From Craft to Community: A Digital Fabrication Framework for Participatory Upcycling of Urban Waste

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Abstract. Addressing the gap between digital craft and community agency in sustainable design, this study explores participatory upcycling with digital fabrication methods. Deploying Research through Design (RtD) methodology, we developed and tested a participatory workflow integrating CNC milling of salvaged wood and heat-shrink waste plastic joints within Hong Kong's high-density Shatin district. Iterative prototyping revealed three key socio-technical tensions: structural precision vs material unpredictability, automation's efficiency vs technician dependency, and standardisation needs vs inclusive co-design. Stakeholder engagement (social workers, engineers, industry partners) further highlighted divergent priorities regarding safety, scalability, and cultural resonance. The resulting five-stage framework—spanning material surveying, co-design, and community assembly—demonstrates how downstream scaling and community-driven micro-production methods can reconcile digital precision with craft participation. Findings suggest such convivial approaches can empower communities to reclaim agency over urban waste streams, though inherent contradictions between technical rigour and participatory flexibility require ongoing negotiation.

Keywords: wood upcycling, design for disassembly (DfD), community craft, digital fabrication, shrink plastic

1 Introduction

As urbanisation progresses, community craftsmanship faces both opportunities and challenges amongst modern methods. Studies have looked at how digital fabrication techniques can synthesise community craft. For instance, Doria et al. 's (2021) Public Parts project proposed to integrate robotic construction with discrete design to facilitate affordable self-built housing. Claypool (2021) analysed such potentials in a post-work society, bridging digital divides through automation. By making architecture processes human-scale and user-friendly, these micro production methods innovate traditional workflows to ensure citizens' right-to-produce.

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While prior work explored digital fabrication in upcycling (Yu et al., 2023; Yu, 2022), few addressed the dual challenges of material variability and community agency: **How can participatory upcycling and digital fabrication be synergised to empower communities in dense urban contexts?** The experience documented contribute to how machine fabrication and automation can be harmonised with human crafts and creativity, innovating environmental design techniques without compromising human-centric considerations.

2 Literature Review

Digital fabrication has emerged as a transformative force in sustainable design and construction by enabling precision workflows and design control, aligning material configuration with product optimisation to enhance efficiency (Bechthold, 2017; Saeed, 2019; Al-Werikat, 2017). Recent advances apply these techniques to upcycling, such as project Mine the Scrap, which employed data-driven and geometric scaling methods to repurpose construction debris into structural components (Certain Measures, 2021). However, such projects often prioritised industrial scalability, struggling with material unpredictability and stakeholder misalignment, thereby sidelining community agency. This reflected a broader gap in the field: while upstream scalability emphasised centralised, resource-intensive production (Herbert Kotzab, 2010), as seen in Build-in-Wood's standardised timber systems (2024), it risked homogenising design intent and material reality.

Conversely, downstream scaling emphasises demand-side economics, focusing on user needs in the architectural process (Ng, 2025; Ng, 2024). Projects like Material Matters actively invite community story and education programs to create a collaborative environment. Automated Architecture (AUAr) experimented with a robotic construction ecosystem to build sustainable and affordable homes and train community skilled workers (Gilles, 2017; Gilles, 2020; Mollie, 2024).

Yet, these efforts often overlooked the integration of participatory design—a critical gap underscored by Schuler's (1993) emphasis on democratising technology and Sanders and Stappers' (2012) "convivial toolbox", which positioned communities as co-creators rather than passive beneficiaries.

Instead of upstream scaling to mass production, our study pilots downstream scaling to community micro-production. By synthesising conviviality with automation, the goal is to empower residents to reclaim agency over waste streams while promoting wider adoption of upcycling and community craftsmanship in urban context—a critical step toward scalable, culturally resonant circular economies.

