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Resources availability driven design (RADD) approach in circular architecture, engineering and construction using decommissioned materials

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ABSTRACT

The Architecture, Engineering, and Construction (AEC) sector faces critical challenges in implementing circularity due to the geometric unpredictability of salvaged materials. This paper proposes the Resources Availability Driven Design (RADD) framework, a unified cyber-physical system composed of three modules: 1) the Material Reclamation System (MRS) for real-time 3D digitisation and "Material Passports"; 2) Structural Typological Optimisation and Assessment (STOA), which utilizes the Wave Function Collapse (WFC) algorithm to translate physical tectonic constraints into generative design rules; and 3) Extended Reality-Assisted Assembly (XRAA) for precision, non-expert construction. Validated through a case study using materials from London's M&S flagship store and iterative prototyping, the framework successfully increased material utilisation and achieved algorithmic convergence across 2820 modules. RADD bridges material unpredictability with formal intelligence, offering a scalable, user-engaged model for sustainable architectural practice.

1. Introduction

The global built environment sector is at a pivotal point, grappling with the need to balance growth with sustainability [1]. Traditional linear models, characterised by extraction, construction, use, and disposal, have led to substantial resource depletion and waste generation [2] (Supplementary Video 01). In response, the Circular Economy (CE) has emerged as a transformative paradigm redesigning these processes to foster resource efficiency, reduce environmental impacts, and promote regenerative systems throughout the lifecycle of buildings and infrastructure [3–7]. CE offers a shift in construction by rethinking material use, prioritising reuse and recovery over disposal, and fostering closed-loop systems [8–11]. As the surge in construction waste and reliance on virgin materials at the end-of-life (EoL) stage continues, sustainable alternatives have become a necessity for the industry [12–14]. CE is underpinned by three core principles: eliminating waste by design, keeping materials in use, and using renewable energy sources. These principles advocate disassembly and reuse of materials, the use of durable, non-toxic products to extend product lifecycles, and the implementation of renewable energy systems to power circular operations efficiently. Integrating these principles across all stages—from production to end-of-life—is critical for maximising resource efficiency. While Design for Disassembly (DfD), modular construction, and reversible connections have been promoted to enable long-term recovery and material tracking, wide-scale adoption remains lacking [15,16].

The adoption of CE in the construction industry is hindered by fragmented supply chains, limited storage for decommissioned materials, and the complexity of designing for multiple material life cycles. A significant barrier to circular construction is the lack of accessible, up-to-date material data, which limits the efficient recovery and reuse of components. Furthermore, real-world applications often fall short of their theoretical promise, resulting in isolated efforts rather than a systemic cradle-to-cradle approach.

Recent advancements in Computer-Aided Architectural Design (CAAD) have begun to influence component reuse through photogrammetry, computational design, and robotic fabrication [17–20]. However, these workflows remain fragmented, often overlooking the aesthetic significance of decommissioned materials. Aesthetic

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considerations are frequently treated as secondary to technical efficiency, despite evidence of their impact on social well-being [19,21]. Bridging these streams, contemporary research advocates for aesthetic retrofitting, treating the irregular characteristics of decommissioned components as assets to enhance the cultural relevance and emotional resonance of circular buildings [22,23].

The reuse of decommissioned building materials remains one of the most technically unresolved challenges in circular architecture [24]. While the circular economy has established strong theoretical frameworks for material recovery, practical implementation in architectural design is constrained by the irregularity, unpredictability, and non-standard geometry of decommissioned components. Existing digital construction workflows are largely optimised for standardised industrial materials and do not adequately address how heterogeneous decommissioned elements can be systematically digitised, recomposed, and assembled at architectural scale. Recent advances in computational design, material digitisation, and extended reality (XR) technologies suggest new possibilities for bridging this gap. However, current research tends to isolate these domains: material databases lack integration with generative design systems; algorithmic design methods assume idealised geometries; and XR assembly tools are rarely tested within circular construction workflows. As a result, there is no unified cyber-physical framework capable of translating irregular decommissioned materials into reproducible, scalable architectural systems.

Here, this research proposed a Resources Availability Driven Design (RADD) framework comprising three main modules for the digital and physical recorded workflow of materials and elements. For material digitisation and selection, we created a material reclamation system (MRS), structural typological optimisation and assessment (STOA) and Extended Reality-assisted for (dis-)assembly (XRAA). More details, In MRS, we developing a workflow that is real-time and fast at gathering point clouds and reconstructing a 3D model in the database library, also measuring the dimension, position, type, joinery method and circularity in material passports; Also, it leverages Wave Function Collapse (WFC) as a generative algorithm, embedding real-world evidence and rationalising insights to extract and refine rules and structural grammar from physical model-making and assemble tests (e.g., 2820 modules resolved in 729 observations). For ease of (dis-)assembly design, the Extended Reality-Assisted for (Dis-)assembly (XRAA) module introduces a novel XR-assisted assembly method. This method prioritises tectonic interlocking over traditional layering, enabling non-experts to construct with precision.

The RADD framework was evaluated using a mixed-methods approach focusing on three specific criteria: a) Resource Availability, tested using stone cladding and timber from the M&S flagship store (Oxford Street, London) to evaluate local reuse potential; b) Design Scalability, Iteratively tested from 1:1 furniture prototypes to a medium-scale pavilion installation, demonstrating the system's ability to handle structural expansion; c) Algorithmic Feasibility, Measured by the WFC solver’s ability to consistently converge on valid solutions within a solutions space of 2820 modules; d) User Accessibility, Informal user testing (observational studies of non-experts) focused on the intuitiveness of MR-guided assembly sequences and error rates in manual alignment.

This research is driven by the need to transition the AEC sector from a linear take-make-waste model to a circular, resource-driven paradigm. This research aims to address identified gaps and develop feasible digital-to-physical workflows for upcycled construction. The primary goal of this research is to investigate how the RADD framework can facilitate efficient data transformation and assist designers in upcycling workflows, particularly in creating pixellated classical designs at various scales. To answer the primary research question, the following sub-questions (SQ) and objectives (O) will be addressed: (Table 1)

Table 1
Research sub-questions and objectives.

Sub-Question (SQ)	Objective (O)
SQ1: How can real-time material data recording and 3D reconstruction be effectively integrated into a digital library to support circular design?	O1: To develop a Material Reclamation System (MRS) that automates the gathering of point clouds and material passports (dimensions, joinery, and circularity) for a real-time database.
SQ2: How can generative algorithms, such as Wave Function Collapse (WFC), be used to translate physical tectonic constraints into digital design rules?	O2: To formulate a Structural Typological Optimisation and Assessment (STOA) module that leverages WFC to extract structural grammars from physical assembly tests.
SQ3: In what ways can Extended Reality (XR) assist non-specialised users in the complex assembly and disassembly of interlocking tectonic systems?	O3: To implement an Extended Reality-Assisted for (Dis-)assembly (XRAA) method that prioritises spatial interlocking and tectonic principles for intuitive construction.
SQ4: How does the iterative application of the RADD framework perform across varying design scales, from furniture to urban installations?	O4: To validate the framework through iterative prototyping, demonstrating the scalability and aesthetic potential of pixellated classical designs in real-world environments.

The aforementioned research sub-questions and objectives are systematically aligned through the three core modules of the RADD framework and its phased methodological workflow. Specifically, to address the integration of material data (SQ1/O1), the Material Reclamation System (MRS) was developed to transform irregular physical salvage into traceable digital assets via real-time 3D scanning and digital 'Material Passports'. To facilitate the automated translation of tectonic logic (SQ2/O2), the Structural Typological Optimisation and Assessment (STOA) module employs the Wave Function Collapse (WFC) algorithm to encode physical assembly constraints into generative design rules, enabling heterogeneous materials to aggregate according to rigorous structural grammars. Regarding the enhancement of user agency (SQ3/O3), the Extended Reality-Assisted Assembly (XRAA) module utilises Mixed Reality (MR) to mitigate the complexity of intricate construction, allowing non-specialist users to achieve precision in adhesive-free interlocking systems. Finally, through the 'Latent RADD-ical' case study—which serves as a longitudinal empirical validation (O4) traversing the entire process—the framework was tested via iterative prototyping ranging from 1:1 furniture components to a medium-scale pavilion. This validation demonstrates the scalability and aesthetic potential of the RADD framework in addressing real-world architectural challenges, successfully converting material unpredictability into digital design opportunities and providing a viable technical trajectory for circular construction practices.

The remainder of this paper is organised as follows: Section 2 reviews the state-of-the-art in material reuse and computational workflows. Section 3 details the technical architecture of the RADD modules. Section 4 validates the framework through a 1:1 scale case study using materials from a decommissioned retail flagship store. Section 5 discusses the scalability of the approach and outlines future research directions.

2. Literature review from material spolia to cyber-physical systems

2.1. Digital spolia in the circular economy

The imperative for circularity within the Architecture, Engineering, and Construction (AEC) sector has transcended mere waste management, evolving into a sophisticated discourse on material longevity and value retention [25,26]. Central to this shift is the concept of 'Spolia'—the historical practice of repurposing building elements from defunct structures into new architectural contexts (Figs. 1 and 2). While traditional spolia was often driven by pragmatic necessity or ideological symbolism [27], its modern counterpart, 'Digital Spolia', necessitates a rigorous computational framework to manage the inherent heterogeneity of salvaged materials [28].

Fig. 1. Frankish Castle in Paros, Greece [29]. a. [FRANKISH CASTLE, PAROS] Constructed in 1260 during the Venetian occupation, the Frankish Castle was built atop the remnants of a 6th-century BC temple, utilising spolia—reclaimed stones from dismantled sanctuaries and ancient structures. Its construction demonstrates an adaptive reuse of available materials, driven not by stylistic preference but by the need to build using what was immediately at hand. The dry stone technique, which involves wedging stones together without mortar, further emphasises the response to material limitations and site-specific constraints. This technique was both practical as it accommodates irregular stone shapes, and reversible, allowing for potential future disassembly or repair. In summary, the Frankish Castle embodies a similar methodology to RADD where it was shaped by the availability of salvaged materials, the constraints of the site, and the novel method of reuse, resulting in a design that is contextually responsive, materially efficient, and historically layered. b. Process of Construction in relation to Resource Availability Driven Design (RADD): Surveying Existing Ruins + Material Stock - Selective Deconstruction - Sorting + Adapting Components - Dry Stone Const. Technique - Design Outcomes as Byproduct of Material Logic. The Design Language, the eclectic visual language of the castle, an irregular patchwork of classical and regular stone elements, was a direct result of material-led design, as it is not a stylistic intention. This aligns with the RADD principle that form emerges from resource constraints and availability, not from predetermined design ideals.

