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Systematic Review

Modular and Flexible Residential Architecture: A Systematic Review

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Abstract

Growing urbanization, housing affordability pressures, and increasing sustainability demands have positioned modular and flexible design strategies as central approaches in contemporary residential architecture. Modularity enhances construction efficiency, reduces material waste, and accelerates delivery through the use of prefabricated, standardized components. Flexibility, in turn, enables spaces to adapt in configuration and function over time, responding to the evolving needs of occupants and communities. Following PRISMA 2020 guidance, a systematic search was conducted across Web of Science, Scopus, and ScienceDirect academic databases resulting in 2140 records. After duplicate removal and sequential screening, 98 studies were included in the final review. The selected literature spans peer-reviewed journal articles and documented case studies, with emphasis on publications from 2015 onwards. The review identifies key advantages of modular and flexible residential systems, including cost-effectiveness, reduced environmental impact, and improved user satisfaction, while also highlighting persistent challenges such as regulatory barriers, standardization constraints, and limited interdisciplinary integration. The review contributes three synthesis outputs: a typology of modular residential systems, a critical comparison of modular–flexible strategies, and a cross-scale conceptual framework linking production logic, occupant adaptation, and sustainability outcomes. The findings underscore the potential of hybrid strategies that combine modular construction with flexible design principles to produce residential environments that are resilient, adaptable, and sustainable. The review provides structured insights and evidence-based recommendations for architects, planners, and policymakers involved in the development of future housing systems.

Keywords: modular construction; flexible design; residential architecture; adaptability; sustainability; prefabrication; systematic review; post-occupancy evaluation

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1. Introduction

Over the past century, urbanization has dramatically reshaped global settlement patterns, creating new housing demands that cities struggle to meet. The urban population is projected to rise from 55% in 2018 to 68% by 2050, with the most significant growth expected in Asia and Africa [1]. This rapid demographic shift intensifies pressure on land use, building typologies, and infrastructure capacity. Urban densification should increase transportation efficiency along with the efficiency of service delivery, but poorly managed growth risks deepening social inequality, worsening housing shortages, and amplifying environmental harm [1].

Compounding this challenge, housing affordability has reached critical levels in many parts of the world. In England, for example, median home prices now stand at 9 to 10 times average annual salaries, nearly double the ratio recorded in 2000 [2]. This economic burden disproportionately affects lower- and middle-income households, limiting equitable access to adequate urban housing. At the global scale, the United Nations has identified affordable and sustainable housing as a central challenge within the Sustainable Development Goals [3], recognizing that conventional construction models are increasingly unable to cope with the pace, cost, and environmental demands of modern urbanization [4,5].

The built environment creates environmental damage, which demands immediate action. In 2019, buildings were responsible for approximately 21% of global greenhouse gas emissions, totalling 12 $GtCO_2$-eq. Within this share, 57% arose from indirect emissions linked to offsite electricity and heat generation, 24% from direct on-site combustion, and 18% from the production of cement and steel used in construction and refurbishment [6]. Energy-related building emissions in the EU decreased by 34% during the period from 2005 to 2022 because of electrification and efficiency improvements [7]. Circular design strategies, including design-for-disassembly, low-carbon material substitution, and end-of-life material reuse, have been documented as effective pathways for reducing embodied carbon across the building lifecycle, contributing to the sector's broader decarbonization objectives [8].

In response to these intersecting pressures, modular and flexible housing systems have emerged as viable and increasingly studied strategies [8]. Three contemporary challenges make their joint examination particularly urgent. First, the global affordable housing crisis demands construction approaches that are simultaneously fast, cost-effective, and adaptable to diverse household configurations, a combination that neither pure modularity nor pure flexibility can deliver independently [2,5]. Second, the transition toward circular construction requires buildings that are not only efficient to produce but also designed for disassembly, reuse, and material recovery at the end of their lifecycle, a requirement that links production logic directly to long-term spatial and structural flexibility [7,9]. Third, climate adaptation demands residential environments capable of responding to changing environmental conditions, occupancy patterns, and energy performance requirements over extended timeframes, again pointing toward the integration of efficient production with adaptive design [6,10]. Modular construction shifts production from labour-intensive on-site processes to controlled factory-based prefabrication, encompassing techniques such as volumetric modular assembly, panelised systems, and industrialized building production [11]. The residential sector increasingly adopts offsite construction methods because these methods demonstrate capabilities to shorten building durations, decrease expenses, reduce material waste, and enhance quality management processes [12,13]. Beyond construction efficiency, housing demands are becoming increasingly dynamic. The number of occupants and their needs shift over time due to changes in family size, age, physical ability, and lifestyle [14]. New residential models must establish systems that can adapt to changing patterns of human behaviour [15]. Architectural design requirements demand flexible designs that enable building operators to modify building space and operational systems according to future needs [16]. Studying modularity and flexibility together is therefore not merely an academic convenience but a response to the structural interdependence of these challenges.