3 Methods

The study identified several challenges of digitally-driven participatory upcycling. First, the need to survey commonly found waste materials and test their fabrication constraints. Second, a user-friendly DfD joinery design for easy user adoption. Third, methods to democratise upcycling through a technology-assisted engagement process. Hence, the objectives are to 1) explore how digital fabrication can enable participatory upcycling in dense urban contexts; 2) understand the socio-technical challenges in scaling community-led micro-production; and 3) test how automation can complement, rather than displace, community crafts.

Grounded in Research through Design (RtD) methodology (Zimmerman et al., 2007), the work employed iterative prototyping and stakeholder collaboration to generate actionable insights, following a three-phased approach.

First, material surveying. Salvaged wood (n=30 pieces) and plastic (n=200 bottles) were collected from Shatin's public housing, performance venues, and university studios. Materials were categorised by type, shape, density, and dimensions.

Second, prototype development using salvaged materials. Progressing from 1:5 to 1:1 chair prototypes, structural stability was validated via load-bearing tests (average adult male static load). CNC milling trials quantified waste margins, aimed at <37%—average wood loss during massive material processing (Sofuoğlu & Kurtoğlu, 2012), while heat-shrink plastic joints were tested for structural strength.

Third, three 1-hour interviews were conducted respectively with a social worker, an upcycling company owner (aka industry partner), and a structural engineer. Each with 7+ years in the field and were recruited via peer recommendation. Questions were semi-structured around the Triple Bottom Line framework (Loviscek, 2021):

- Social: Safety, accessibility, and community cohesion.
- Environmental: Material efficiency and waste reduction.
- Economic: Cost-effectiveness and scalability.

Transcripts were coded using Braun and Clarke's (2006) six-phase approach, categorising responses into themes, and compared across stakeholders input.

Finally, the insights are used to refine the participatory workflow (Fig. 1), integrating five stages—Survey, Preparation, Design, Fabrication, and Assembly—to transform urban waste into functional furniture. Community involvement spanned co-design workshops, material sorting, and guided assembly, while technicians managed CNC workflows and structural validation, bridging craft with automation.

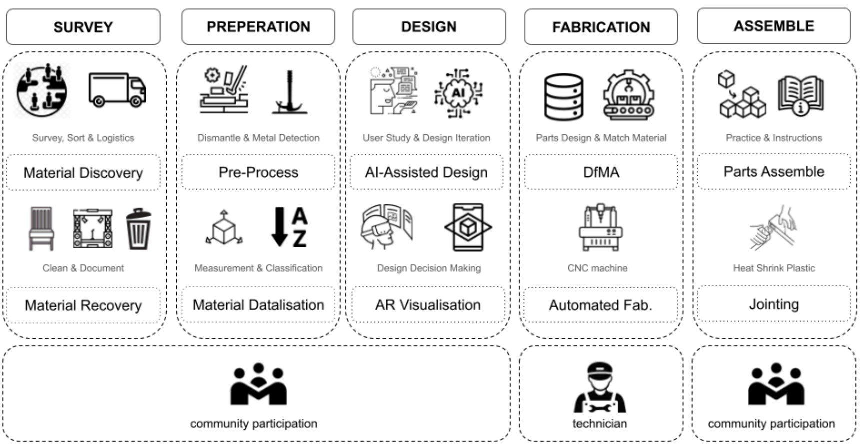

Fig. 1. Proposed workflow combined material survey, co-design, and community production.

4 Survey & Design

The Shatin district is home to over 700,000 people, featuring many high-density housing completed in the 1980s during the New Town Movement (Chow, 1997). These homes and public spaces, now over 50 years old, are facing redecoration or reconstruction, generating significant solid waste, with 90% ending up in landfills (Environment and Ecology Bureau, 2022). Our NGO partner noted that residents often bring worn furniture to community centers seeking recycling options, but these centers do not offer such services (Fig. 2).

The surveyed materials encompass three categories (Table 1 & 2), beginning with discarded furniture from residential areas, which are durable, easily disassembled rectangular wood pieces suited to CNC processing. However, challenges arise from treated surfaces, embedded metal fittings, and inconsistent supply, with materials often left exposed to weather damage on streets. Our industry partner highlighted the labour intensive complexities of upcycling these salvaged resources.

