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Research Article

Discrete Design in Architecture: An Integrated Design-to- Assembly System

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Abstract

This paper explores the integration of digital discretisation strategies with robotic assembly to advance architectural design and production within the framework of Design for Manufacturing and Assembly (DfMA). Discretisation—understood as a digitally driven method of breaking down design into modular, adaptable parts—enables flexible, scalable systems where components can be modified without compromising structural coherence. It supports precision, efficiency, and sustainable construction practices.

As part of an ongoing research project on discrete design in DfMA, this paper builds on two previously developed classification systems derived from the parametric reconstruction of built and academic case studies (ZamaniGoldeh, Dounas, & Agkathidis, 2025). The methodological classification—Computational Growth, Subdivision Surfaces, and Cross-Sectional Techniques—focuses on geometric discretisation methods. The strategic classification—Top-Down, Bottom-Up, and Hybrid—centers on the modelling logic and design progression. To validate these systems, the research employs a dual approach: digital simulation and physical prototyping. Algorithms are implemented through robotic simulations in Grasshopper. Subsequently, a selection of discrete prototypes is physically assembled, allowing for assessment of joints, accuracy, stability, and constructability.

This paper provides insights into the assembly logic of discrete design systems and highlights the potential of digital fabrication workflows to transform architectural practice. Going forward, it offers valuable learnings for DfMA from design to assembly and lays the groundwork for further physical validations and scaled modelling. The outcomes reinforce the practical relevance of the classification systems and offer a foundation for future, real-scale applications of robotic-based architecture.

Keywords: Discrete Design; Digital Fabrication; Computational Design; DfMA; Integrated Design Systems

Highlights

- How do different discretisation methods influence the ease and effectiveness of assembly in the prototyping stage?
- What challenges arise in the physical fabrication of prototypes based on discretisation techniques, and how might these be mitigated?
- To what extent do the assembled prototypes stay to the anticipated outcomes derived from computational models?

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1 Introduction

Architecture is Architecture is undergoing a major transformation, driven by rapid advances in computational tools, digital fabrication, and growing demands for sustainability and adaptability. As the industry seeks more efficient and scalable strategies, integrating digital processes across the design-to-assembly pipeline has become crucial. Within this context, discretisation has emerged as a flexible design approach supporting both creative exploration and practical fabrication. Discretisation rethinks architectural production through modular, parametric logic, where design and assembly are interconnected to improve adaptability and efficiency (Retsin, 2016, p144). By focusing on individual components and their assembly into larger systems, it enables precise, responsive design aligned with material and fabrication constraints. It also suits robotic and automated construction, which favour repeatability and digitally driven workflows. Recent studies show its compatibility with DfMA strategies, especially where computational design enhances constructability and reduces waste (Glick & Guggemos, 2009, p. 3). Discretisation strengthens DfMA by offering scalable, robotic-ready solutions.

Despite its growing role in experimental design, discretisation remains under-theorised as a structured methodology. Many architectural projects use it yet lack a systematic framework to classify and test strategies for digital fabrication and robotic assembly. Existing studies often focus on speculative forms or isolated workflows, missing the link between design intent and fabrication outcomes. Meanwhile, start-ups are exploring discretised approaches in real-world settings. In the UK, prefabricated modules—often called Volumetric Construction Methods (VCM)—illustrate the industry's growing interest in modular, off-site strategies aligned with discretisation principles (Brennan et al., 2024). Our study at this stage, builds on prior research analysing discretisation through case studies and parametric reconstructions, identifying shared logics behind discrete thinking (ZamaniGoldeh, Dounas, & Agkathidis, 2025). It extends this by validating the previously introduced classification systems—methodological (computational growth, subdivision surfaces, cross-sections) and strategic (top-down, bottom-up, hybrid)—through digital and physical applications. The research tests these through algorithm development, simulation, and prototyping with a robotic arm, aiming to evaluate feasibility, adaptability, and assembly logic across digital and real-world contexts. A key gap addressed is the weak connection between early-stage digital design and production workflows. Although tools and technologies have advanced, integration remains limited, often resulting in inefficiencies and reduced scalability of innovative solutions (Maslova, Holmes, & Burgess, 2021, p. 16).