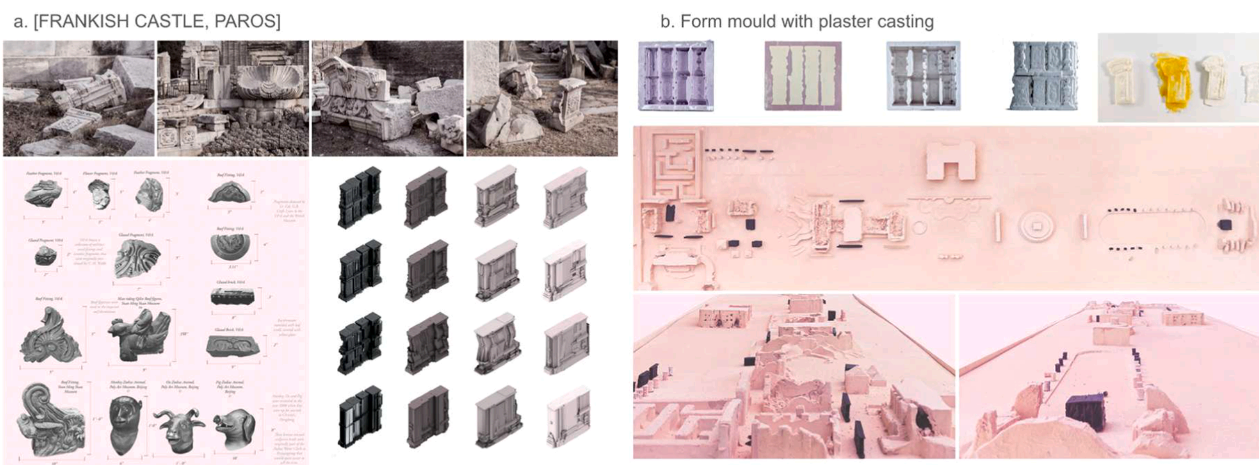

Fig. 2. Precedential studies: Speculative Spolia from Amelia Gan's thesis, "Speculative Spoliation [28]. Amelia Gan's thesis, "Speculative Spoliation," explores the concept of spolia-artefacts or materials with ingrained place identities repurposed into new architectural contexts. Her project aims to reimagine how spolias carry meaning across time through a series of digital experiments. Material catalogue: She uses 30 scanning, photogrammetry, and digital modelling to document, fragment, and reassemble architectural remnants. These tools allow her to experiment with different spatial and material configurations, creating new compositions that blur the line between past and present. The digital process enables precise manipulation of artifacts, allowing them to be layered, stacked, or infilled into contemporary designs while preserving their historical identity.

Current Circular Economy (CE) frameworks in architecture predominantly advocate for 'Design for Disassembly' (DfD) [15]. However, these top-down approaches often assume the use of pristine, standardised components. The true challenge for a regenerative AEC sector lies in 'Design from Availability'—a bottom-up paradigm in which the design process is dictated by the stochastic nature of reclaimed resources rather than by idealised geometries.

2.2. Digital material passports and the challenge of stochastic geometries

A fundamental barrier to the widespread adoption of material reuse is the 'information gap' between decommissioned sites and new construction projects. Material Passports (MPs) have emerged as a critical tool for documenting the provenance, dimensions, and circularity potential of building components. Recent studies [13] have demonstrated the efficacy of BIM-integrated MPs in tracking standardised industrial elements such as structural steel beams or precast concrete panels.

Despite these advancements, existing MP frameworks remain significantly limited when confronted with non-standardised, irregular mineral waste or weathered timber—what this study terms 'stochastic geometries'. Current documentation processes are often manual and static, failing to capture the real-time geometric complexity required for high-precision computational assembly [18,30,31]. There is a persistent technological void regarding automated workflows that can transition from the physical unpredictability of a demolition site to a high-fidelity 'digital twin' database. The proposed Material Reclamation System (MRS) seeks to bridge this void by integrating real-time 3D scanning with dynamic QR-coded digital passports, thereby establishing a foundational dataset for the reuse of irregular materials Catherine De Wolf, [24].

2.3. Algorithmic aggregation and tectonic logic

The transition from a material database to a viable structural form requires generative logic capable of handling massive combinatorial complexity. In recent years, discrete design and computational aggregation have gained prominence as methods for managing modular complexity. Specifically, the Wave Function Collapse (WFC) algorithm, originally developed for procedural level generation in the gaming industry, has shown potential for architectural application due to its ability to manage local adjacency constraints [32].

However, a critical review of current WFC applications in architecture reveals a persistent 'tectonic disconnect'. Most algorithmic frameworks operate within vacuum-like digital environments where 'modules' are treated as idealised voxels. These models often ignore the physical realities of gravity, material friction, and interlocking joinery. While some research has explored structural optimisation within WFC, few have addressed the translation of tactile, physical tectonic grammar—derived from manual prototyping—into digital design rules. This research identifies a need for a Structural Typological Optimisation and Assessment (STOA) module that encodes physical assembly constraints into the 'collapse' logic of the algorithm, ensuring that generative outputs are not merely formally complex but structurally and constructionally viable.

2.4. Human-Computer interaction and the democratisation of assembly (XRAA)

The final stage of the circular workflow—physical assembly—is frequently the most cost-prohibitive, particularly when dealing with irregular components that require bespoke placement. Traditional masonry restoration or complex interlocking timber construction has historically relied on highly skilled artisans. While industrial robotics has been introduced to automate these processes [31,33], the high capital costs and the need for specialist operators limit its scalability in community-led or low-resource contexts.

Extended Reality (XR) offers a transformative middle ground between manual labour and full automation. By overlaying digital assembly instructions onto the physical workspace, Mixed Reality (MR) can mitigate the cognitive load of interpreting complex 3D puzzles. Although XR has been utilised for precision-guided construction, its application as a tool for 'user agency' in circular construction remains underdeveloped [19]. There is a specific lack of research into how XR can empower non-expert stakeholders to engage with the assembly of 'digital spolia'. The XRAA module addresses this gap by prioritising 'tectonics over layers', using holographic interfaces to guide users through the precision assembly of interlocking, adhesive-free systems.

2.5. Comparative analysis and research positioning

To better position the Resources Availability Driven Design (RADD) framework within the current technological landscape, it is essential to compare it against existing high-performance reuse methodologies. Pioneering institutions such as the *Circular Construction Lab* [15] and *ICD/ITKE* [34] have advanced the logic of material-informed fabrication. However, their workflows often necessitate intensive material pre-processing (subtractive manufacturing) or high-cost robotic infrastructure.

Whilst seminal research by Melenbrink et al. [35] and Knippers et al. [34] demonstrates the sophistication of integrative computational design, their reliance on robotic subtractive manufacturing inevitably incurs substantial material offcuts and significant technical overheads.

The RADD framework addresses these systemic gaps by shifting the operative focus from 'material processing' to 'resource matching' (Table 2). Unlike discrete systems that demand standardised inputs, RADD's STOA module employs the Wave Function Collapse (WFC) algorithm to accommodate the geometric unpredictability of decommissioned materials in their found state. By substituting capital-intensive robotics with XRAA-led manual assembly, this research offers a scalable and socially inclusive pathway for circular construction, ensuring high-fidelity architectural outputs without the prohibitive costs of industrial automation.

The existing body of work establishes a robust foundation for circularity but fails to provide a cohesive, end-to-end workflow for the systematic reuse of irregular building components by diverse stakeholders. The following sections detail the methodology of the RADD framework, designed to address these identified gaps through the integration of material digitisation, algorithmic generation, and assisted assembly, validated through the Latent RADDical case study.

3. Methods and materials

The Resources Availability Driven Design (RADD) framework is conceptualised as a unified cyber-physical system. To ensure scientific rigour and replicability, the methodology is structured as a linear, causal sequence where the outputs of one phase serve as the functional prerequisites for the next. As illustrated in the integrated workflow (see Figs. 3 and 5), the research progresses through five chronological phases (Phases I–V), which are operationally driven by three core technological modules: the Material Reclamation System (MRS), Structural Typological Optimisation and Assessment (STOA), and Extended Reality-Assisted Assembly (XRAA). This phased approach moves from foundational resource identification to advanced prototyping, with continuous consultation from MAKE Architects ensuring the practical relevance of each stage. The relationship between the operational phases and the technical modules is strictly sequential, ensuring that material unpredictability is systematically converted into structural intelligence through the following workflow: Data Ingestion (Phases I & II - MRS Module): The process commences with the MRS, which resolves the information gap in circular construction by digitising physical salvage into a 'Digital Library'. Phase I establishes the foundational context through site and precedent studies (using the M&S Oxford Street building as a case study), while Phase II focuses on the digitisation of these reclaimed resources. Without the granular 'Material Passport' data generated by the MRS in these initial phases, subsequent algorithmic generation remains impossible. Logic Translation (Phases III & IV - STOA Module): These digital assets are subsequently processed by the STOA module, acting as the 'generative engine'. In Phase III, tectonic and craft-based studies are conducted to identify physical assembly constraints, which are then translated in Phase IV into digital adjacency rules using the Wave Function Collapse (WFC) algorithm. This causal link ensures that the generative design is rooted in the physical reality of the material offcuts. Physical Realisation (Phase V - XRAA Module): Finally, the XRAA module bridges the gap between the virtual model and physical construction. Corresponding to Phase V, this stage involves the prototyping and fabrication of architectural elements, such as columns and pavilions. By using Mixed Reality (MR) to overlay digital instructions onto the physical workspace, the XRAA module enables non-expert users to execute the complex, generated designs with precision, thereby validating the end-to-end viability of the RADD framework.

3.1. Case study implementation: the M&S Re-X project

To evaluate the operational feasibility of the RADD framework, this section presents a practical implementation involving decommissioned materials sourced from the Marks & Spencer (M&S) flagship store on Oxford Street, London (Fig. 4). This use case serves as a controlled validation of the three-module system—MRS, STOA, and XRAA—under real-world conditions of geometric unpredictability. By applying the

Table 2
Comparative analysis of the RADD framework against contemporary computational workflows for material reuse.

Category	Methodologies & Representative Cases	Material Strategy	Limitations & Research Gaps	References
Subtractive Manufacturing	Robotic Resurfacing: Milling or sawing irregular timber/stone into standardised geometric forms.	Standardising materials by removing 'uncertain' geometries.	Drawbacks: Results in significant material waste; necessitates high-energy, high-cost industrial robotic infrastructure.	Melenbrink et al. [35]; Knippers et al. [34]
Discrete Digital Systems	Voxel/Modular Assembly: Rule-based tiling based on idealised modules (e.g., WikiHouse).	Reliance on pre-defined, standardised components.	Drawbacks: Low tolerance for native geometric deviations in decommissioned materials; lacks adaptability to non-standard resources.	Retsin [37]; Greenhalgh [27]
Point-Cloud-to-Design	Scanned Log Structures: 3D scanning raw timber to customise every individual connection joint.	Bespoke tectonic logic for each discrete material item.	Drawbacks: computational overhead; connection joints are overly complex and non-generalisable, hindering large-scale convergence.	AA School [38]
RADD Framework (Proposed)	Integrated CPS (MRS + STOA + XRAA): Utilising WFC algorithms to process heterogeneous resources.	Resource-driven: Preserving original geometries with minimal intervention.	Advantages: Circumvents geometric conflicts via algorithmic intelligence; enables precision assembly by non-experts through holographic guidance.	This Study

