the boards into 2D boundaries, facilitating a laminated 3D structure through stacking. The development of an AR application is integral to this process, encompassing visualization, 3D model processing, user interface design, and algorithm development. The workflow operates in a loop of four stages: surveying, nesting, cutting, and assembling (Figure 4). The AR environment, constructed in Unity and visualized with the Meta Quest Pro see-through mode, is critical in efficiently surveying objects and linking them to customization and assembly. It visualizes nesting boundaries and material efficiency, documents nesting patterns, updates cutting lines, and designates assembly locations, thus ensuring a seamless integration of digital feedback into the physical construction process.

Figure 3. Reclaimed timber boards ranging from 0.3 to 0.6 meters in length and 0.3 to 1.2 meters in width

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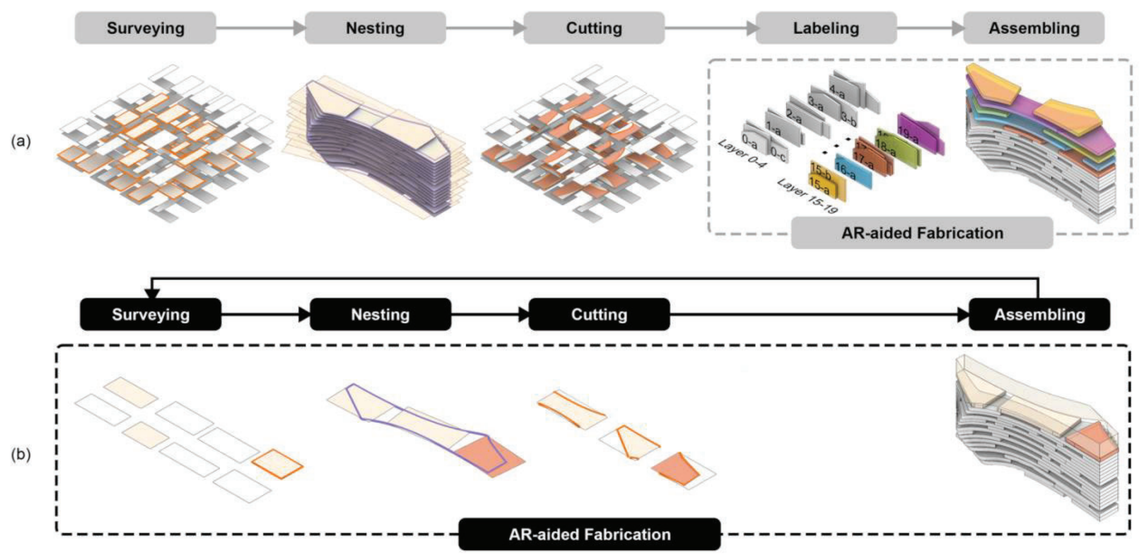

Figure 1. Comparison of AR roles in material upcycling between typical and proposed design-to-fabrication workflows. (a) AR-aided fabrication in the usual workflow. (b) AR-aided fabrication in the proposed workflow.

The environment setup consists of four platforms: surveying platform, nesting platform, cutting platform, and assembling platform (Figure 4). All the colored parts in Figure 4 are virtual environments visualized by a VR headset in see-through mode. The physical setup consists of a box of reclaimed materials, four tables designated for surveying, nesting, cutting, and assembling, and a cutting tool. The **surveying platform** creates the digital model of physical objects powered by a surveying camera. The loading table presents a limited amount of timber boards randomly loaded from unsorted material stock for each iteration. After loading, the surveying camera captures a photograph, which is used to update the virtual stock by boundary recognition using OpenCV. The **nesting platform** visualizes nesting boundaries, enabling artisans to position and adjust virtual objects while displaying real-time material efficiency. After confirming the nesting, the **cutting platform** visualizes customized cutting lines sequentially. Cutting can be executed manually or with a digital tool guided by the virtual pattern. Usable cutoff parts can be reloaded to the surveying table or placed into the stock box. The **assembling platform** visualizes the final target design and sequentially illustrates the placement of each cut object.