For this review, two core concepts require precise definition at the outset. Modularity refers to a construction approach in which buildings are composed of prefabricated, standardized units or components manufactured off-site and assembled on-site, enabling efficiency, scalability, and quality control across the production process [12,13]. Flexibility, by contrast, refers to an architectural design principle through which buildings are designed to accommodate change over time in response to evolving occupant needs and lifecycle demands [17,18]. While modularity is primarily a production strategy and flexibility is primarily a design strategy, this review argues that their integration represents a qualitatively distinct approach to residential architecture that neither concept alone can achieve.

While numerous studies have examined modular construction efficiency and housing adaptability in isolation, a growing body of review literature has begun to address these domains more systematically. Kamali and Hewage [19] produced one of the earliest critical lifecycle reviews of modular buildings, establishing a performance baseline but without addressing flexibility as a design principle. Wuni and Shen [12] subsequently reviewed the drivers of offsite construction adoption through an interpretive structural model, identifying sustainability and SDG alignment as key motivators, yet their scope did not extend to occupant adaptability or spatial reconfiguration. More recently, Parracho et al. [20] conducted a PRISMA-based review of digital technologies in modular construction, covering smart and sustainable innovations across three thematic pillars but excluding the flexibility dimension and occupant-centred outcomes. Kim [21] reviewed the present status and future challenges of prefabricated and modularized residential construction, focusing on structural systems and production logistics, with limited engagement with flexible design strategies. Mlote et al. [22] reviewed building adaptability research across multiple building types and scales, identifying a lack of standardized performance indicators and methodological consistency as critical gaps, but without integrating modular production logic into the analysis.

Zohourian et al. [23] provided a comprehensive review of modular construction covering structural, economic, and environmental dimensions, but did not address flexibility as a lifecycle strategy or examine user adaptation outcomes. Collectively, these reviews reflect three recurring limitations: they address either modularity or flexibility but rarely both in combination; they prioritize construction-phase metrics over long-term occupant and lifecycle outcomes; and they lack a unified framework linking production logic, spatial adaptability, and sustainability performance across scales. The present review addresses these gaps by explicitly connecting modular construction typologies with flexibility mechanisms within a cross-scale framework, and by synthesizing evidence on environmental, economic, and social performance within a single analytical structure. These contributions have direct practical implications for architects designing for adaptability, for developers navigating the cost–flexibility trade-off, and for policymakers seeking evidence-based frameworks for sustainable housing regulation.

Only a limited number of works systematically connect modularity with flexibility as a use-based strategy, across design scales and life-cycle stages. Existing reviews typically emphasize either technological optimization or user adaptability, but they rarely address how their interaction affects long-term sustainability [22,24,25]. This review addresses that gap by synthesizing modular and flexible strategies into a unified framework that links design decisions, user adaptation, and environmental performance.

The review focuses on single-family and multi-unit residential buildings, including detached houses, row houses, and multi-storey apartment blocks, with emphasis on developments from 2015 onwards to capture the most recent innovations and trends. Sources include peer-reviewed journal articles and documented case studies, ensuring that theoretical design principles are grounded in real-world applications.

This review provides structured insights and evidence-based recommendations for architects, planners, and policymakers working toward residential environments that are resilient, adaptable, and environmentally responsible. Accordingly, this review addresses three questions: (1) Which modular construction typologies and material systems are most consistently reported in residential architecture? (2) Which flexibility mechanisms, digital enablers, and performance outcomes are supported by the reviewed evidence? (3) Where do the main trade-offs, knowledge gaps, and research priorities lie when modularity and flexibility are combined across scales and over time?