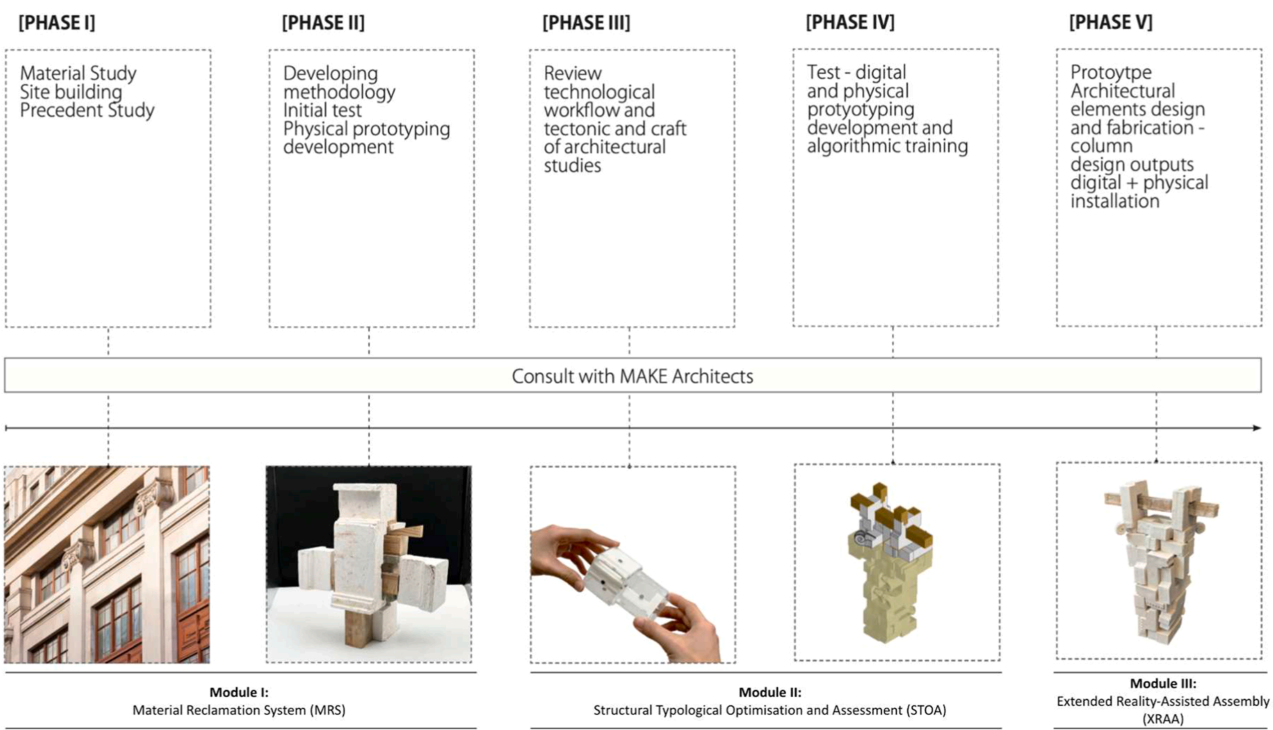

Fig. 3. The RADD framework workflow and the Latent RADDical experimental plan. This diagram illustrates the chronological progression of the case study across five distinct phases (Phases I–V) and explicitly maps them to the three core technological modules of the cyber-physical system: Module I (Material Reclamation System - MRS) drives the data ingestion and material digitization in Phases I and II; Module II (Structural Typological Optimisation and Assessment - STOA) governs the physical tectonic studies and algorithmic generation in Phases III and IV; and Module III (Extended Reality-Assisted Assembly - XRAA) facilitates the physical realization and multi-scale prototyping in Phase V.

Fig. 4. Marks & Spencer Building, Marble Arch, London (crediting: Re:store competition, Save Britain's Heritage).

theoretical logic established in the previous section to these specific heterogeneous resources, the study demonstrates the framework's capacity to translate raw material data into structured architectural output.

Rather than a standalone application, this M&S material stock serves as the empirical input driving the entire cyber-physical pipeline: its raw physical elements are first ingested by the MRS (Section 3.2), translated into computational rules by the STOA (Section 3.3), and finally physically reassembled via XRAA (Section 3.4).

3.2. Module I: material reclamation system (MRS) — digitisation and passports

This research utilises a comprehensive Cyber-Physical System (CPS) architecture, designated as the Resources Availability Driven Design (RADD) framework, to transform unpredictable decommissioned materials into high-precision architectural components. The framework facilitates a closed-loop workflow—ranging from physical resource extraction and digital optimisation to augmented reality-assisted assembly—through three core modules: the Material Reclamation System (MRS), Structural Typological Optimisation and Assessment (STOA), and Extended Reality-Assisted (Dis-)assembly (XRAA) (Fig. 5).

The Material Reclamation System (MRS) serves as a robust cyber-physical interface, facilitating the systematic transition of decommissioned physical elements into high-fidelity digital twins. To ensure high-resolution geometric and textural accuracy, the data acquisition pipeline utilises a hybrid methodology that integrates photogrammetry and real-time point cloud scanning to capture the complex, irregular characteristics of salvaged stone and timber. These digital assets are managed via cloud-based Digital Material Passports (DMPs) that assign unique identification markers, such as QR codes, to each physical component [16] (Fig. 6). More details, MPs are crucial digital tools for promoting circularity and resource efficiency in the AEC sector. They systematically document a product's technical and operational characteristics and track its physical condition throughout its lifecycle, from manufacturing to decommissioning. This comprehensive data facilitates the evaluation of a material's circularity and reusability potential. However, current MPs face significant challenges, often being static, requiring substantial manual input, and lacking standardisation and interoperability across different systems.

To reconcile the inherent heterogeneity of reclaimed materials with the requirements of computational design, a voxel-based segmentation workflow was implemented to normalise components into modular volumetric units. This methodology employs three distinct geometric processing strategies: fragmentation, the extraction of standardised rectangular cuboids, and the selective preservation of original irregular geometry to maintain historical character. Physical processing is executed through a precision track saw setup, specifically configured to minimise mechanical vibration and reduce material offcuts during the transition from salvaged element to modular component.

3.3. Module II: structural typological optimisation and assessment (STOA) — algorithmic generation

The STOA module focuses on the intelligent recomposition of reclaimed materials into coherent architectural systems. By applying digital segmentation techniques, the framework organises materials into modular clusters inspired by the geometric logic of the Soma Cube [36]. This segmentation strategy generates intricate interlocking geometries that are rigorously evaluated for their spatial, structural, and aesthetic properties. Central to this module is the investigation of advanced joinery methods, specifically the adaptation of traditional Japanese techniques and the development of algorithmically generated interlocks. This "tectonic instead of layers" approach prioritises the physical articulation of connections, enabling multi-directional nodes that support structural expansion without the need for adhesives or mechanical fasteners, thereby ensuring material purity and facilitating ease of disassembly.

Procedurally, the STOA module maps heterogeneous material inputs into high-performance structural layouts using the Wave Function Collapse (WFC) algorithm at Rhino-Grasshopper [16]. This generative method utilises a set of deterministic adjacency rules and structural constraints derived directly from physical prototyping experiments [18]. By encoding rigorous spatial and material data into the algorithm's logic, the system effectively transforms material unpredictability into a structured design grammar. The performance of the STOA module was validated by the WFC solver's capacity to achieve convergence within a complex solution space. Specifically, the algorithm successfully resolved a configuration of 2820 modules across 729 observations, demonstrating the computational robustness required to translate irregular

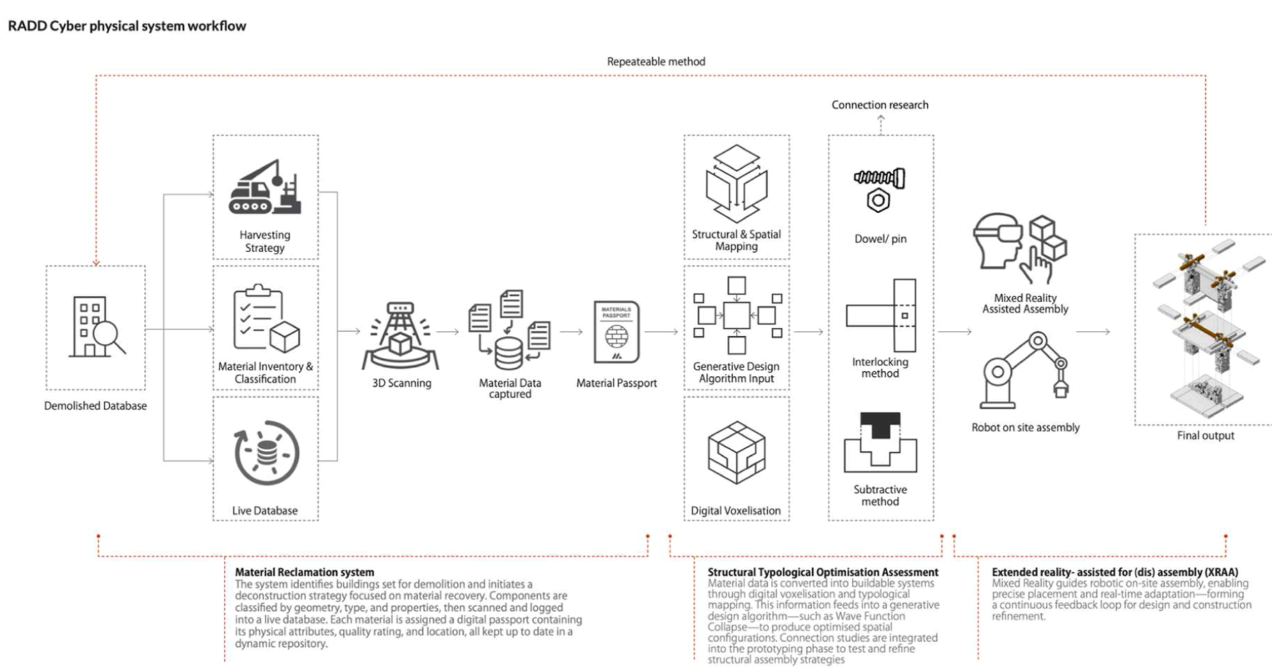

Fig. 5. Resources availability driven design (RADD) framework.

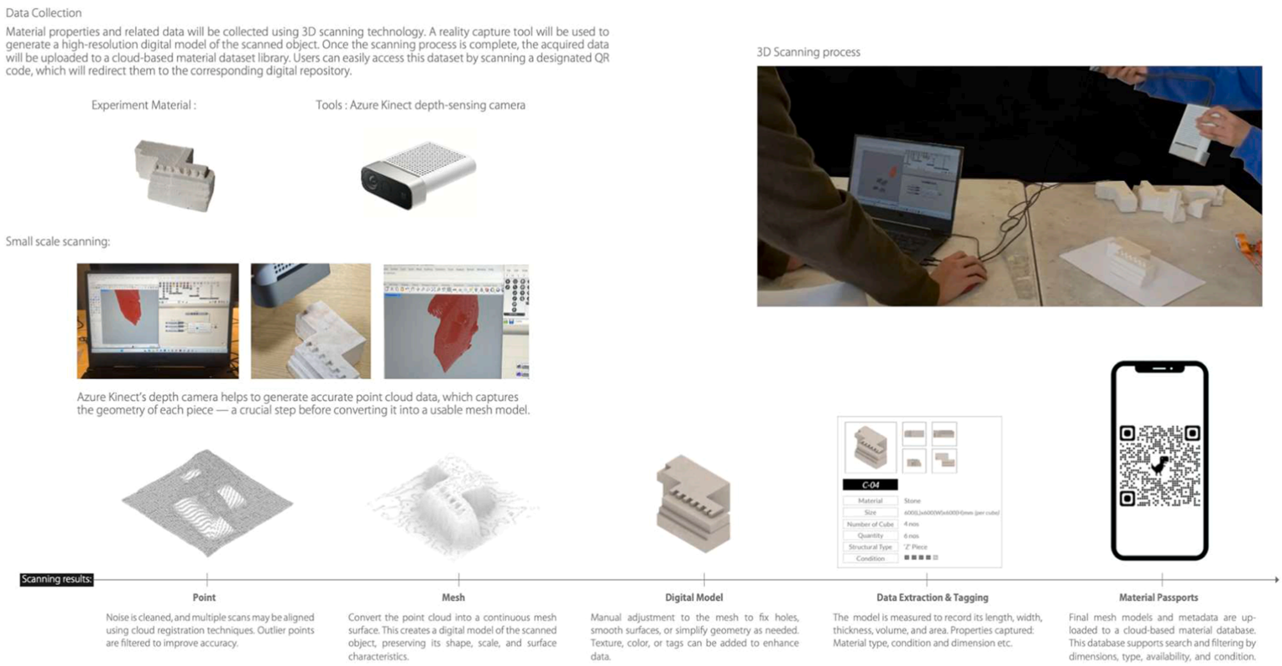

Fig. 6. The data collection workflow for MRS (https://boyuanyu.com/radd-dataset).

reclaimed elements into viable, pixellated classical architectural forms.