Four spatial anchors and four virtual control buttons are integrated into the AR environment to synchronize the physical and virtual processes. Spatial anchors are defined by the artisan at the initiation of the AR application to ensure precise alignment of virtual platforms with physical tables. This configuration enhances the adaptability of the virtual environment, enabling seamless integration into various physical workspaces. Four virtual control buttons are integrated into the workflow to loop through different stages smoothly. The loading button triggers the surveying camera, updates the virtual stock, and visualizes the next nesting boundary on the nesting table. The nesting button finalizes the nesting pattern in the virtual environment, records the gaps in the current layer, and prepares the cutting lines. The cutting button projects the cutting lines to the cutting origin and highlights the corresponding physical object on the surveying table. After cutting, the assembly button indicates the placement of the cut object.

4 – DESIGN PROCESS

4.1 AR AIDED WORKFLOW

This research explores the construction of a parametric wall by horizontally slicing it into layers, each defining a nesting boundary. The topology and shape of the wall are unrestricted, provided they are compatible with horizontal slicing. The slicing process accommodates various thicknesses, but only materials of the same thickness can be arranged within the same layer. The fabrication process constructs this free-form structure by sequentially cutting and assembling layers, and each layer comprises several timber boards with gaps in between. To ensure structural integrity, each layer must cover the gaps of the previous one, resulting in a sparse yet stable configuration that matches the target design. Following this design logic, the key elements for the AR application are outlined below:

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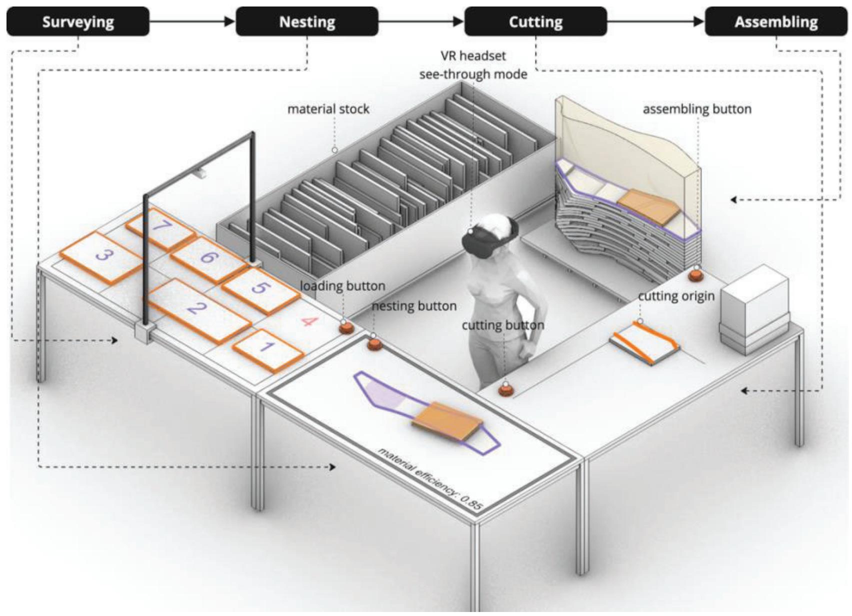

Figure 4. Environment setup for AR-aided fabrication workflow with colored parts representing the virtual environment.

- **Inventory Cloning**: Align the virtual material stock with the physical stock on the surveying table by updating geometric information captured by the overhead surveying camera.
- **Nesting and Visualization**: Visualize the nesting boundaries for the current layer and the gaps from the previous layer. Updating top-view nesting pattern and related material efficiency. Signal a successful arrangement when more than 50% of the nesting area is covered.
- **Cutting Pattern Visualization**: Display cutting lines based on the nesting pattern and highlight corresponding physical objects. Visualize cutting lines as digital markers for manual cutting or transform G-code/vectorized cutting patterns for digital cutting.
- **Positioning and Assembly**: Projects virtual overlays to indicate the assembly locations of the cut object.