In addressing these questions, the review gives equal emphasis to three performance dimensions (sustainability outcomes, housing performance, and construction efficiency), recognizing that a comprehensive evaluation of modular and flexible systems requires evidence across all three rather than privileging any single dimension.

2. Materials and Methods

This systematic literature review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [26]. The review protocol was not prospectively registered, as registration is not mandatory for non-clinical systematic reviews in the fields of architecture and built environment research. Nevertheless, all PRISMA 2020 reporting recommendations were followed, including comprehensive search strategies across three academic databases, transparent inclusion and exclusion criteria, systematic screening procedures, and structured thematic synthesis. A complete PRISMA 2020 checklist is provided in the Supplementary Materials.

Three academic databases were searched: Web of Science, Scopus, and ScienceDirect, which together index a broad range of peer-reviewed journals, conference proceedings, and technical reports relevant to architecture, civil engineering, and environmental science; however, only peer-reviewed journal articles and documented case studies meeting the predefined inclusion criteria were retained for screening.

The search strings were adapted to the syntax of each database but built around the same core terms. The following representative search string was applied across all three databases: ("modular construction" OR "modular housing" OR "prefabricated housing" OR "offsite construction" OR "industrialized building") AND ("flexibility" OR "adaptability" OR "flexible design" OR "design for adaptability" OR "convertibility") AND ("residential" OR "housing" OR "dwelling"). Additional supplementary searches were conducted using the terms "circular construction", "design for disassembly", "open building", and "occupant satisfaction" in combination with "modular" or "prefabricated" to capture studies addressing circular economy and occupant-centred dimensions. Searches were restricted to peer-reviewed publications in English, with no strict date limitation applied at the search stage.

The search resulted in 2140 total records, which included 695 records from Web of Science, 821 records from Scopus, and 624 records from Science Direct. Following deduplication, the 775 remaining records were screened by title and abstract. Screening was conducted independently by three reviewers using ASReview 2.0, an open-source active-learning software for systematic review screening [27]. Each reviewer manually labelled records as relevant or irrelevant according to the predefined inclusion and exclusion criteria; after each decision, ASReview re-ranked the remaining records by predicted relevance, prioritising those most likely to be relevant for subsequent review. All 775 records were screened manually in full: no automatic stopping criterion was applied, and the software made no autonomous inclusion or exclusion decisions at any stage, serving solely as a prioritisation and efficiency tool. Disagreements between reviewers were resolved through discussion and consensus, with the supervising authors making the final determination where consensus could not be reached. Following this process, 578 records were excluded for not meeting the inclusion criteria, and 197 records were sought for full-text retrieval. Of these, 88 could not be accessed despite retrieval attempts through institutional access, open-access repositories, and direct author contact, leaving 109 records assessed for eligibility. Full-text screening and all eligibility assessments were conducted manually by the authors without software assistance; ASReview was used exclusively during title and abstract screening and did not support data extraction, which was performed manually by the lead author and verified by the co-authors. Eleven records were excluded at this stage due to insufficient data or methodological detail, resulting in 98 studies included in the final review (Figure 1). The high duplicate rate (65%; n = 1365) is attributable to the substantial overlap among the three databases searched (Web of Science, Scopus, and ScienceDirect), which index many of the same peer-reviewed journals in the fields of architecture, construction engineering, and environmental science. Duplicates were identified and removed prior to screening using reference management software, leaving 775 unique records for title and abstract screening.