2 Literature Review

2.1 First and Second Digital Turn: A Shift in Architectural Thinking

After the 2008 global financial crisis, the integration of digital technologies into architecture became closely associated with a broader neoliberal agenda—an era that Carpo refers to as the "First Digital Turn" (Carpo, 2017, p. 3). This period was characterised by the alignment of digital tools with market-driven strategies, shaping architectural practices in ways that sparked mixed reactions. While some critics argued that these developments reduced design to a commodified process, others saw them as a catalyst for creative innovation (Carpo, 2017, p. 9; Carpo, 2019, p. 86). The debates surrounding this time also highlighted broader concerns about how digitisation might either intensify or counteract the social and economic impacts of neoliberal policies on cities and the built environment, thereby adding a deeper socio-political layer to the technological evolution of architectural design. Carpo's perception of the "Second Digital Turn" marks a notable transformation in the way digital architects approach their work, characterised by the widespread use of novel design methods and algorithmic processes (Carpo, 2017, p. 159). This transition reflects a more profound and ongoing evolution in digital practice, where technology is not just adopted, but actively reshapes the way architects conceptualise and develop their designs. The emergence of advanced digital tools has enabled an unprecedented degree of complexity and customisation, indicating a new level of maturity in digital design and craftsmanship—one that continues to shape the future direction of the design profession.

2.2 Discretisation in AEC: Tracing the Roots

In Since the late 20th century, architecture has undergone major shifts, with digital tools reshaping its connection to industrial production (Bayram, 2021, p. 173). The Fourth Industrial Revolution introduced technologies that merge digital and physical realms, boosting automation, accuracy, and adaptability ((Schwab, 2024, p. 30). In architecture, robotics and 3D printing have improved construction efficiency, while the rise of CAAD in the 1990s expanded access to computational design across the AEC industry (Koutamanis, 2004, p 40). Discretisation builds on this evolution, linking computational modelling with physical construction through modular thinking (Retsin, 2016, p149; Picon, 2010, p. 150). By dividing forms into manageable units, it supports scalable and efficient fabrication. Beyond a technique, it's a mindset enabling flexible, reusable systems (e.g. books like Retsin, 2019; Kolarevic, 2011). Yet, unequal access to digital tools raises equity concerns, making inclusive strategies essential for broader adoption.

2.3 Discretisation Logic: Mathematics and Computation

Discretisation—the process of converting continuous models into discrete units—is central to what Morel (2019, p. 14) calls the “era of effectiveness.” It reflects a growing shift toward computational approaches and echoes Wigner’s (1960) notion of the “unreasonable effectiveness of mathematics.” With rising demands for scalable models, especially in the age of Artificial General Intelligence (AGI), discretisation enables efficient data handling and algorithmic reasoning. Grounded in fields like graph theory and numerical methods, it supports adaptive systems and machine learning (Morel 2019, p18; (Cichocki & Kuleshov, 2021, p1). Practical uses span from simulation to solving differential equations—such as Bar-Sinai, Hoyer, Hickey, and Brenner (2019) low-resolution method—making discretisation fundamental across disciplines including architecture, finance, and engineering (Gustafsson, 2018, p. 228).

2.4 Mereology & Discretisation Philosophy in Architectural Thinking

The concept of modularity—using standardised, interchangeable components within structured systems—trace its origins back to the early 20th century, marking a shift from traditional craftsmanship to more systematic construction methods (Soikkeli, 2014, p 628). While the ideas of repetition and standardisation existed earlier, they weren’t formally recognised as modularity (Masini, Fonseca, Geraldi, & Sabino, 2004, p. 8).