3.4. Module III: extended reality-assisted (Dis-)assembly (XRAA) — tectonics and interaction

The Extended Reality-Assisted (Dis-)assembly (XRAA) module serves as a critical bridge between digital design intent and material reality, utilising Fologram and Rhino-GH platform to provide real-time guidance during the physical construction process. By accurately overlaying digital models onto physical prototypes, this stage enables high-precision component alignment and facilitates human-in-the-loop corrective adjustments, which are essential when handling inherently non-standardised and asymmetrical reclaimed materials. The registration method uses a Meta Quest 3 headset integrated with the Fologram interface, with digital holographic overlays anchored to the physical workspace via specific XR markers to ensure spatial accuracy [19]. Central to this module is a novel tectonic grammar characterised by a nested, interlocking system that utilises additive and subtractive design principles to replace traditional adhesives or mechanical fasteners (Fig. 7).

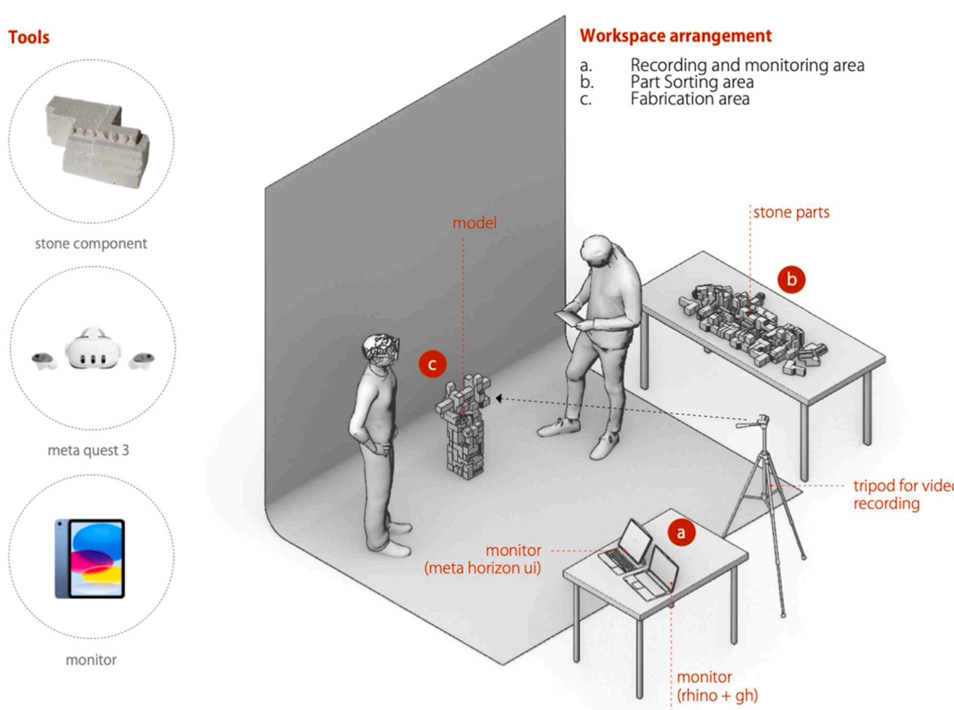

Fig. 7. MR assembly workspace arrangement.

The XRAA module leverages XR technology to democratise the construction process, specifically simplifying the assembly of complex interlocking systems for non-expert users. To evaluate the effectiveness and accessibility of this human-computer collaboration, an informal user evaluation protocol was implemented with non-experts in assembly experiments lasting 10–15 min. Performance metrics for this evaluation focused on assembly precision (alignment tolerances), time-to-completion efficiency, and the interface's intuitive quality. These XR applications demonstrate significant potential for improving skill acquisition and stakeholder collaboration within the architecture, engineering, and construction (AEC) sector. By fostering a seamless integration between digital workflows and material variability, the XRAA module validates a scalable model for algorithmically driven circular design that is both environmentally responsible and accessible to a broader public.

3.5. Evaluation criteria and performance metrics

To systematically validate the effectiveness of the RADD framework in bridging material unpredictability with precise computational design, a structured evaluation protocol was established. The system's performance is assessed across four critical dimensions, each corresponding to a specific operational phase of the cyber-physical pipeline (Table 3).

3.5.1. Resource availability - module I (MRS) testing

The MRS is evaluated through the system's capacity to translate raw, irregular physical components into structured, machine-readable datasets required for algorithmic design. And validate the capability of the hybrid scanning workflow (Azure Kinect and photogrammetry) to capture and categorise heterogeneous materials into a functional digital material passport database.

3.5.1.1. Components capacity. The total number of viable modular components successfully catalogued and the diversity of topological categories generated.

3.5.1.2. Time efficiency. The average temporal cost: scan time and mesh processing time, required to convert a physical element into a usable digital twin.

3.5.2. Design scalability - module II (STOA) testing

The framework's structural scalability is qualitatively evaluated by observing the transition of the nested interlocking mechanism across different aggregation scales. This validates the system's capacity to manage complex architectural configurations rather than being limited to isolated, monolithic prototypes.

3.5.2.1. Structural adaptability. Evaluating the ability of the self-restricting nested interlocking mechanism to maintain stability when scaling from a single component node to a medium-scale spatial arrangement.

3.5.2.2. Multi-material integration. Assessing the capacity of the algorithmic design system to successfully incorporate and coordinate diverse reclaimed inputs—such as load-bearing stone walls, timber rafters, and reclaimed window roofing—into a cohesive building system.

3.5.3. Algorithmic feasibility - module II (STOA) testing

The STOA module is evaluated based on the Wave Function Collapse (WFC) solver's capacity to process non-standard geometries and translate physical tectonic constraints into viable digital assemblies. This assesses the computational robustness and efficiency of the generative algorithm.

3.5.3.1. Rule complexity. Evaluating the total number of adjacency constraints generated from translating empirical physical interlocking tests into deterministic WFC logic.

3.5.3.2. Solver efficiency & stability. Measuring the computational solution time and the number of observations required by the solver to reliably reach a 100% deterministic outcome across varying scales (e.g., comparing a pilot-scale cluster against a large-scale pavilion) without collapsing into error states.

3.5.4. Assembly precision and user accessibility - module III (XRAA) testing

The XRAA workflow is evaluated through its practical implementation during the physical construction phase, with a focus on human-computer interaction. This validates whether Extended Reality (XR) guidance can effectively democratise the assembly of complex interlocking systems for non-expert participants with no prior masonry experience.

3.5.4.1. Learning curve & efficiency. Measuring the intuitiveness of the

Table 3
Summary of the RADD framework evaluation criteria and performance metrics.

Evaluation Criteria	Performance Indicators, Measurement & Scope	Corresponding Module
Resource Availability	**Components capacity** Measuring the total number of viable modular components successfully catalogued and the diversity of topological categories generated. **Time efficiency** Calculating the average temporal cost (scan time and mesh processing time) required to convert a physical element into a usable digital twin.	Module I (MRS)
Design Scalability	**Structural adaptability** Evaluating the ability of the self-restricting nested interlocking mechanism to maintain stability, scaling from a single component node to a medium-scale spatial arrangement. **Multi-material integration** Assessing the system's capacity to successfully incorporate and coordinate diverse reclaimed inputs (e.g., load-bearing stone walls, timber rafters, and window roofing) into a cohesive building system.	Module II (STOA)
Algorithmic Feasibility	**Rule complexity** Counting the total number of adjacency constraints generated from translating empirical physical interlocking tests into deterministic WFC logic. **Solver efficiency & stability** Measuring the computational solution time and tracking the required observations for the solver to consistently reach a deterministic outcome across varying scales without error collapses.	Module II (STOA)
Assembly Precision & User Accessibility	**Learning curve & efficiency** Measuring the intuitiveness of the XR interface and recording the average temporal cost for users to identify, retrieve, and accurately place complex interlocking segments. **Error analysis** Monitoring the spatial accuracy of the digital overlay, specifically assessing the occurrence, magnitude, and impact of holographic drift resulting from marker occlusion or environmental lighting.	Module III (XRAA)

XR interface and recording the average temporal cost required for users to identify, retrieve, and accurately place complex interlocking segments.

3.5.4.2. Error analysis. Monitoring the spatial accuracy of the digital overlay relative to the physical environment, specifically assessing the occurrence, magnitude, and impact of holographic drift resulting from marker occlusion or environmental lighting during dynamic motion.

4. Results

The following results are structured to mirror the five chronological phases and three core technological modules of the RADD framework. First, Section 4.1 details the outcomes of the data ingestion and material digitisation process, corresponding to Phases I and II under the Material Reclamation System (MRS) module. Next, Section 4.2 presents the findings from the physical tectonic studies (Phase III) and their subsequent algorithmic translation into generative design rules (Phase IV), which constitute the Structural Typological Optimisation and Assessment (STOA) module. Following this, Sections 4.3 and 4.4 outline the physical realisation and structural scalability of the framework, representing Phase V's multi-scale prototyping efforts driven by the Extended Reality-Assisted Assembly (XRAA) module. Finally, Section 4.5 provides a comprehensive evaluation of the system's performance across all phases and criteria.

4.1. Phases I & II: data ingestion and material library (MRS)

The application of the digitisation framework produced a comprehensive inventory of materials collected from the M&S building. This collection comprises a heterogeneous mix of structural and ornamental elements, specifically categorised into volumetric stone elements (Series C), façade components (Series F), and steel-framed glazing units (Series W) (Fig. 8). Unlike standardised manufacturing inputs, the resulting dataset captures the inherent geometric variability of the available resources, establishing a foundation for circular reuse logic.

The realised Material Passport system functions as an operational cloud-based library (Fig. 8). By integrating physical tags and digital twins, the database stores critical metadata for each unique element, including precise dimensions, material composition, source location, and proposed reuse logic. This online repository bridges physical constraints and digital design, providing a searchable, open-access interface that visualises the as-found conditions of the reclaimed stock.

4.2. Phases III & IV: algorithmic convergence and generative design (STOA)

4.2.1. Segmentation results

Building directly upon the digital inventory of the decommissioned M&S materials established in Phase II, the STOA module translates these specific irregular stone geometries into computable assets. To reconcile the native heterogeneity of the M&S stone with the strict adjacency requirements of the WFC algorithm, a voxel-based segmentation