In this setup, the artisan is looping through four processes: **Surveying Process**: the artisan starts by loading several objects from the stock box onto the surveying table and pressing the loading button to update the virtual stock (Figure 5a). At the same time, the next nesting boundary will be visualized on the nesting table. If it has a previous layer, the gaps from the last layer will be marked in red. **Nesting Process**: The artisan selects objects from the virtual stock and places them within the nesting boundary. During this process, a top-view nesting pattern and its material efficiency are visualized in front of the nesting table (Figure 5b). Objects change from half-transparent to black after placement to create a clear pattern. The artisan adjusts the nesting pattern until more than half the boundary area is covered, triggering a green signal. The artisan then confirms the pattern by pressing the nesting button. This action triggers the calculation of the cutting lines and updates the gap information for the next layer. **Cutting Process**: Once nesting is confirmed, the cutting button becomes active, allowing the sequential transfer of cutting lines for each object to the cutting platform. Meanwhile, a pink signal indicates the corresponding physical object on the loading table (Figure 5c). The artisan then picks the highlighted piece, aligns it to the cutting origin, and performs the cut (Figure 5d). **Assembly Process**: After cutting, the artisan presses the assembly button to visualize virtual guidance in the assembly area and locate the cut object (Figure 5e). This process is repeated: pressing the cutting-assembling button to visualize the next object's cutting line, followed by cutting and assembling until all objects in the current layer are finished. Finally, the artisan needs to load new material or the cutoffs onto the surveying table, proceed to the surveying process, and initiate the next layer.

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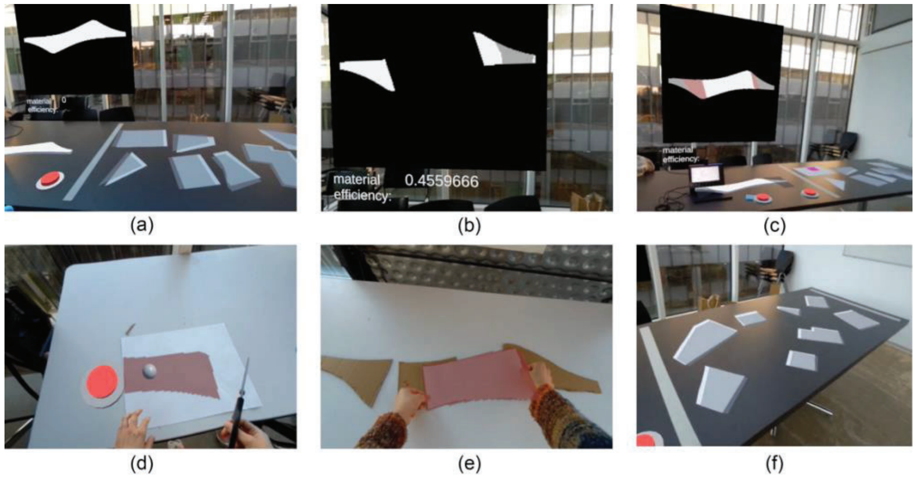

Figure 5. The interface of one AR-aided design-to-fabrication loop (a) The loading table with the current material stock and the nesting table with the nesting boundary. (b) Visual representation of the nesting pattern and material efficiency. The nesting boundary is depicted in white, placed materials are shown in black, and objects currently being placed appear as transparent gray. (c) The pink light signals the physical object that is ready to be cut. (d) Perspective from the cutting table, including the location of the assembly button. (e) Perspective from the assembly table, illustrating the assembly scenario. (f) The loading table with the newly updated material stock.

4.2 THE NESTING SCENARIOS

This research proposed three different nesting strategies to explore the roles of human intuition in the object arrangement, the influence of computational design tools in determining nesting patterns, and the integration and potential assistance of AR environments in the nesting process, including virtual nesting, physical nesting, and computational nesting.

Virtual nesting involves configuring a layer by drag-and-drop or pick-and-place virtual objects into a virtual boundary. This process provides instant feedback on the nesting pattern and efficiency, benefitting from direct operation in the digital world. Tracking the selected objects and their transformations for further cutting and assembly processes is also easier. Artisans can arrange objects without the physical effort of lifting and moving them. Additionally, for heavier materials or large-scale target designs, the virtual nesting environment allows for scaling the nesting boundary and virtual objects to a manageable scale.

Physical nesting requires moving physical objects to cover virtual boundaries on the nesting table, either visualized through a VR headset or a laser projector. This hybrid approach retains the tangible benefits of interacting with physical objects, facilitating spatial awareness and accurate adjustments. Laser projections enhance collaboration by opening and transparent the nesting process, allowing team members to engage in and contribute to layout adjustments easily. However, ensuring perfect alignment between the digital and physical worlds while nesting can be challenging, potentially leading to inaccuracies in calculating material efficiency or cutting lines. This method is best suited for lightweight materials and furniture-scale designs.