Discretisation challenges traditional architectural norms by emphasising computational logic and part-to-whole relationships (Retsin 2019, p8). It promotes flexible, iterative systems over stylistic wholes, embedding digital tools into core practice (Carpo 2019 p160; Kolarevic, 2011, p. 33). This marks a shift from intuition-led design to methods driven by data and automation. Architects become coordinators of digital systems, enabling decentralised, cost-effective production and context-responsive structures. Mereology—the study of part-to-whole relationships—offers a valuable lens for architectural design at both urban and building scales. In this framework, no single element dominates; instead, the whole emerges through the interaction of parts (Retsin, 2019, p 10). This non-hierarchical structure allows for open-ended, adaptable forms. Discrete design shifts the architectural focus from monolithic forms to a language of modular, adaptable components (Retsin, 2016, p 163). This method simplifies building syntax while supporting complexity through assembly rather than uniqueness. Standardised elements reduce production costs and increase design accessibility, without compromising creativity (Popescu, Mahale, & Gershenfeld, 2006, p. 58). By merging digital computation with fabrication logic, architects create buildings that are materially grounded yet abstract in their conceptual structure (Dörfler et al., 2016, p. 204).

2.5 Digital Fabrication and the Future of Discrete Design

Discretisation supports modular, sustainable, and adaptable design, making it ideal for temporary housing and dynamic infrastructure (Gregg, Kim, & Cheung, 2018). By treating architecture as reconfigurable parts rather than fixed wholes, it enables innovation in composite materials optimised for performance and environmental impact (ZamaniGoldeh & Dounas, 2022). Robotic methods such as 3D printing and pick-and-place systems complement discrete design, allowing for precision, efficiency, and real-time integration of design and assembly (Kolarevic, 2003, p. 6). However, challenges in interoperability, materials, and regulation remain, and future advances in AI and machine learning are expected to enhance the adaptability of discrete systems (Agkathidis & Gutierrez, 2016, p. 210)

3 Methodology

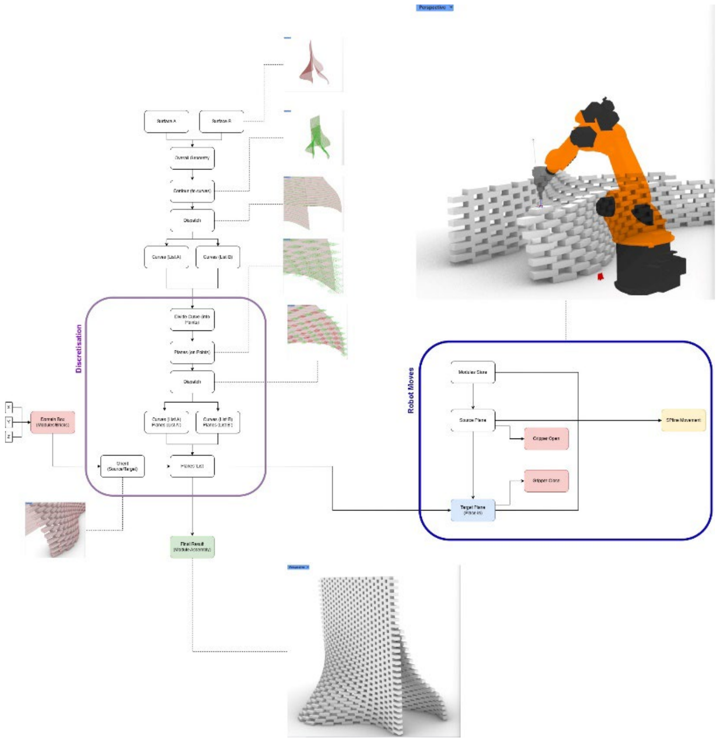
This study employs a design-led approach that blends digital modelling, physical prototyping, and systems thinking to explore the practical application of discrete design strategies. Rather than focusing purely on speculative design or theoretical modelling, the methodology emphasises hands-on testing and iterative development of discrete modules to investigate how they perform in terms of adaptability, material efficiency, and readiness for integration into construction workflows.