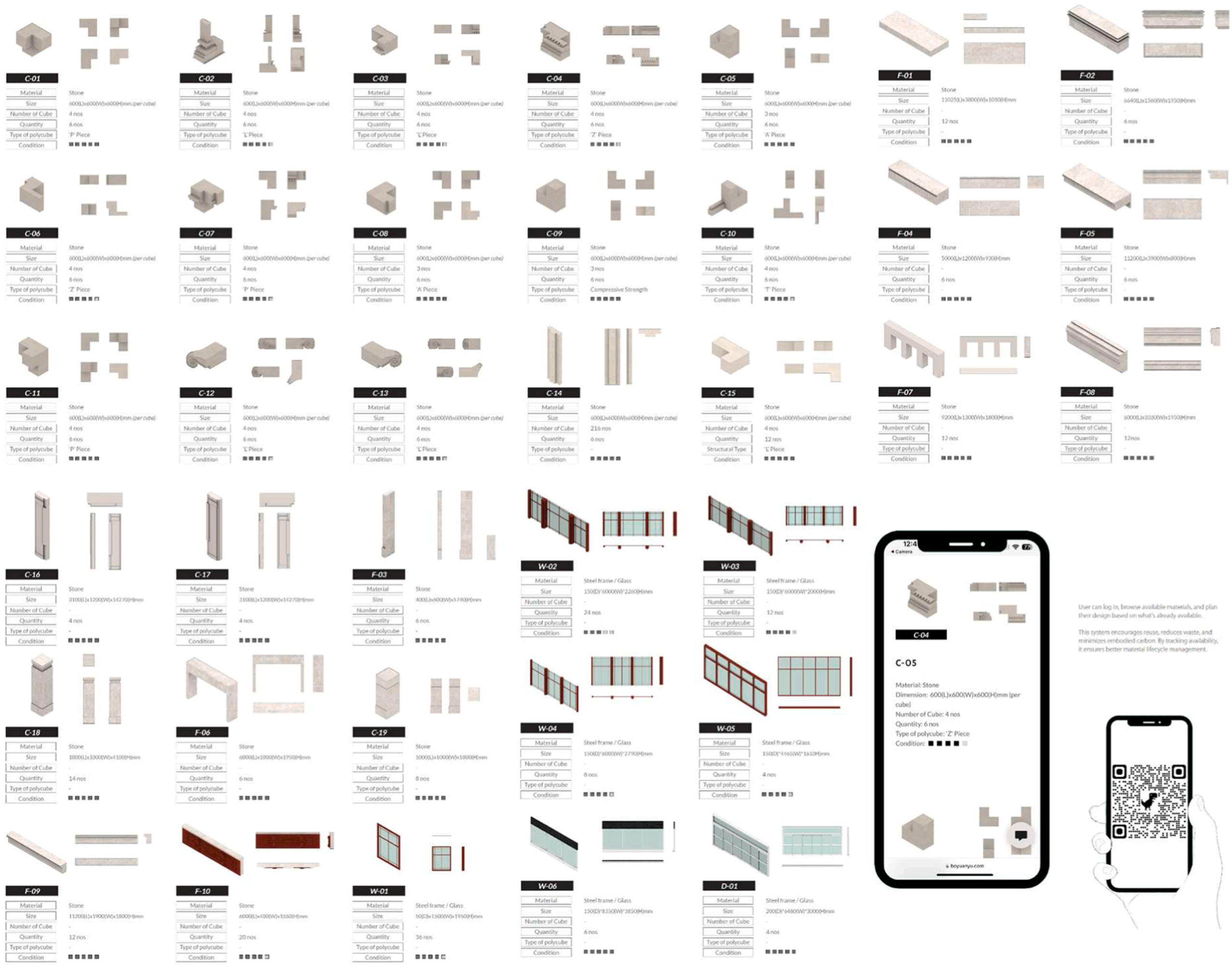

Fig. 8. Open access online material database library, and the material passport system (https://boyuanyu.com/radd-dataset).

workflow was implemented. This process yielded a categorised inventory of modular units, distinct in their geometric fidelity and reuse potential." The implementation of the voxel-based segmentation workflow yielded a categorised inventory of modular units, distinct in their geometric fidelity and reuse potential (Fig. 9). The standardised cuboid strategy successfully produced the Series-C (Volumetric Units), a collection of 600 mm voxel-compatible elements classified into specific polycube typologies (e.g., 'P', 'Z', 'T' pieces). Conversely, the selective preservation strategy resulted in the Series-F (Façade Elements), which retained the original planar dimensions of large stone panels to maintain historical surface character. The fragmentation strategy was instrumental in defining the irregular boundaries of the polycubes, translating raw material breaks into digitally recognised geometric connectors.

4.2.2. Physical prototyping

The physical prototyping phase produced a tectonic grammar derived from casting craft models. The empirical findings from these experiments were translated into adjacency rules and constraints to guide the Wave Function Collapse (WFC) generative algorithm (Fig. 10).

4.2.3. Interlocking logic

The Soma Cube puzzle was used as a controlled system to establish a foundational tectonic grammar. From the standardised Series-C inventory, the 'L' (Piece 2) and 'Z' (Piece 4) polycubes were isolated for detailed structural testing due to their asymmetrical protrusions. Physical analysis of these components revealed three distinct interlocking behaviours, categorised by their kinematic constraints:

- Surface Contact (Unconstrained): The physical models demonstrated that this connection, where the flat faces of the 'L' and 'Z' pieces align, is stable primarily under gravitational compression. It offers no mechanical resistance to shear or tensile forces, allowing components to slide freely against one another.
- Corner-to-Corner (Partial Lock): The experiments showed that this configuration, in which the corner of one piece hooks into a corresponding void on the other, effectively prevents movement along one or two axes, offering resistance to shear forces in specific directions. However, the connection is only partial, as the components can still be separated along a single, unconstrained vector.
- Nested Interlock (Fully Constrained) (Figs. 11 and 12): The physical models confirmed that this arrangement, achieved by nesting multiple pairs of 'L' and 'Z' pieces, prevents movement along all axes, creating a fully constrained and self-restricting assembly. Its key characteristic is a path-dependent assembly sequence; pieces must be slid into place in a specific order, which in turn locks the entire structure without requiring any adhesives or external fasteners.

4.2.4. Algorithmic translation and validation

These physical behaviours were codified into a complex set of 39,332 adjacency rules for the WFC algorithm. To prioritise structural integrity, the nested interlock configuration was assigned the highest probability weight, biasing the solver towards configurations that maximise self-supporting connections.

In initial testing (Fig. 13a), the algorithm successfully resolved a cluster of 512 modules integrated with 12 timber subtractive components. The solver achieved a deterministic state within 50.8 s, requiring only 230 observations to satisfy the adjacency constraints. Subsequent upscaling (Fig. 13b) demonstrated the system's scalability. Expanding the solution space to 2820 modules with a slot count of 5220, the solver maintained logical consistency. Despite the increased complexity, it successfully computed a valid, deterministic architectural form in 168 s, utilising 729 observations to resolve the global geometry.

4.3. Phase V: empirical validation and multi-scale prototyping (XRAA)

To empirically validate the Mixed Reality (MR) guided assembly process before manipulating the heavy, actual M&S stone components, a surrogate rapid-prototyping approach was employed. A column prototype was assembled using high-precision plaster casts to simulate the exact geometric interlocks derived from the M&S digital library. This phase yielded results on the efficacy of the digital guidance system and highlighted practical challenges in the cyber-physical workflow. A column prototype was assembled to test the MR-assisted fabrication process. This phase yielded results on the efficacy of the digital guidance system and highlighted practical challenges in the cyber-physical workflow. The process, bridging CNC milling for positive form generation and alginate moulding for negative impressions, successfully produced a kit of high-precision plaster components (Fig. 14).

The system successfully guided the construction of the column through a dynamic visualisation overlay. The interface's colour-coded logic—distinguishing active components (highlighted in blue) from secured elements (rendered in orange)—reduced cognitive load for the

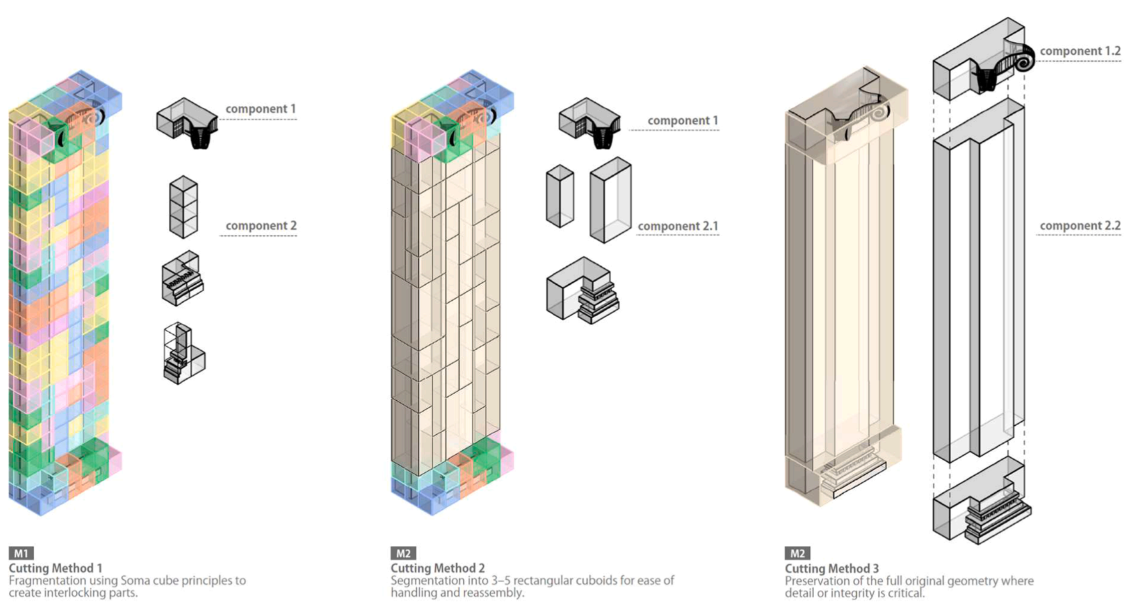

Fig. 9. Segmentation method, adapting voxelisation to material and design needs.

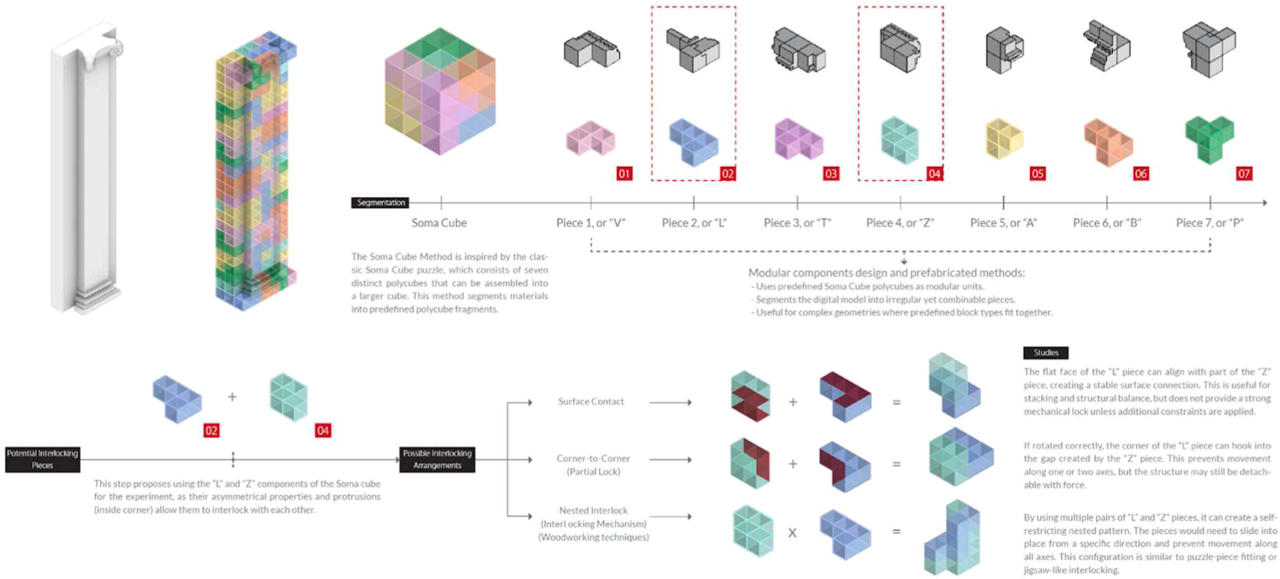

Fig. 10. Translation of physical tectonic grammar into algorithmic constraints.