The second category comprises solid waste from performance venues, notably Shatin Town Hall hosts weekly shows and Xiqu performances, often using one-off stage sets and props discarded due to high storage costs. Local university drama clubs contribute similarly, utilising wooden sets for 20-30 annual performances, peaking in November and summer. While this wood is advantageous due to its large, flexible area for CNC use, predictable collection schedules tied to fixed performance timetables, and opportunities for pre-planned material optimisation through stage designer collaboration, challenges persist. These include excessive nail-gun fastenings complicating disassembly, generally lower-quality timber, and irregular thickness and shapes that hinder processing efficiency.

The third category stems from architecture studios, where presentation model production generates substantial waste each semester. While entire wood sheets are occasionally discarded due to surplus stock for laser-cutting contingencies, most offcuts are too small or thin to repurpose effectively, compounded by CNC blade thickness constraints. Nevertheless, these remnants serve as viable resources for prototyping and scaled models, enabling practical experimentation before full-scale fabrication. Separately, widely available plastic bottles in campuses offer potential through their malleability and heat-shrink properties, applicable to DfD joinery concepts. However, inconsistent shrinkage rates across bottle types necessitate further investigation to establish standardised reuse protocols.

Fig. 2. The target public housing (>9000 residents) was found to discard large furniture weekly; each of its recycling bins collect 20–30 plastic bottles daily. The amount of gun-nails found per m² of the salvaged wood averaged to 100-200 pieces, costing huge amounts of labor to remove.

Table 1. Salvaged waste material matrix.

Source	Supply Consistency	Ease of Processing	Material Quality
Discarded Furniture	★☆☆	★★☆	★★★
Performance Waste	★★☆	★☆☆	★★☆
Studio Wood Waste	★★★	★☆☆	★☆☆
Plastic Bottles	★★★	★★☆	★☆☆

Table 2. Qualitative comparison of common salvaged material from different urban contexts.

Source	Advantages	Limitations
Discarded Furniture	Durable, rectangular wood ideal for CNC milling.	Inconsistent supply (often left outdoors, damaged by weather), embedded metal fittings, and labour-intensive pre-processing.
Performance Waste	Large, flexible wooden stage sets from Sha Tin Town Hall and university drama clubs, with predictable collection schedules.	Low-quality wood, irregular shapes, and nail-gun overuse complicating disassembly.
Studio Wood Waste	Consistent semesterly supply of wood offcuts for prototyping.	Small/thin remnants (40% unusable due to CNC blade constraints).
Plastic Bottles	Ubiquitous and malleable for heat-shrink joints.	Variable shrinkage rates (e.g., Bonaqua bottles performed best, while others deformed).

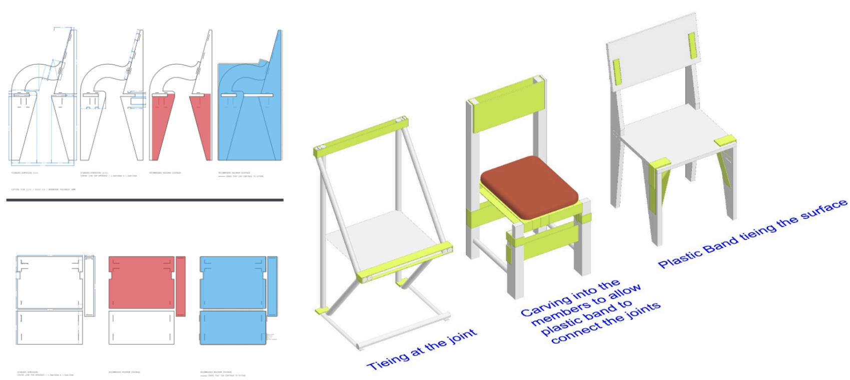

Fig. 3. Heat-shrink plastic joint design iterations (left to right) improved joint stability from 60° to 90° alignment. Bonaqua bottles achieved optimal shrinkage at 180°C (right).