Three types of discrete parts were explored through this process:

- **A cubic surface-based module**, tested exclusively through digital simulations to assess its feasibility within controlled computational environments.
- **An L-shaped modular component**, investigated in both digital and physical formats, used to explore flexible assemblies that can generate non-linear, curvilinear wall structures.
- **An adaptive cubic module**, also examined in digital and physical contexts, designed to study part-to-whole relationships with higher geometric regularity.

Each module was evaluated in terms of its capacity for assembly, adaptability to varied spatial configurations, and its compatibility with fabrication constraints. The physical prototypes were tested at scale to evaluate their interlocking joints and to analyse their adaptability within modular assemblies. These tests aimed to explore the structural performance and assembly feasibility of discrete elements when subjected to physical constraints. The research also includes a systems integration perspective, where the transition from discrete geometry to robotic pick-and-place logic is studied. Going forward, this exploration will inform how the digital-to-physical bridge can be strengthened through prototyping and algorithmic feedback, guiding future studies toward real-world applications of discretised design in architectural production. This is guided by a digital flow diagram connecting discretisation logic to fabrication movements, outlining how digital modelling decisions can inform real-time assembly paths.

Figure 1 Building on earlier research into discrete design, this simulation reinterprets the Serpentine Pavilion 2016 (one of the recreated case studies) through a parametric and robotic lens. Using the KUKA plugin, robotic movements—gripper control, spline paths, module placement, and system integration—were mapped to explore how such complex geometries could be assembled through automated means.

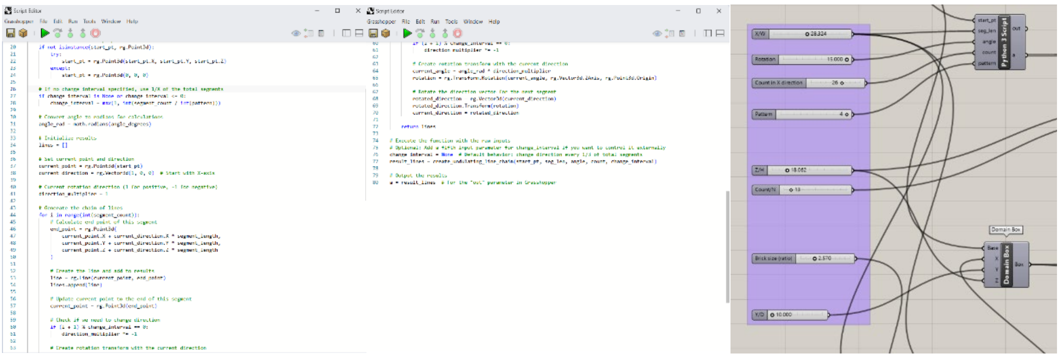


4 Results- Prototyping Outcomes and Evaluation

This section presents the results of three discrete design prototypes developed to evaluate different strategies for modularisation, geometric adaptability, and robotic compatibility. Each prototype was analysed both in terms of its generation logic and, where applicable, its physical validation. The section is organised by prototype type, outlining the design intention, digital parameters, and fabrication feasibility.