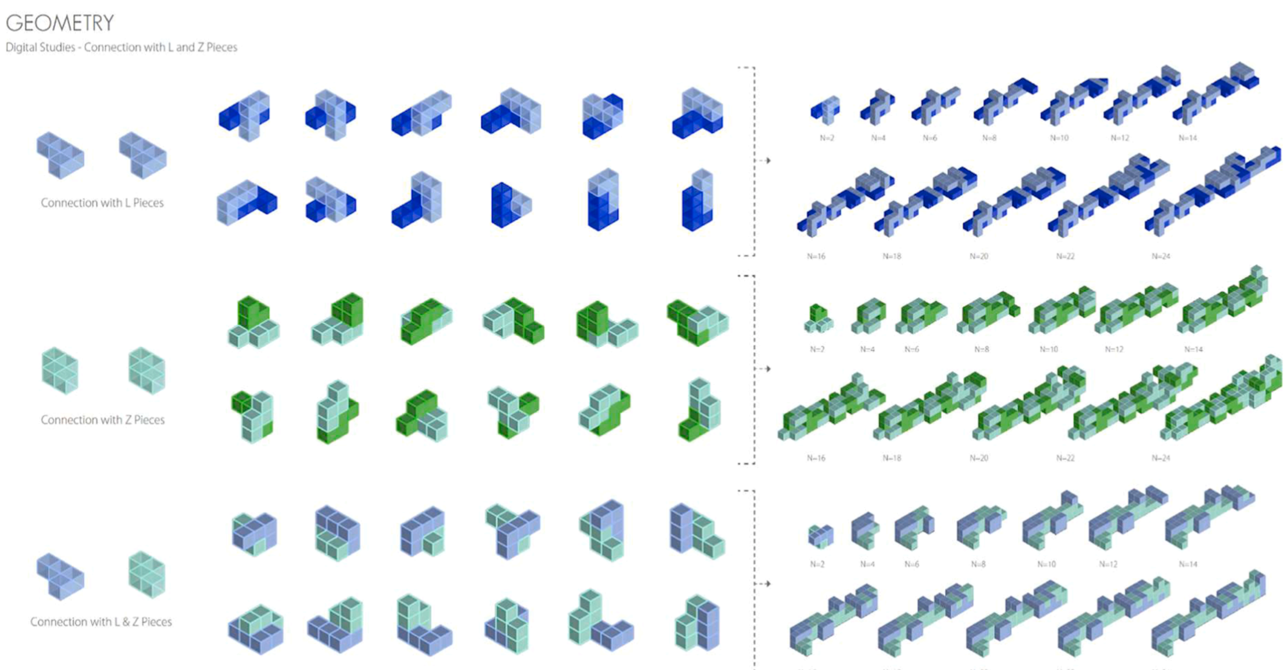

Fig. 11. Digital studies of nesting interlock of "L" and "Z" pieces.

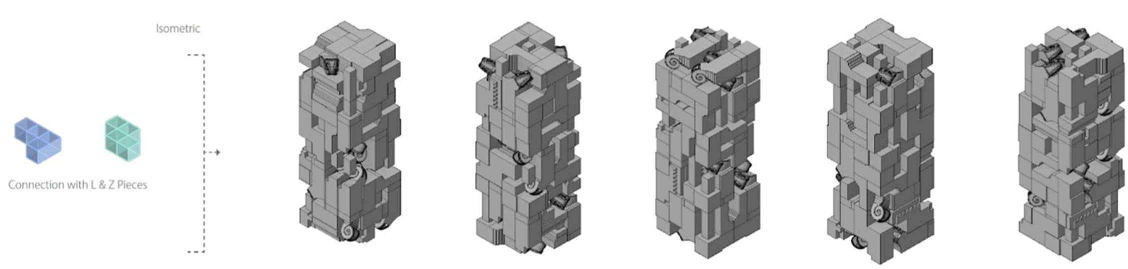

Fig. 12. Aggregation WFC studies using "L" and "Z" pieces derived from nested interlock methods.

user, enabling accurate placement of asymmetrical blocks without reference to 2D drawings (Fig. 15, step 2–3). The integration of the User

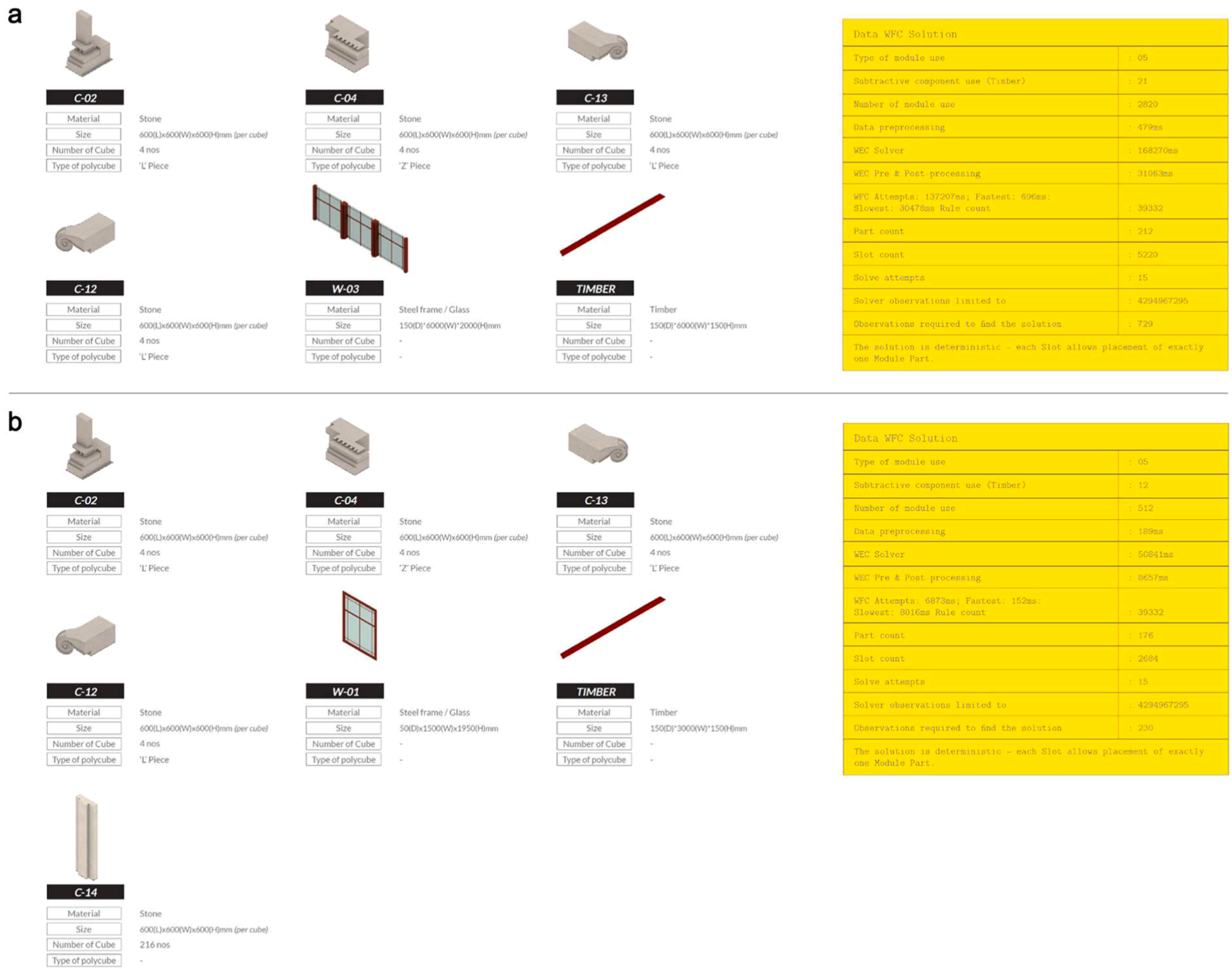

Fig. 13. a) Material data and WFC data output for the pilot study (512 modules), showing a solution time of 50,841 ms and 230 observations; b) Material data and WFC data output for the scaled aggregation (2820 modules), validating solver stability with 729 observations.

Fig. 14. Fabrication process. (1) CNC cutting is employed to produce the required geometry for mould preparation. (2–4) Alginate is used as an alternative moulding material to accelerate production. (5) A Vaseline layer is applied to prevent adhesion before plaster is poured into the alginate mould. (6) After setting, the plaster prototype is removed. (7–8) Alginate moulds yield prototypes with greater precision and surface quality compared to polystyrene forms. (9) The components are then prepared for assembly (Supplementary Video 01).

Interface (UI) enabled real-time sequence adjustments, confirming that digital guidance can adapt to the variability of manual construction speeds.

4.4. Phase V (Continued): structural expansion and scalability

4.4.1. Node formation

Building upon the validation of physical interlocking mechanisms, the research expanded the WFC configuration methodology to generate macro-scale structural components. The critical enabler for this scaling

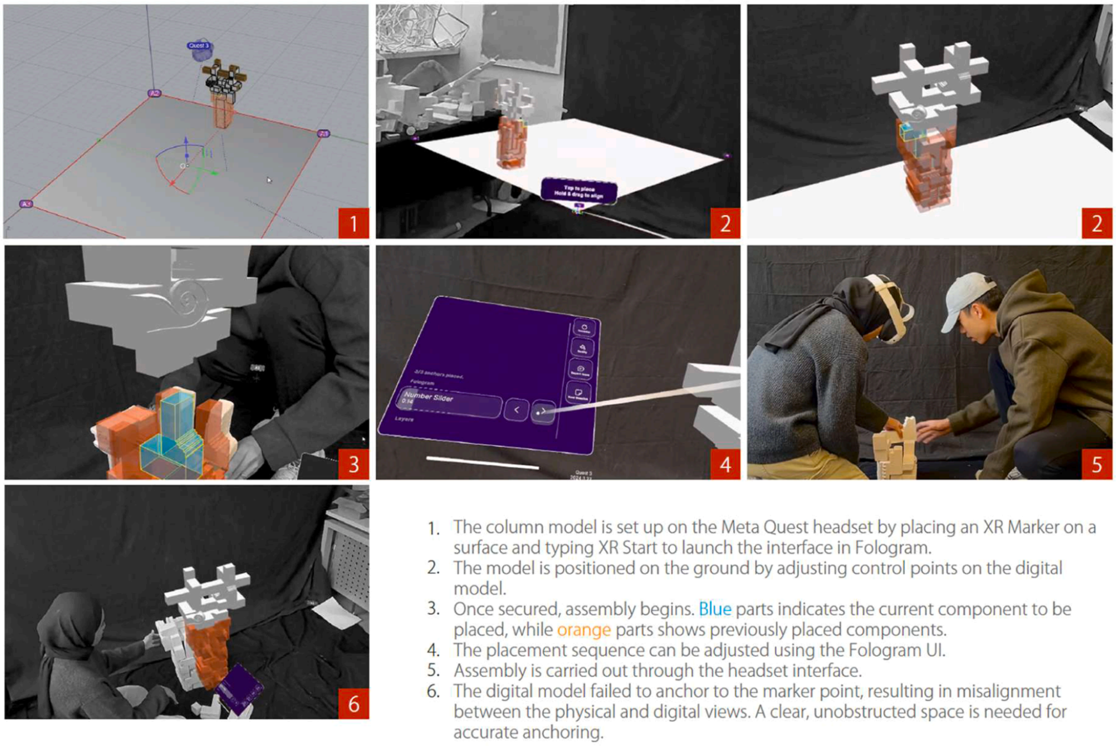

Fig. 15. Mixed reality assembly process.

process is the development of the node. Each node functions as a highly constrained junction point composed of paired interlocking elements that dictate structural and spatial continuity across a three-dimensional grid. Fig. 16 reveals that these nodes facilitate multi-directional articulation—specifically through L-axial vertical joints for column generation and X-perpendicular joints for integrating horizontal supports. Crucially, the system introduces linear timber elements as locking mechanisms within these voxelized nodes, binding disparate stone clusters into coherent generative blocks that can interconnect adaptively.