5 Prototyping

From the initial surveying, it was discovered that the use of nail gun and metal fittings posed immense labour challenges in the upcycling and digital fabrication process. Thus, the prototyping focused on developing a DfD joinery system (Fig. 3) that does not require nails or screws to extend the afterlife of wood pieces, utilising commonly found waste materials that can be easily manipulated by residents for co-production —heat-shrinking discarded plastic bottles. The assembly process involved three key steps (Fig. 4):

Step 01: Customization of Furniture Parts with CNC Milling. Designing parts for manufacture with a 3-axis CNC machine, with precise cutting and design detailing. It is also effective with our heat shrink plastic joint, making 90-degree connections, which are easy to assemble. CNC can customise mortise joints in standard size, ensuring average quality of fabrication, flexibility of wood shapes. Automated fabrication ensures safe participation of communities, replacing dangerous parts of woodworking. The parts and joints are marked with numbers for easy recognition.

Step 02: Reclaiming Plastic Waste & Wrapping. Collect and clean plastic waste from local areas for connections of wood parts. Cut bottles into thin strips to wrap around custom mortise joints using double crossed knots.

Step 03: Heat Gun Application for Plastic Shrinkage. Hot guns were used to apply controlled heat to the plastic for shrinkage, fixing the wood parts firmly in place. Type I & II plastics are ideal for heat shrink, with Bonaqua and Vita plastic water bottles performing the best, soft to cut and manipulate, fast to shrink, higher melting point, and holds strongly.

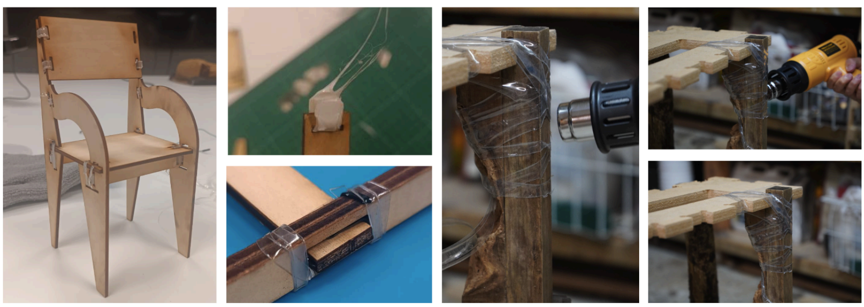

Fig. 4. Initial 1:5 scale tests revealed material challenges: Type I PET plastics exhibited inconsistent shrinkage rates (120–180°C), with only 40% achieving viable joint stability. Documentation of thermal thresholds informed revised protocols for full-scale trials, prioritising Bonaqua bottles (optimal at 180°C).

The process encountered several technical challenges rooted in material variability and fabrication constraints (Fig. 5). Salvaged wood often exhibited warping and surface irregularities, with thickness deviations averaging ±3mm, leading to marginal alignment errors during CNC processing (mean: 1.2mm deviation). These inconsistencies complicated load-bearing capacity estimations, which varied by

15–20%, necessitating iterative finite element analysis (FEA) to validate structural integrity. Mortise joint precision was further constrained by the CNC milling head's 6mm minimum kerf, requiring manual adjustments for nearly a third of smaller joints. Plastic joints, while innovative, presented durability trade-offs: Type I PET strips offer stronger tensile strength if thicker (≥0.1mm), but demanded advanced knotting techniques to prevent slippage during shrinkage.

Material waste emerged as a critical limitation. Laser cutting and CNC milling generated 40% and 45% waste margins, respectively, due to irregular material dimensions. However, standardising salvaged wood or component design into modular blanks can improve yield, which needs further testing. Sustainability trade-offs were evident: while CNC reduced labour hours compared to traditional carpentry, energy consumption increased. Lifecycle analysis is needed to suggest carbon costs offset and the minimum number of reuse cycles.