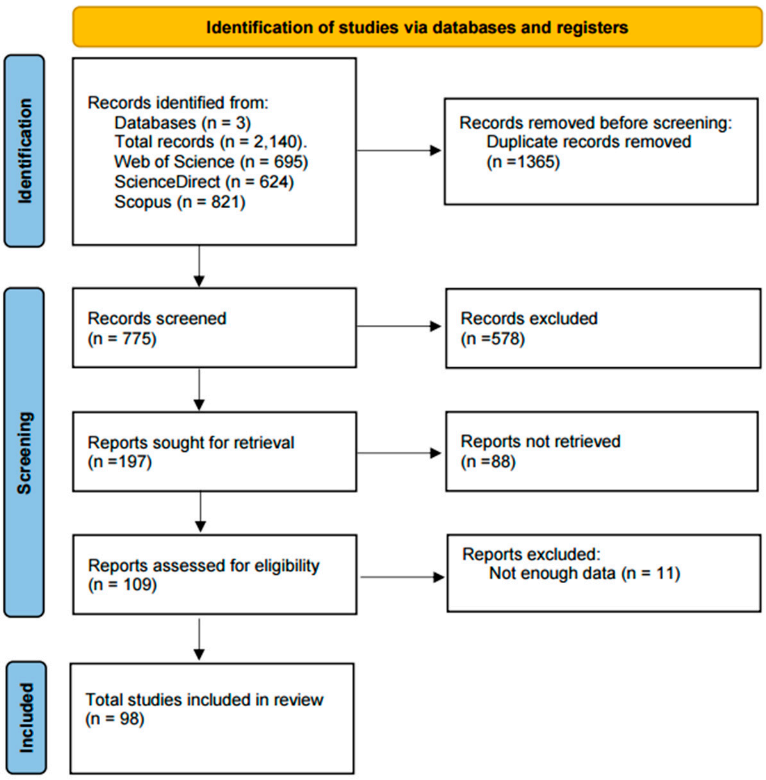

Figure 1. PRISMA-based flow diagram illustrating the literature screening and selection process for the study.

To ensure a targeted and high-quality sample, the following inclusion and exclusion criteria were applied during the screening process:

Inclusion criteria:

- Peer-reviewed journal articles, conference papers, and book chapters focusing on residential buildings emphasising modular or prefabricated construction techniques;
- Studies addressing design flexibility or adaptability principles specifically related to residential environments;
- Primary research articles, case studies, comparative studies, or systematic reviews published in peer-reviewed venues with sufficient methodological detail;
- Publications written in English;
- Studies providing extensive engineering or architectural documentation, such as case studies or prototypes demonstrating real-world applications;

Exclusion criteria:

- Works consisting solely of unsupported opinion with no empirical, technical, or documented conceptual content;
- Studies not specifically related to residential architecture;
- Reports with insufficient data or inadequate methodological detail;
- Non-peer-reviewed sources.

All extracted data were subsequently reviewed and verified manually by the authors to ensure accuracy, consistency, and alignment with the review objectives. Extracted data included study type, modular construction forms, materials used, flexibility strategies, and environmental efficiency metrics such as energy consumption and lifecycle assessments.

The extracted data were then subjected to thematic analysis to identify recurrent patterns, emerging innovations, and areas of divergence across the literature. Narrative synthesis was combined with comparative tabulation to highlight both qualitative insights and quantitative trends. Because the included evidence comprised heterogeneous study types, a single formal risk-of-bias tool was not considered methodologically appropriate. Conventional risk-of-bias instruments such as the Cochrane Risk of Bias Tool or CASP checklists are designed for clinical or experimental studies with standardized outcome reporting and are not transferable to the mixed evidence base typical of built environment and architectural research [26]. In the absence of a universal quality appraisal tool suited to this evidence type, a structured quality assessment framework was applied during data extraction. Each included study was evaluated against four explicit criteria: (1) methodological transparency—whether the study clearly described its data collection methods, analytical approach, and scope; (2) evidence type—whether findings were grounded in empirical data, documented case studies, or experimental results, rather than unsupported opinion; (3) outcome specificity—whether performance claims were supported by quantitative metrics, measured indicators, or documented outcomes rather than qualitative assertion alone; and (4) geographic and contextual scope—whether the study's findings were clearly bounded by context, enabling appropriate interpretation during synthesis. Studies were not excluded on the basis of these criteria alone, as methodological heterogeneity is inherent to the field; however, these criteria directly informed the weight attributed to individual findings during thematic synthesis, and are explicitly noted where evidence was assessed as limited or preliminary. This approach is consistent with established practice in systematic reviews of built environment research where methodologically diverse evidence bases preclude the application of standardized risk-of-bias instruments [20,22]. Thematic subsections were organized according to historical development, construction typologies and materials, flexibility mechanisms, digital technologies, and environmental and economic performance indicators.

To characterize the included evidence base, descriptive statistics were extracted across all 98 included studies (Figure 2). Publication output showed a clear upward trend, rising from 3 studies in 2016 to 21 in 2025, confirming growing scholarly interest in modular and flexible residential architecture over the past decade. Geographically, international or multi-country studies accounted for the largest identifiable share (n = 13), followed by China (n = 9), South Korea (n = 5), and Canada (n = 4). A substantial proportion of studies (n = 55) were either international in scope or did not report a single country context, reflecting the cross-national nature of much modular construction research. In terms of research methods, literature and systematic reviews were most frequent (n = 24), followed by case studies (n = 23), mixed methods studies (n = 20), comparative studies (n = 16), and simulation or experimental approaches (n = 15). This methodological diversity is consistent with the heterogeneous evidence base described in the Section 2 and informs the interpretive approach adopted during thematic synthesis.