4.4.2. *Scalability from component to community architecture*

The scalability of this tectonic grammar is demonstrated through the algorithmic generation of defined architectural spaces. By strictly adhering to predefined assembly rules, multiple component pairs are aggregated into a self-restricting, nested interlocking system. A primary output of this logic is the diagonal configuration, where modular components are rotated 45 degrees (Fig. 17). In this arrangement, each piece slides into place along a specific vector, progressively forming a structurally stable diagonal wall. Crucially, the bill of materials (BOM) for these scaled configurations is strictly constrained by the actual resource

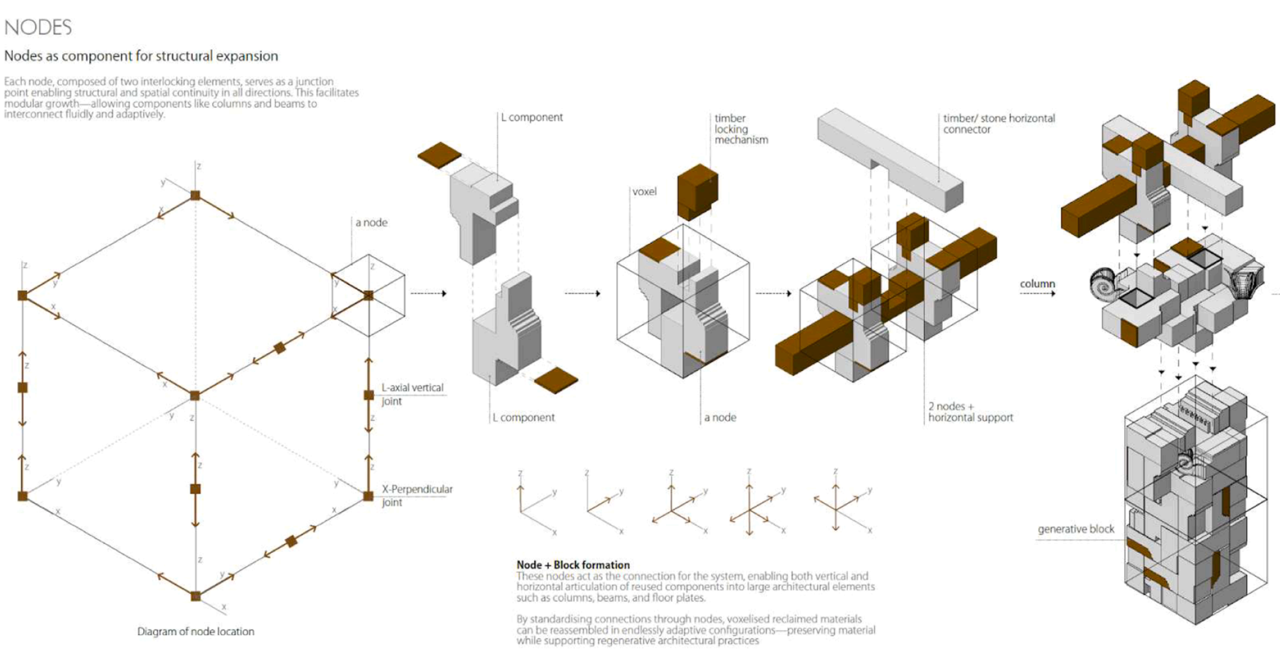

Fig. 16. Formation of components into nodes as structural expansion.

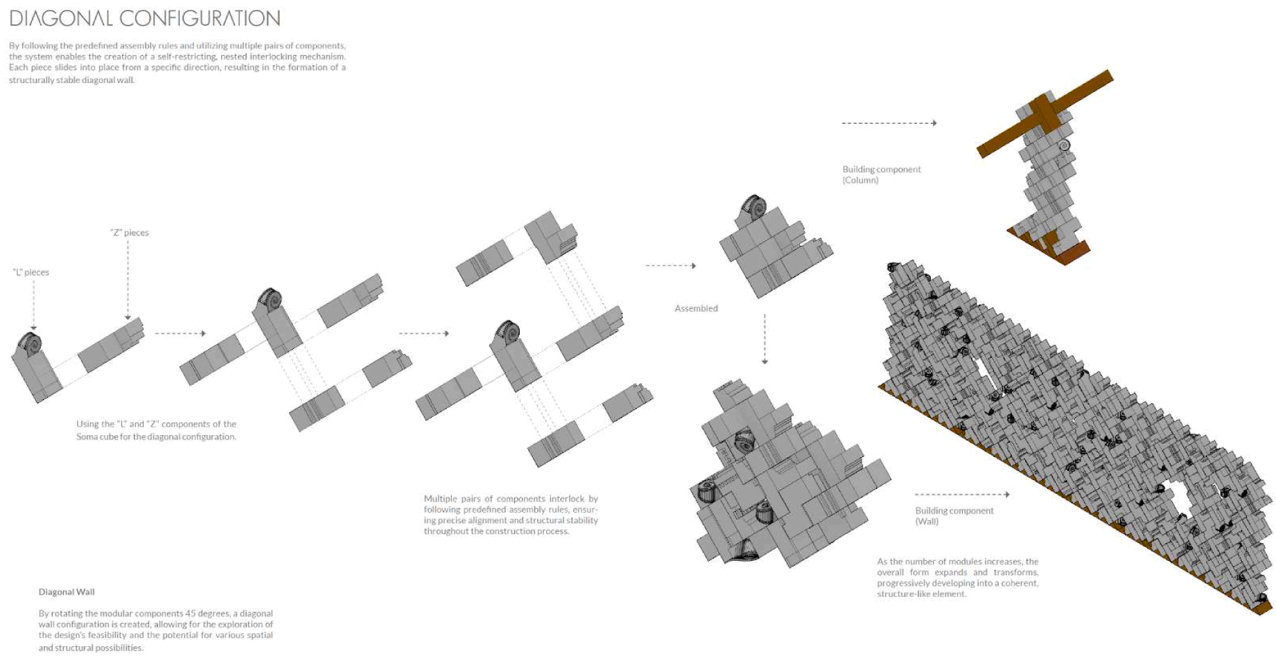

Fig. 17. Diagonal configuration.

availability mapped from the M&S flagship store. By strictly adhering to predefined assembly rules, multiple surrogate component pairs are aggregated into a self-restricting, nested interlocking system. A primary output of this logic is the diagonal configuration, where modular components are rotated 45 degrees, proving that the specific geometric typologies salvaged from the site can generate stable, complex architectural forms.

As the module count increases, these diagonal walls and corresponding columns enclose defined liveable spaces. The final iteration illustrates the system's capacity for complex architectural synthesis: voxelized stone walls provide primary load-bearing capacity, integrated timber rafters span the resulting enclosures, and repurposed reclaimed windows are utilised as modular roofing components. This progression—from a singular 'L' piece to a functional, small-scale wall (Fig. 18), a medium-scale pavilion (Fig. 19), and a large-scale building (Fig. 20)—validates the methodology's potential to transform reclaimed, unpredictable materials into resilient, scalable building systems for community applications.

4.5. *Evaluation of the RADD framework*

To validate the efficacy and practical viability of the RADD cyber-physical framework, the system's outcomes were systematically assessed against the four performance criteria. Together, these findings demonstrate the framework's capability to successfully transform unpredictable reclaimed materials into precise, scalable building systems.

4.5.1. *Resource availability*

The MRS module was evaluated on its capacity to efficiently convert heterogeneous physical waste into a machine-readable digital inventory (Fig. 21a).

4.5.1.1. Components capacity. The hybrid digitisation workflow successfully catalogued 35 unique geometric typologies, comprising >500

Fig. 18. Small-scale wall.

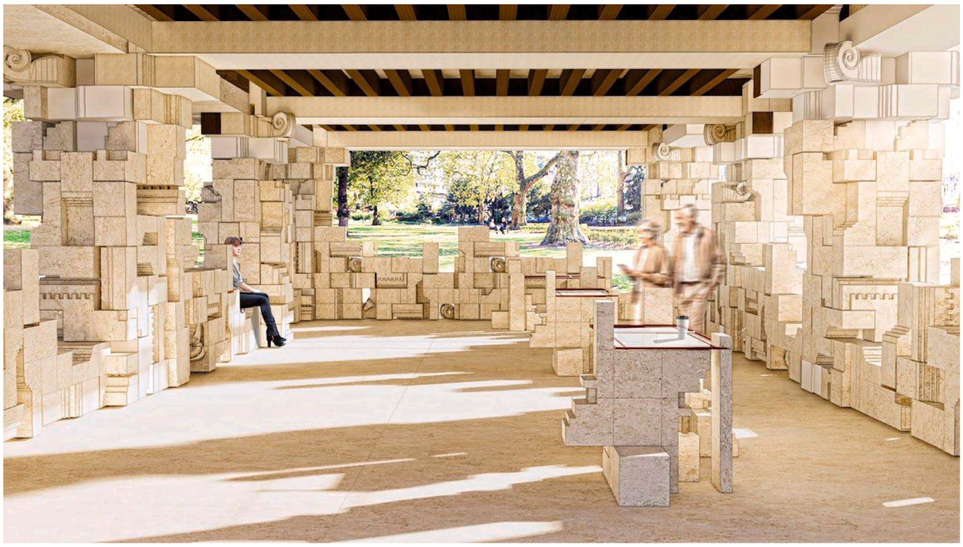

Fig. 19. Medium-scale pavilion.

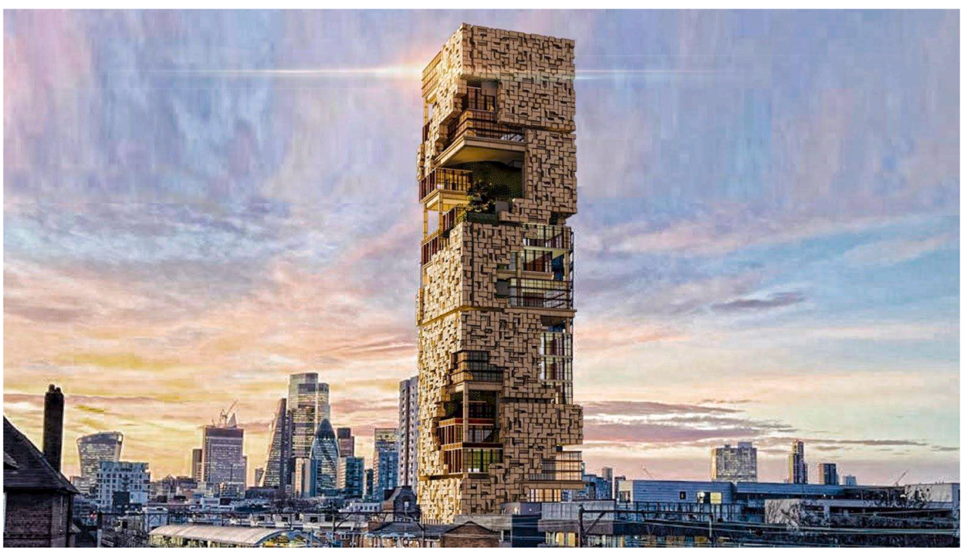

Fig. 20. Large-scale building.

usable components. To support computational design, the dataset was systematically classified into three categories based on reuse potential: volumetric stone for spatial interlocking (Series-C, 19 types), preserved façade panels (Series-F, 10 types), and steel-framed glazing units (Series-W, 6 types).

4.5.1.2. Time efficiency. The average scan and initial mesh generation time per component was recorded at approximately 0.1 to 3 s. This rapid turnaround validates the pipeline's operational viability for scaling to large demolition sites and outperforming highly labour-intensive traditional photogrammetry methods.

4.5.2. Design scalability

The framework's structural scalability was qualitatively validated by the successful generation of progressively more complex architectural configurations (Fig. 21b). This confirmed the system's capacity to manage complex building systems well beyond isolated, monolithic furniture prototypes.

4.5.2.1. Structural adaptability. The successful generation of the diagonal wall configuration validated the system's structural adaptability. The transition from a single "L" piece node to a medium-scale pavilion demonstrates that the nested interlocking mechanism remains self-restricting and stable regardless of the scale of aggregation.

4.5.2.2. Multi-material integration. The algorithmic design system effectively incorporated and coordinated diverse reclaimed inputs into a cohesive building system. The final iteration successfully integrated stone load-bearing walls with timber rafters and repurposed reclaimed windows acting as modular roofing, proving the framework's capacity to manage complex, multi-material spatial formations.