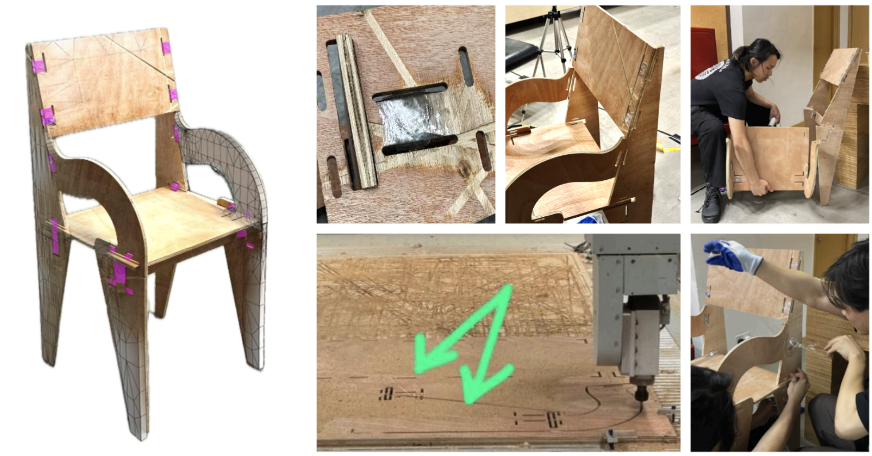

Fig. 5. Full-scale CNC-milled salvaged wood components (left) and heat-shrink plastic joints (right). Load tests validated an adult male capacity (average Asian weights 70 kg), while special markings help reduce assembly errors. However, the CNC milling had to be adjusted a few times due to inconsistent thickness of salvaged wood. Future work should investigate how material variability can be adaptively considered and automated along fabrication processes.

6 Stakeholder Feedback

Feedback from social workers, structural engineers, and industry partners encompassed aspects of material sustainability, design adaptability, structural integrity, community practicality, and sustainability trade-offs (Table 3).

All groups emphasised sustainable material reuse, with social workers advocating for community-led waste collection activities, while industry partners prioritised technical selection of waste to exclude compromised materials (e.g., bark-laden wood prone to insect damage). Further tension arose from engineers who advocate on material homogeneity for stability calculations (Euler's formula, safety factors ≥2.0), whereas industry partners favoured aesthetic "live-edge" boards to engage users, despite irregular geometries.

Reviewing the design, social workers prioritised modular, space-saving furniture and intergenerational usability (e.g., collapsible chairs for high-density housing, flexible stages for community events). While industry partners agreed on the importance of tailoring design to local culture and promoting longer use of products, they prioritised the standardisation of basic DfD joint design for scalability. They also have doubts in the durability of plastic joints for critical connections and suggest trying aluminium brackets for high-stress nodes.

Structurally, engineers drew parallels to the 1111 Lincoln Road "shear wall" concept, advocating for over-engineered joints to handle dynamic loads. This clashed with CNC fabrication constraints, leading to a compromise: standardised DfD joinery with ±5mm adjustability for field modifications. Engineers also cautioned against planar leg alignment, advocating triangulated bases. Also, they highlighted joint quality: well-connected joints ensure rigidity and effective moment transfer, while poorly connected ones only manage pressure or tension, necessitating heat-shrink cross-knotting.

Community engagement in the production process was highly encouraged, with social workers suggesting to involve older residents in the process and provide colour-coded joints. However, industry partners suggested value lies in engineering methods for collective work, where local communities can produce independently to promote wider adoption, suggesting a more narrow set of user groups who are digitally-literate. To balance the framework's socio-technical aspects, the following was considered:

- Discrete designs accommodate engineers' safety factors (FoS=2.5) while enabling social workers' tool-free assembly.
- Community training workshops equipped residents with knotting skills, addressing initial joint failures.
- Hybrid materials balancing structural robustness demands (aluminium brackets) with malleability of plastics.
- Iterative Prototyping incorporating stress tests and community feedback to inform adaptive solutions, paying attention to joinery design in ±5mm tolerances and CNC milling head constraints.