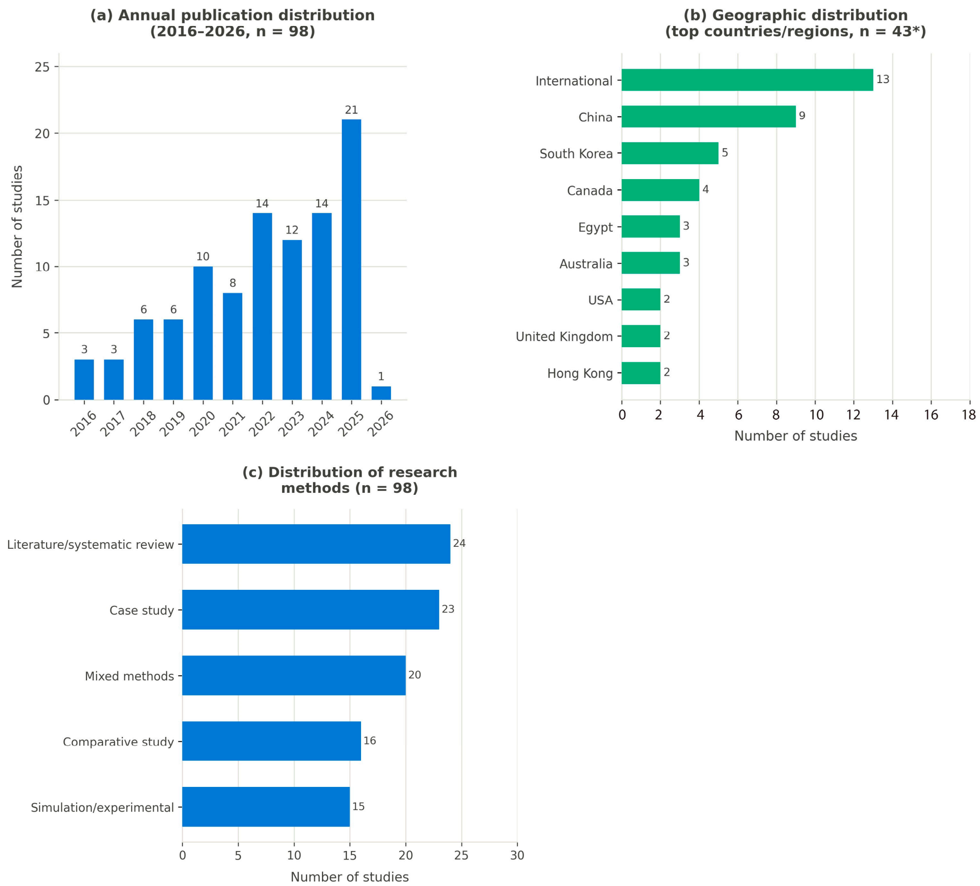

Figure 2. Descriptive characteristics of the 98 included studies: (**a**) annual publication distribution 2016_2026; (**b**) geographic distribution by country or region; (**c**) distribution of research methods.

3. Results

3.1. Historical Development of Modular and Flexible Residential Systems

Offsite construction techniques were first developed before industrialization, according to historical records, which show that prefabricated building components existed during the post-medieval period. The Industrial Revolution, together with post-World War II housing requirements, created a situation that drove the growth of modular construction methods [28].

The United Kingdom initiated its Emergency Factory-Made (EFM) housing program to address the severe housing crisis that emerged after World War II. The Temporary Housing Programme delivered more than 156,000 prefabricated units between 1945 and 1951, representing approximately 13% of the 1.2 million new homes constructed during that period. While modest in proportional terms, this contribution was significant given the experimental nature of the programme and the speed at which these units were designed, manufactured, and delivered under post-war conditions [29,30]. The first prefabricated buildings developed the main concepts that define residential building construction through factory methods by using fast building methods and standardised designs that builders could use to create identical structures.