Computational nesting uses predefined heuristic rules to determine optimal positions for a selected object or the best-so-far combinations and transformations of the surveyed objects. When combined with an AR environment, computational nesting can speed up the nesting process, find the optimal material efficiency, and visualize the solution by sequentially highlighting the selected object and illustrating corresponding cutting lines. However, this method also positions humans as performers rather than creators, potentially reducing creativity. It may fall short in tasks requiring aesthetic judgment and material sensitivity.

This research selected virtual nesting for its ability to provide instant feedback and its adaptability to different scales of material stock and target design. The nesting logic of this method is illustrated in Figure 6. The task involves using available material to cover at least 50% of the current layer while ensuring the gaps from the previous layer are also covered. Initially, a set of available timber boards and the current nesting boundary are visualized (Figure 6a). The artisan manually selects from the virtual stock and positions the pieces to cover the nesting boundary (Figure 6b). Material efficiency,

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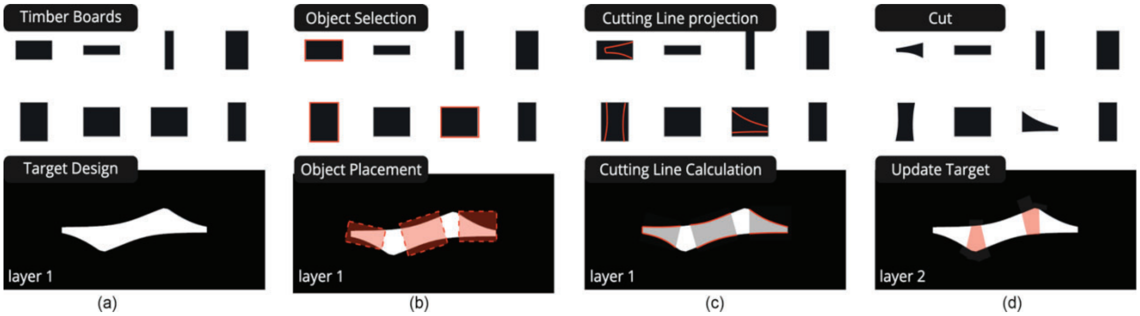

Figure 6. The nesting logic of the AR-aided fabrication loop

defined as the ratio of the covered area to the area of used objects, is updated in real time to indicate the efficiency of the material usage. This allows the operator to experiment with different object selections and combinations to achieve higher material efficiency or desired nesting patterns. Once the nesting is confirmed (Figure 6c), the cutting line is automatically calculated and associated with the original objects. The gaps in the current layer are documented and will be visualized as a reference for nesting the next layer (Figure 6d). Prioritizing gap coverage and fulfilling the nesting density is crucial for valid stacking and structural stability.

4.2 THE CUTTING AND ASSEMBLING SCENARIOS

This research proposed two cutting strategies and one connection logic to examine the flexibility of craftsmanship in material customization and the role of digital fabrication tools within a cyclical workflow, including manual cutting, digital cutting, and connection-informed assembly. This research utilized manual cutting for its wide accessibility.

Manual cutting refers to cutting manually with AR instructions. Cutting lines are visualized through the headset, enabling artisans to follow digital marks for execution. Artisans can either cut directly along these virtual lines or create physical marks, the latter mitigating potential inaccuracies if the object shifts during cutting. This method mirrors traditional cutting techniques, requiring minimal additional training and incurring low entry costs. Furthermore, when integrated with AR, this approach enhances workflow efficiency by allowing sequential cutting and effective tracking of cutting objects.

Digital cutting utilizes Shaper Origin™, a handheld CNC router, to perform precise cuts based on vectorized cutting patterns. The process needs to transform the cutting pattern into scalable vector graphics and upload them to a server, which can be transferred to Shaper via a USB drive or a user account. It requires the artisan to manage file transfers, align the material under the router, and oversee the cutting process. Conducting digital cuts enhances cutting accuracy and contributes to a safer construction environment. However, transitioning from digital design to local machine execution demands data handling, potentially disrupting the workflow. Additionally, it entails an initial investment and requires the operator to acquire proficiency with the new tools.