Table 3. Triangulating stakeholder perspectives.

Aspect	Social Workers	Structural Engineers	Industry Partners
Material	Challenges in waste management, especially plastic and electronics. Community-led waste collection.	Instead of structural strength, main issues are stability and robustness. Add "safety factors" to reduce error-proneness	Issues (sugar, moisture, insects, shrinkage, degradation); suggests live-edge birch boards or discarded furniture.
Design	Modular, mobile, space-saving furniture for community events	1111 Lincoln Road project "shear wall": triangulated bases.	Adaptable, culturally relevant designs to prolong use to minimum reuse cycle.
Sustainability	Not mentioned	Not mentioned	Concerns on plastic durability and energy use to heat shrink.
Structure	Not mentioned	Over-engineered joints for safety. Statically indeterminate structures vs dynamic loads and movements.	Hybrid metal joints; encourage standardise DfD joinery design for scalability.
Community	Exciting to involve residents in design, inclusive to older adults, safety considerations.	Not mentioned	Upcycling methods that communities can adopt independently for long-term benefits

7 Proposed Participatory Pipeline & Design Adaptivity

Consolidating all lessons learnt, the participatory framework was refined as a workflow chart with defined decision-points (Fig. 6), and would be used to engage local communities in the next study phase. Explicit decision nodes (e.g., "Is material damaged?" or "Joints secure?") make the workflow's iterative, evidence-based logic visible and communicable to novice and beginners.

These are found to be especially important for documenting failure points (e.g., "35% joint slippage in initial trials") to strengthen credibility and problem-solving. Annotated thresholds (e.g., "45% CNC waste margin") help quantify environmental trade-offs and invite participatory validation. Also, technical annotations (e.g., "Heat-shrink at 180°C" or "CNC kerf: 6mm") provide actionable details for replication, satisfying demands for quantitative rigor. Further, decision points should highlight where technical constraints (e.g., material tolerances) intersect with community input (e.g., design approval) to harmonise automation and craftsmanship.

Visualising trade-offs (e.g., "Redesign if stakeholder approval = No") shows how differing priorities between engineers, social workers, and industry partners can be resolved iteratively, aligning with RtD approaches. Finally, structured decision logic aim to guide participants through complex socio-technical workflows, making the research accessible to interdisciplinary audiences (e.g., policymakers, engineers, NGOs), and highlighting adaptivity (e.g., "Adjust toolpaths if parts fail") for diverse urban contexts. The workflow commenced with a material survey:

- Materials were assessed for damage, with compromised items directed to pre-processing and intact ones cleaned, measured, and logged digitally. Those meeting design specifications were cataloged, while unsuitable materials were diverted to recycling.
- During the design phase, generative AI algorithms help to iterate furniture design to align community requirements, after which stakeholders review 3D models via AR visualisation. Stakeholders approval progress to fabrication.
- The fabrication phase employed DfD principles to optimise CNC toolpaths. Components were milled using automated machinery, achieving >45% reduction in waste through parametric nesting. Fabricated parts underwent quality checks.
- In the assembly phase, community members constructed prototypes using colour-coded visual guides. Structurally stable assemblies progressed to heat-shrink joining, where plastic strips were applied at 180°C for 30 seconds to secure joints.

In the next phase, pilot testing with local residents should underscore these refinements with post-workshop surveys to score and refine intuitiveness, reduce design misinterpretation, easy assembly of furniture within 1-hour (IKEA standard), community reuse rate, and real-world durability assessments under variable conditions.