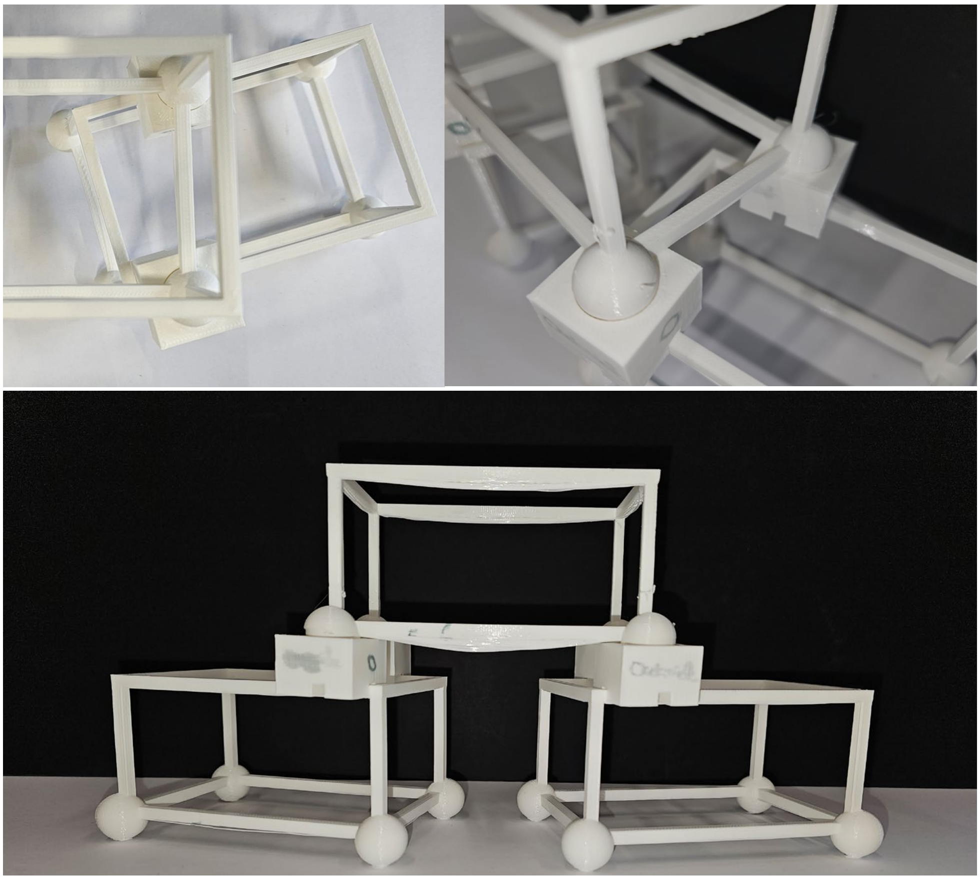
Prototype 1: Modular Interlocking Cubic Brick: The first prototype was developed to explore a modular cubic system capable of rotational adaptation for use in dry-jointed, mortarless construction. The aim was to introduce curvature into wall assemblies using identical modules that could rotate and interlock without additional connectors. Each module is framed as a rectangular brick with integrated spherical male nodes and corresponding socket recesses, enabling controlled rotational articulation around the joints. The generation logic was implemented using a Python-based script within Grasshopper. This script constructed an undulating chain of lines, parametrised by segment length, direction change frequency, and rotation angle. The logic enabled the generation of curved wall paths by alternating directional rotation based on a user-defined interval. The modular brick geometries were mapped onto these curves and adjusted to follow the resulting path, ensuring uniformity across all units.

Figure 2 the Script and parametric logic to create the whole geometry. the changeable parameters are module sizes, geometry, and ratio. Created by Erfan ZamaniGoldeh



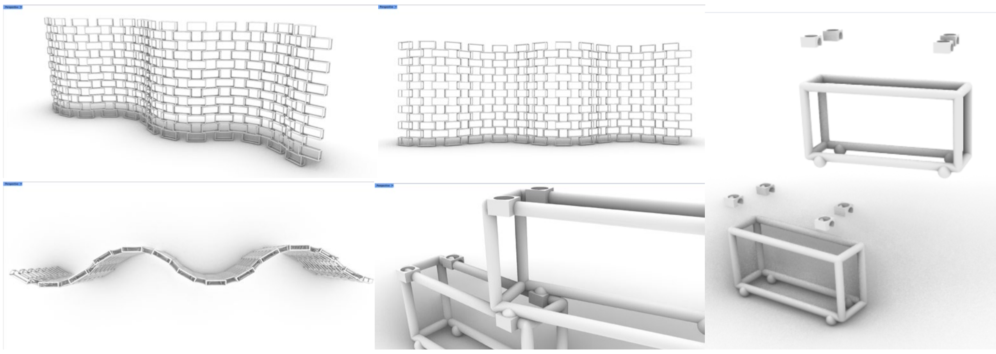
Physical validation was performed using 3D-printed components. A set of modules was assembled into a freestanding double-curved wall form, successfully demonstrating the interlocking behaviour. The interlocking tolerance was tested and allowed rotational displacement between approximately 5 and 15 degrees between units, verifying the rotational adaptability of the system.