Connection-informed assembly refers to using reversible connections to inform the assembly process. As shown in Figure 7, connections can be created during nesting by generating wood dowel/post-tension holes via heuristic rules or predefined design patterns. The hole drilling can be integrated into the cutting process alongside the cutting pattern. This system could replace AR-guided assembly, determining the position of the cut object by matching/aligning it with existing connections. This approach can simplify the AR-aided workflow and reduce the number of operation buttons from four to three. Moreover, the reversible system offers benefits for reclaiming the entire structure by reintroducing all nested elements back to the stock box, forming a sustainable loop to keep valuable materials in circulation.

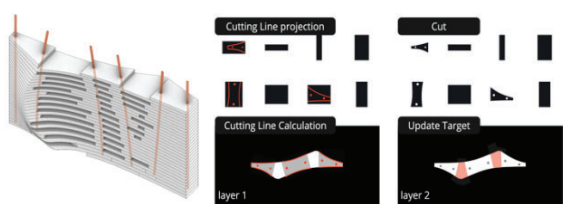

Figure 7. Development of Reversible Connections in Connection-Informed Assembly Scenarios

5 – RESULTS

This research highlights a conceptual transition in the use of AR in architectural research and fabrication processes. It emphasizes the shift from rigid, instruction-based systems to more flexible, intuitive systems where human judgment and creativity play a significant role. Artisans

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are empowered to visualize complex data, arrange materials, and recall previous configurations effortlessly, while making decisions based on experiential factors like appropriate distance or aesthetic balance—elements that are challenging to automate through algorithmic procedures. This approach values the artisan's expertise, resulting in more personalized design outcomes. Thus, this research advocates prioritizing human input over strict heuristic rules, especially in tasks that demand domain knowledge, aesthetics, and material sensibility. This conceptual framework not only complements the technical processes discussed but also justifies the use of AR as a tool to enhance human creativity and efficiency.

This proposed design-to-fabrication workflow employs AR to connect digital design targets to physical non-uniformed material stocks. The synchronized coordination between physical setup and virtual environments allows for flexible spatial arrangements and material stock updates. The AR user interface is easy to master, featuring four buttons to control the iteration between key stages: surveying, nesting, cutting, and assembling. These straightforward controls require minimal training, allowing artisans to concentrate on the tasks at hand. The surveying system has a maximum detection error of 3 millimeters when updating edge lengths, though most detection errors are typically within 1 millimeter. The imprecision is negligible and does not impact the nesting, cutting, and assembling processes. A certain margin of error is allowed because the objects on the same plane are not arranged adjacently. Overall, this workflow guarantees a seamless transition between digital info and physical arrangements, enabling artisan to have risk-free experimentation with their creations.

This research focuses on the creative use of available materials to craft target shapes. It explores the possibility of upcycling reclaimed objects using a virtual environment with limited knowledge of reclaimed materials. This approach balances material efficiency and fabrication efficiency, bypassing the need for extensive inventory management and labeling processes. Additionally, the stacking logic does not heavily rely on the strength of individual materials, configuring robust overall structures by stacking 2D planar elements into diverse 3D forms, making it more suitable for upcycling reclaimed materials. It efficiently reintroduces commonly available rectangular waste materials into free-form components, offering aesthetic and structural benefits.

6 – CONCLUSION

This research is situated at the intersection of AR-aided fabrication and circular construction. The proposed cyclical workflow values human input alongside technological advancements, facilitating a seamless integration of digital and physical processes that enhance creativity and sustainability. This framework blends digital design with hands-on craftsmanship, leveraging AR to create free-form structures from waste timber boards. It explores the potential to enhance decision-making in a virtual environment, enabling artisans to experiment with different configurations based on visual feedback. The integration of technology ensures precision while allowing for creative input and customization. This research uses a VR headset with see-through mode, which may raise safety concerns during manual cutting or exhibit inherent imprecision in the camera projection. AR headsets, such as Microsoft HoloLens, can mitigate these issues. For future research, the integration of real-time computational nesting suggestions into the virtual nesting process presents a promising advancement. This approach would provide immediate feedback on the optimal placement of one selected timber board, effectively serving as an AI-augmented design assistant. It can enhance material efficiency while allowing artisans to retain control over adjustments and final decisions.