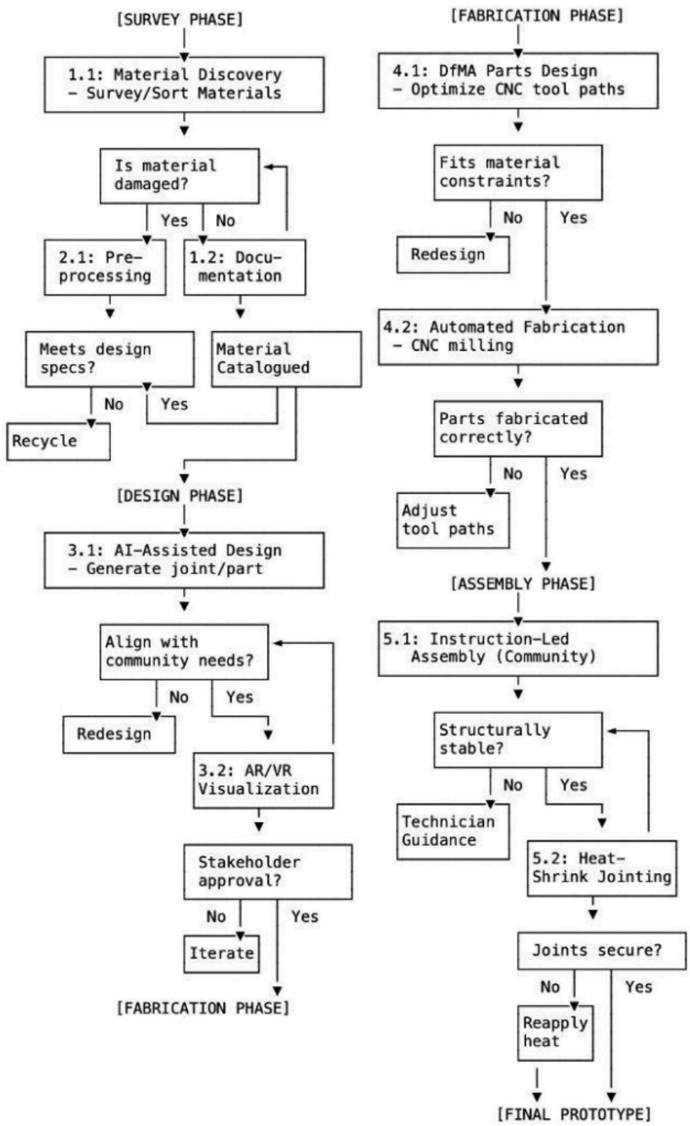

Fig. 6. A structured workflow, integrating material handling, design, fabrication, and assembly with community participation. Decision points guide iterative adjustments based on material conditions, stakeholder feedback, and technical feasibility.

To address scalability, the workflow can further adopt Design for Adaptability principles (Kendall, 1999). For instance, standardising a Kit-of-Parts with discrete designs and interchangeable joints can reduce dependency on pristine fabrication conditions. Responding to stakeholders' feedback, this can also benefit co-design workshops, where residents can adapt standardised parts to adjustable ergonomics dimensions (e.g., tailored seat heights to older adults' physiology), local needs (e.g. community stage furnitures) and cultural traditions (e.g. Taishi chair), promoting sustained use of the product.

As a proof-of-concept, a few design iterations (Fig. 7) that synthesised our DfD joint with stakeholders' feedback as prompts are developed using Midjourney, a platform-based AI image generation tool that can be used to engage residents in co-design processes. Further, 3D models of the designs were visualised in-situ using a web-based AR platform (w3rlds) to simulate and communicate how the furniture can adapt to target contexts, informing decision nodes 3.1 and 3.2 (Fig. 6).