Figure 3 First physical prototyping to test the rotation tolerance. Created by authors



The model also demonstrated the capacity for vertical stacking, further extending its architectural potential. Through additional testing, it was observed that despite minor tolerances introduced through the 3D printing process, the modules consistently maintained geometric alignment and articulation. The full assembly simulation created a rigid structure, confirming the feasibility of rotational dry-joint systems for digitally generated and physically realised walls.

Figure 4 Part to whole assembly logic, The result consists of two parts; modules and joints. created by authors



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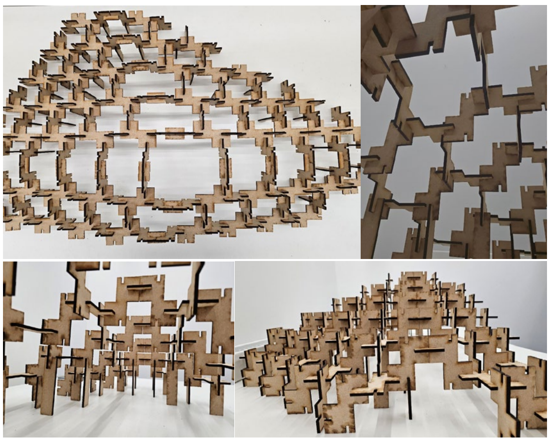
Prototype 2: L-Shaped Modular Assembly: The second prototype focused on developing an L-shaped modular unit capable of assembling into continuous curvilinear structures. This approach was chosen to evaluate directional articulation and continuity across modular systems with a more complex geometry than the cubic units. The aim was to investigate how an L-form can introduce directional shifts within discrete assemblies and to assess its feasibility within robotic workflows. The digital generation of this prototype followed a top-down modelling strategy. A target geometry was first defined, and then discretised into contour curves, from which base points were extracted. These points informed the orientation and placement of L-shaped units using curve tangent vectors, enabling the alignment of module arms along intended directional flows. *T*he evaluation focused on digital design generation and physical prototyping. The modules featured consistent orientation and base alignment derived from the curve tangents of the host geometry. Their flat gripping faces and predictable placement logic suggest suitability for future robotic workflows, although these remain to be developed and tested in subsequent research phases.

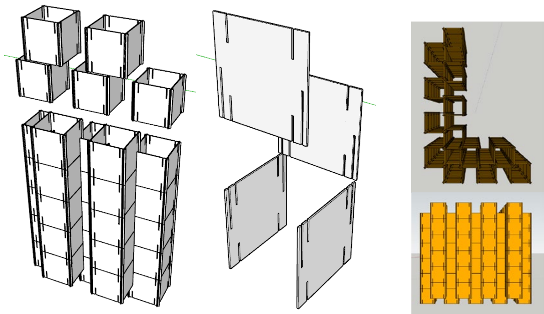
Figure 5 Final Structure Alternative; The built Scale Model of L-shape Modules, Created by Erfan ZamaniGoldeh



Scaled physical prototyping was conducted to analyse the interlocking behaviour and geometric alignment of the assembled structure. The modules were manually assembled to form a continuously bending wall with alternating offsets. The resulting model confirmed the geometric stability of the L-shaped parts and their capacity to align across directional changes. While this prototype did not focus on rotational joints, it provided essential insights into orientational control, structural continuity, and potential robotic pre-programmed paths. It effectively demonstrated the capacity of L-shaped modules to adapt to directional variation without sacrificing stability, a key challenge in discrete design systems.