7 – REFERENCES

[1] Augustynowicz, Edyta, and Nikita Aigner. "Building from scrap: Computational design and robotic fabrication strategies for spatial reciprocal structures from plate-shaped wooden production waste." Journal of Architectural Sciences and Applications 8.1 (2023): 38-53.

[2] Eversmann, Philipp. "Robotic fabrication techniques for material of unknown geometry." Humanizing Digital Reality: Design Modelling Symposium Paris 2017. Singapore: Springer Singapore, 2017.

[3] Parigi, Dario. "Minimal-waste design of timber layouts from non-standard reclaimed elements: a combinatorial approach based on structural reciprocity." International Journal of Space Structures 36.4 (2021): 270-280.

[4] Haakonsen, Sverre M., et al. "Automation of circular design: A timber building case study." International Journal of Architectural Computing (2024): 14780771241234447.

[5] Sun, Qiming, et al. "A Systematic Literature Review on Computational Design Methods for Non-Uniform Found Objects." Available at SSRN 4952086 (2024).

https://doi.org/10.52202/080513-0486

[6] Reisach, Dominik, et al. "A Design-to-Fabrication Workflow for Free-Form Timber Structures Using Offcuts." International Conference on Computer-Aided Architectural Design Futures. Cham: Springer Nature Switzerland, 2023.

[7] Witt, Andrew. "Through a Machine Lens: Case Studies of Computer Vision and Machine Learning in Design Methodology." Loci Communes. International Journal of Studies on Spaces in Arts and Humanities, Anthropology and Architecture 1.2 (2022): 1-16.

[8] Larsson, Maria, Hironori Yoshida, and Takeo Igarashi. "Human-in-the-loop fabrication of 3D surfaces with natural tree branches." Proceedings of the 3rd Annual ACM Symposium on Computational Fabrication. 2019.

[9] Denaro, Gianni. "Industry 4.0 and New Artisans: Between Hand-crafted Design and Digital Production." The International Journal of Design Management and Professional Practice 14.3 (2020): 1.

[10] Song, Yang, Richard Koeck, and Shan Luo. "Review and analysis of augmented reality (AR) literature for digital fabrication in architecture." Automation in construction 128 (2021): 103762.

[11] Lok, Leslie, and Jiyoon Bae. "Timber De-Standardized 2.0: Mixed Reality Visualizations and User Interface for Processing Irregular Timber." Proceedings of the 27th CAADRIA Conference. Sydney: CAADRIA. 2022.

[12] D. Mitterberger, S. Ercan Jenny, L. Vasey, E.Lloret-Fritschi, P. Aejmelaeus-Lindström, F. Gramazio, and M. Kohler. "Interactive robotic plastering: Augmented interactive design and fabrication for on-site robotic plastering." In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, (2022), pp. 1-18.

[13] Zivkovic, Sasa, and Leslie Lok. "Extended Reality (XR) Workflows for Multi-Material Assemblies." ACADIA (2023): pp. 318-329.

[14] Lok, Leslie, Asbiel Samaniego, and Lawson Spencer. "Timber de-standardized." Proceedings of the 41st Annual Conference of the Association of Computer Aided Design in Architecture (ACADIA), New York, NY, USA. 2021.

[15] Jahn, Gwyllim, et al. "Holographic construction." Impact: Design With All Senses: Proceedings of the Design Modelling Symposium, Berlin 2019. Springer International Publishing, 2020.

[16] Liu, Yifang, et al. "Deep Q-learning for dry stacking irregular objects." 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2018.

[17] Wang, Qianqing, et al. "An image convolution-based method for the irregular stone packing problem in masonry wall construction." European Journal of Operational Research 316.2 (2024): 733-753.

[18] Marshall, D., and S. Kennedy. "A Shingled Glass Envelope System Constructed from Reclaimed Insulated Glass." Journal of Physics: Conference Series. Vol. 2600. No. 19. IOP Publishing, 2023.

 https://doi.org/10.52202/080513-0486