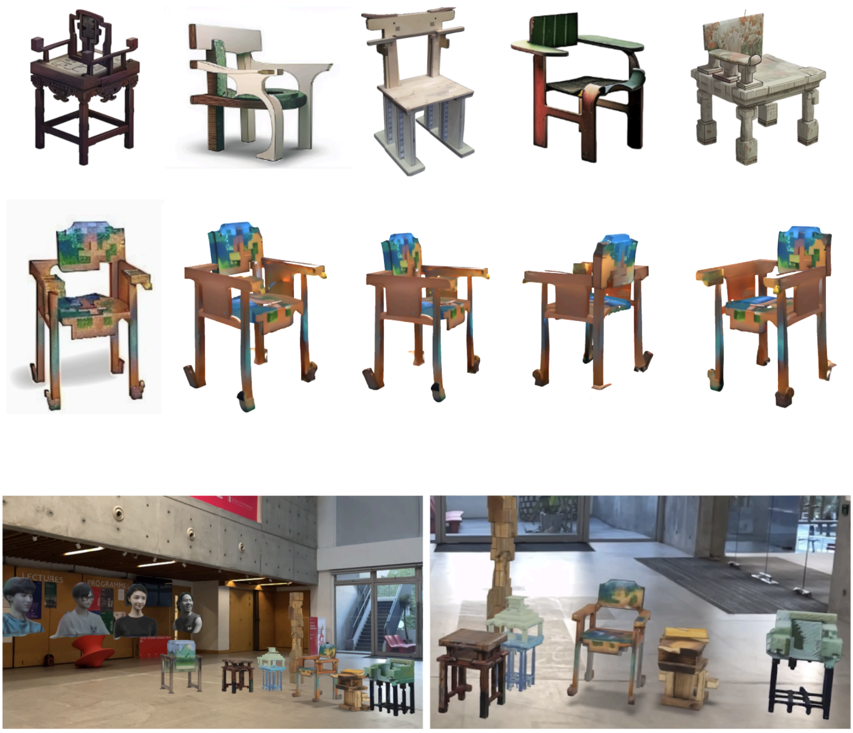

Fig. 7. AI-generated design iterations synthesised the DfD joint with stakeholder feedback as prompts, while web-based AR visualises 3D models in-situ, with virtual avatar experiencing the space in different user perspectives. This informs decision nodes 3.1–3.2 to democratise design agency, ensuring scalability and cultural resonance.

8 Discussions & Conclusion

This study demonstrated how participatory digital fabrication can democratise upcycling in high-density urban contexts, offering two key contributions: 1) a replicable framework for community-driven micro-production, integrating salvaged materials with accessible automation, and 2) critical insights into overcoming material variability through adaptive design strategies, such as joint optimisation and modular DfD principles. By decentralising production and prioritising horizontal collaboration, the framework empowers communities to reclaim agency over waste streams, reducing reliance on centralised systems while fostering social cohesion.

The pipeline's modularity enables adaptation across diverse settings: urban communities could substitute wood with other solid wastes (e.g. melted plastic bricks, corrugated cardboard blocks), while makerspaces might integrate 3D printing for complex geometries. Such flexibility positions the framework as a practical tool for advancing UN SDG 11 (Sustainable Cities) and SDG 12 (Responsible Consumption). Lessons from Hong Kong's public housing—such as balancing technical precision with community engagement—could inform projects in other hyper-dense aging suburbs, where space and material scarcity similarly demand innovative solutions.

However, when implementing the framework, several limitations have to be considered. Despite enhancing design control and offering a safer means for residents to engage in woodwork, CNC automation entrenched technician dependency and constrained material typology to paneling. Although stakeholder feedback encouraged its implementation, the sampling method risked participation bias and lacked longitudinal data. Also, tensions between structural rigour and participatory flexibility resulted in a compromised design of the DfD joints, limiting scalability to larger structures. Future study implications emphasised action research methods to transition the framework from a proof-of-concept to a validated urban resilience toolkit.

Phase 2 of this study will partner with three NGOs over six months to implement the framework in Hong Kong's real-world community context, with success measured through: Social Impact (surveys assessing community cohesion and skill development), Environmental Metrics (tracking waste diversion rates and carbon savings), and Technical Refinement (iterating heat-shrink protocols for tropical humidity and expanding AR tools for non-digital natives).

By bridging craft and automation, this work challenges traditional architectural production, demonstrating that inclusive, sustainable design is achievable when designers work with stakeholders and users to lead the process.

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