Prototype 3: Cubic Surface-Based Module: The third prototype investigates the use of uniform cubic modules to discretise a double-curved surface. The objective was to assess the adaptability of regular, grid-based units across complex geometries and to identify the limits of modular repeatability under curvature variation. This prototype was only tested in a digital environment. The generation process began with defining a non-planar surface, which was then subdivided through a contouring process. These contours were used to extract sectional curves at set intervals, from which grid points were generated. The position and orientation of the cubic modules were defined using local coordinate planes derived from surface tangents and *normal*. These informed the modular placement logic, resulting in an array of uniformly scaled cubic units mapped across the undulating surface.

Figure 6 Structure Deign Alternative, Vertical wall inspired by traditional brick Wall; Cubic Planner Module with 8 Joints, Created by Erfan ZamaniGoldeh



5 Discussion: Comparative Reflection

The following table summarises key observations from the three discrete design prototypes based on their classification, performance, and implementation approach:

Table I. Comparing the prototypes. Created by Erfan ZamaniGoldeh

Feature	Prototype 1: Interlocking Cubic Brick	Prototype 2: L-Shape Module	Prototype 3: Surface-Based Module
Methodological Classification	Computational Growth	Computational Growth	Subdivision Surfaces
Strategic Classification	Bottom-Up / Hybrid	Top-Down	Top-Down
Growth Capability	Multi-directional	Directional Curvature	Surface-conforming (2.5D)
Flexibility	Very High	High	Low to Moderate
Stability	Good	Very Good	Limited (Digital Only)
Digital + Physical Evaluation	✓ (3D Printed)	✓ (Scaled Physical Model)	✗ (Digital Simulation Only)

6 Conclusion: What to Do Next?

This research demonstrates how integrating discretisation into design and fabrication can reshape architectural workflows, enabling adaptable, non-linear systems compatible with digital and robotic techniques. The prototypes offer scalable, data-informed strategies suited to diverse contexts, laying a foundation for further exploration. By embracing computational methods, architects can create structures that evolve over time, supporting sustainability through adaptability, maintenance, and reuse. This shift redefines architectural practice, positioning architects as facilitators of digital and physical systems who use algorithmic tools to address environmental and societal needs. The recommendations that follow propose key pathways for advancing sustainable and inclusive innovation in architecture.

Table 2 Strategic Recommendations for Advancing Architectural Innovation through Digital Discretisation and Computational Methodologies. This table presents a comprehensive roadmap for future research, focusing on areas critical for the development of sustainable, efficient, and culturally responsive architectural practices. Each recommendation is elucidated with an explanation, highlighting its significance and potential impact on the field of architecture. Created by Erfan ZamaniGoldeh

Recommendation	**Explanation**
Expansion of Discrete Design Methodologies	Future studies should delve into a wider array of computational tools, including AI and wider generative systems, to uncover new possibilities in design creativity, efficiency, and innovation.
Digital Material Integration	Investigating the synergy between digital material and architectural design can lead to sustainable and innovational building methods and materials.
Cross-Disciplinary Collaborations	Collaborative efforts across fields such as engineering, computer science, Robotic, and materials science can foster innovative solutions to architectural challenges.
Sustainability and Environmental Impact	Prioritising research focused on reducing the environmental footprint of buildings through computer-based integration will contribute significantly to sustainable development goals.
Parametric Design Education	Enhancing architectural education to include parametric and computational design will equip future architects with the necessary skills to tackle emerging design methods.
Standardisation and Best Practices	Establishing standards and best practices for the use of computational methodologies in architecture will ensure their ethical and efficient application.
Public Engagement and Participation	Exploring ways to involve the public in the design process using digital tools can democratise architecture and enhance community engagement.

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