4.5.3. Algorithmic feasibility

The STOA module was evaluated based on the WFC solver's ability to handle complex, non-standard geometric rules and translate physical tectonic constraints into viable digital assemblies (Fig. 21c). The data outputs (Fig. 13) indicate high computational robustness and efficiency:

4.5.3.1. Rule complexity. The translation of empirical physical interlocking tests into deterministic WFC logic generated a highly complex

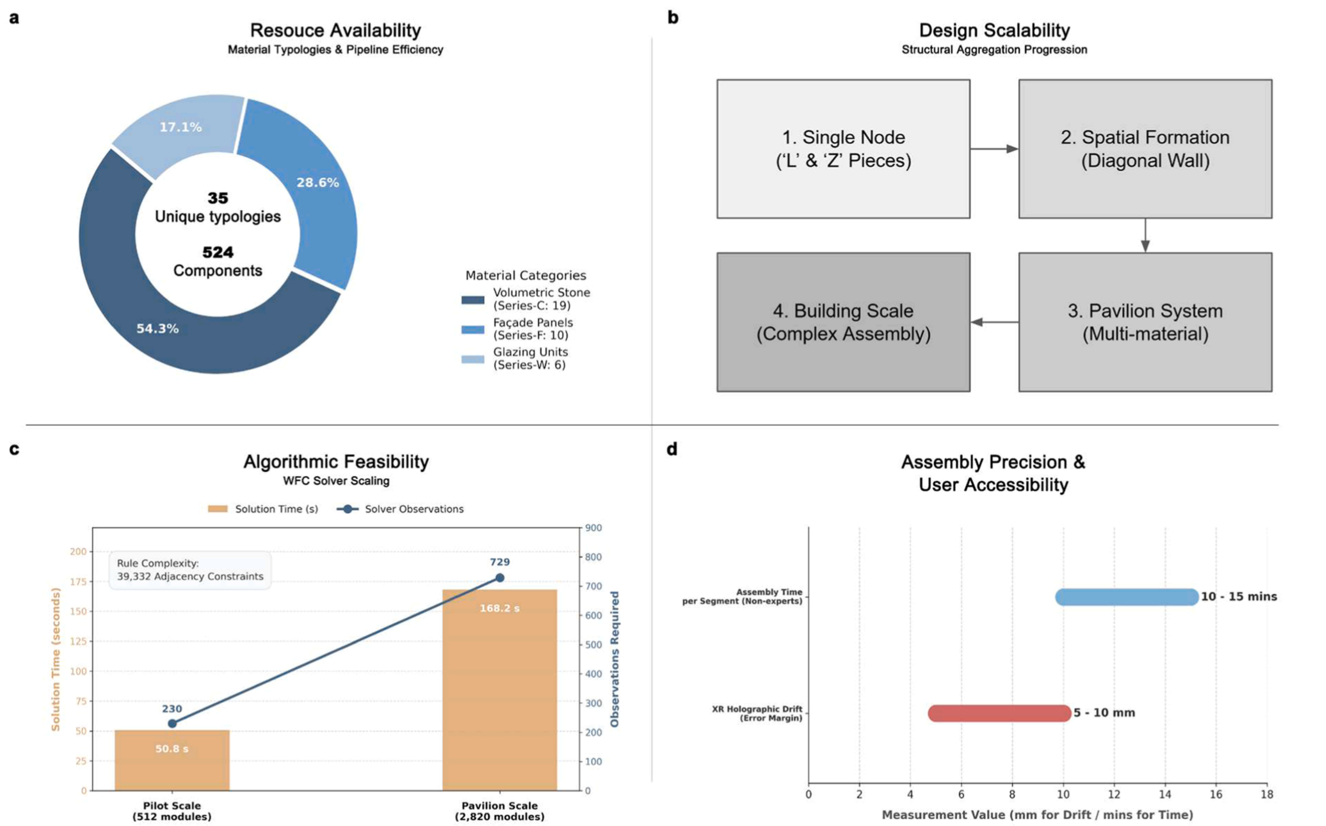

Fig. 21. Evaluation dashboard of the RADD framework. (a) Material inventory breakdown demonstrating resource availability and typological diversity; (b) Diagrammatic progression of design scalability across multiple architectural scales; (c) Computational scaling performance of the WFC solver, validating algorithmic feasibility; and (d) Recorded metrics for XR-assisted assembly precision and user efficiency.

rule set comprising 39,332 adjacency constraints.

4.5.3.2. Solver efficiency & stability. The solver demonstrated computational efficiency and linear scalability across varying scales. For a pilot-scale cluster of 512 modules, the computational solution time was 50.8 s, requiring only 230 observations. When scaled to a large-scale community pavilion context with 2820 modules, the solution time increased to 168.2 s, and the number of observations required increased to 729. In both scenarios, the solver reliably reached a 100% deterministic outcome, demonstrating its ability to efficiently organise irregular reclaimed materials into coherent structures without collapsing into error states.

4.5.4. Assembly precision and user accessibility

The XRAA workflow was evaluated through an assembly workshop involving non-expert participants (students with no prior masonry experience) (Fig. 21d). The evaluation focused on assembly time, cognitive load, and tolerance control.

4.5.4.1. Learning curve & efficiency. Participants using the Fologram interface reported a minimal learning curve and immediately understood the colour-coded placement logic (Blue/Orange). The average time to identify, retrieve, and place a complex interlocking segment was recorded at 10–15 min.

4.5.4.2. Error analysis. The primary limitation observed was holographic drift. Environmental occlusion of QR markers caused digital overlays to misalign by 5–10 mm during dynamic movement. While the human-in-the-loop could manually correct these errors, this highlights a dependency on stable lighting and unobstructed visual fields for Meta Quest 3.

5. Discussion

The findings of this research, derived from the three-stage RADD framework, offer a novel trajectory for integrating irregular building salvage into contemporary digital workflows. By aligning the empirical results of the 'Latent RADDical' case study with the previously identified research gaps, the following sections discuss the systemic implications of the proposed cyber-physical pipeline.

To clarify the conceptual progression of this research, it is essential to align the terminology introduced across the RADD framework. This study operationalizes the theoretical paradigm of 'Design from Availability' —a necessary evolution from top-down 'Design for Disassembly' (DfD) approaches. Within this paradigm, salvaged elements are not merely recycled waste but are treated as 'Spolia', possessing historical and geometric significance. By digitizing these irregular elements, the MRS module converts physical 'stochastic geometries' into 'Digital Spolia'. Ultimately, the STOA and XRAA modules process these digital twins to generate a novel architectural language, defined here as 'pixellated classicism'. The introduction of these distinct terms is therefore necessary to articulate the translation of raw material unpredictability into structured, culturally resonant computational design.

5.1. Data intelligence and the reconstruction of form grammar (MRS & phase II)

The Material Reclamation System (MRS) successfully addressed the 'information gap' in circular construction identified by Honic et al. [13]. The results from Phase II demonstrate that the stochastic geometries of the M&S Oxford Street salvage can be transformed into a searchable, transparent architectural resource.

A critical insight from this digitisation process involves the re-evaluation of data accuracy requirements. Our evaluation reveals that successful algorithmic generation does not strictly necessitate sub-millimetre scanning precision; rather, the baseline depth-sensing accuracy of accessible hardware is sufficient to drive the Wave Function Collapse (WFC) algorithm. By focusing on topological categorisation rather than perfect geometric fidelity, the MRS module effectively lowers the technical barrier to material digitisation. This reframes reuse not as an ad hoc salvage operation, but as a data-rich generative design condition where material history becomes a legible design grammar—a condition we describe as 'pixelated classicism'. In this paradigm, sustainability operates not as an external ethical layer but as an internal generator of architectural language.

5.2. Transformation of tectonic logic: algorithmic feasibility and tectonics (STOA & Phases III-IV)

The STOA module facilitated a fundamental shift from traditional layered construction to interlocking tectonic systems. This transition addresses the 'digital vacuum' in computational aggregation noted by Sandhu et al. [32] by encoding tactile, physical constraints from Phase III into digital adjacency rules in Phase IV.

The adaptation of Japanese joinery principles into computational rule sets demonstrates how ornamental traditions can be reinterpreted as structural systems. Experimental interlocking prototypes confirmed that multi-directional nodes enable spatial expansion without adhesives or fasteners. Ornament is thus translated into structural performance, extending the lifespan of materials through reversible assembly (Fig. 22).

5.3. System performance and threshold evaluation: democratisation of assembly and human-in-the-loop agency (XRAA & Phase V)

The XRAA module validated the final link in the causal chain, bridging the gap between digital idealism and physical reality. While pioneering projects by ICD/ITKE [34] often rely on high-cost robotic infrastructure, our Phase V results suggest a more accessible model for circular construction.

The deployment of Mixed Reality (MR) guidance successfully externalised complex assembly knowledge into spatial overlays, reducing the reliance on expert craftsmanship. This 'human-in-the-loop' model does not replace traditional craft but augments it with computational memory. By lowering technical barriers, the XRAA module suggests a model for democratising circular construction, enabling non-specialists to participate in complex building processes without sacrificing the geometric accuracy required for interlocking systems.

5.4. System performance, limitations, and future trajectories

Despite the framework's success in multi-scale prototyping—from furniture to pavilion-scale installations—several structural limitations remain. Evaluation of the physical fit of interlocking nodes revealed a high sensitivity to fabrication tolerances. Dimensional drift in foam-mould prototypes introduced friction that complicated manual assembly, highlighting a discrepancy between idealised models and physical material behaviour. Future deployments will require higher-fidelity fabrication, such as CNC milling directly from reclaimed stock, to meet the strict requirements of nested interlocking.

Furthermore, the workflow remains semi-automated, requiring manual compensation for 'holographic drift' caused by environmental factors like inconsistent lighting. While the current framework provides a reproducible pipeline for transforming waste into architecture, advancing toward fully responsive cyber-physical integration will demand more robust spatial anchors and tighter feedback loops between the MRS, STOA, and XRAA modules. Ultimately, RADD reframes reuse as a computational discipline, demonstrating that architectural expression can emerge from the rigorous negotiation among availability, constraints, and computation.

6. Conclusion

This study presents the Resources Availability Driven Design (RADD) framework, providing a systematic closed-loop pathway for the AEC sector to transition from the traditional linear "take-make-waste" model to a resource-driven circular paradigm. The research demonstrates that the Wave Function Collapse (WFC) algorithm can effectively translate the physical constraints of irregular decommissioned materials into innovative generative design rules, achieving a "pixellated classical" aesthetic while ensuring structural integrity and algorithmic feasibility within complex solution spaces. Furthermore, the introduction of Extended Reality-Assisted Assembly (XRAA) significantly reduces the reliance on specialised skills for complex construction, democratising and automating the assembly of high-precision interlocking systems through real-time guidance. Validated through multi-scale iterations ranging from 1:1 furniture prototypes to medium-scale community pavilions, the framework demonstrates exceptional design scalability, efficient resource utilisation, and the potential to transform waste components into high-value architectural assets. While challenges remain regarding fabrication precision, material diversity, and the level of full automation, this research establishes a robust foundation for transparent, efficient, and aesthetically profound circular architectural practices by bridging material unpredictability with formal intelligence, charting a course for future adaptive digital design and construction

Fig. 22. Interlocking column structure using 3D printing, casting, and craft techniques. (Supplementary Material - Portfolio 01–02).

workflows.

CRediT authorship contribution statement

Nur Rasyidah Nizam: Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation, Conceptualization. **Chan Seng Koh:** Writing – original draft, Visualization, Supervision, Software, Resources, Methodology, Investigation, Conceptualization. **Jianing Luo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Adam Holloway:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Sebastian Hicks:** Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Elliot Rogosin:** Validation, Supervision, Resources, Project administration, Conceptualization. **Boyuan Yu:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rineng.2026.110172.

Data availability

Data will be made available on request.

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