A parallel trajectory occurred across Eastern Europe, where large-scale prefabricated concrete panel construction became the dominant housing typology during the second half of the 20th century. In Romania and other Eastern European countries, precast large concrete panel systems were widely deployed to meet mass housing demands under centralized planning. These buildings, while efficient to construct at scale, have since required significant structural and thermal rehabilitation interventions to meet contemporary performance and comfort standards [31]. The opportunities and barriers associated with deep rehabilitation of this collective housing stock remain a significant challenge across the region, with implications for both sustainability and social equity [32].

Architectural design in modular systems achieved its peak development in Western Europe and North America. Moshe Safdie created Habitat 67, which stands as the most recognizable representation of this architectural era, from his design for Expo 67 in Montreal [33]. The project used prefabricated concrete modules to show that high-density housing can achieve structural efficiency while creating unique spatial designs that permit residents to connect with their community through their personal space [34]. From the 1970s to the 1990s, interest in prefabricated housing fluctuated, typically rising during periods of social or economic crisis and declining during periods of relative stability [35]. The sector underwent a significant transformation in the late 20th and early 21st centuries, driven by advances in digital design tools, sustainable materials, and environmental awareness.

A bibliometric analysis of prefabricated timber construction from 1990 to 2023 documents the growing prominence of cross-laminated timber (CLT) as a modular building material, particularly for systems designed for disassembly and reuse [36]. Steel and concrete modular systems similarly evolved during this period, with comparative studies examining their structural performance, lifecycle environmental impact, and applicability across different residential typologies [37].

From 2015 onwards, the literature reflects an accelerating convergence between modular construction and flexible design principles. Studies increasingly document hybrid systems that combine the efficiency and scalability of prefabrication with spatial strategies that allow reconfiguration over the building's lifetime [38,39]. In this review, hybrid systems refer to integrated residential solutions that combine modular construction (prefabricated structural or volumetric components) with flexible design strategies (adaptable layouts, open building principles, and reconfigurable infill) at the building system level, rather than at the scale of individual structural components.

The distribution of included studies by publication year (Figure 2) confirms this trend, showing a clear upward trajectory from 3 studies in 2016 to 21 in 2025, coinciding with growing policy attention to housing sustainability and affordability.

These historical trends set up today's tension: while modular production enables efficiency, flexibility in use was not originally designed in. This history thus motivates the combined focus of this review.

Despite the rich historical record of modular prefabrication, the literature reveals a recurring and unresolved tension: periods of intensive modular construction have consistently failed to produce lasting industry transformation, with adoption rates declining once the immediate pressure subsided [35]. The reasons for this cyclical pattern remain inadequately theorized. Existing historical studies are predominantly descriptive rather than analytical, focusing on what was built rather than on the institutional, regulatory, and economic conditions that shaped adoption and abandonment. The transferability of historical lessons to contemporary contexts is assumed rather than examined.

3.2. Typologies and Materials Used in Modular Construction Systems

The literature identifies several distinct typologies of modular construction systems used in residential architecture, which designers can use to create different architectural designs through their various building methods and construction processes, as well as their ability to create movable architectural elements. The different typologies exist as separate categories because designers frequently create hybrid systems that use multiple typologies together to build their designs [40,41].

Two-Dimensional Panelised Systems consist of flat prefabricated panels (wall, floor, and roof elements) that are produced in factory conditions and assembled on-site. Panelised construction allows for a high degree of architectural variation in plan and elevation while maintaining production efficiency. Open-panel systems leave space for services and insulation to be added on-site, while closed-panel systems arrive fully finished [40,42].

Three-Dimensional Volumetric Systems represent the highest degree of prefabrication, involving the off-site manufacture of complete three-dimensional units (rooms or entire apartment modules) that arrive on-site largely finished and ready for connection. Volumetric systems offer significant time and quality advantages but require precise logistical coordination and impose constraints on transport dimensions [43].

Open Building Systems are based on the principle of separating the permanent structural support from the adaptable interior infill. This separation allows occupants or building managers to modify interior layouts independently of the primary structure, enabling long-term spatial flexibility without structural intervention [44,45].

Plug-in and Expandable Systems enable users to add, remove, or adjust modular components according to their changing requirements and site conditions [46].

Kit-of-Parts Approaches treat the building as an assemblage of standardized, interchangeable components that can be combined in multiple configurations. The method uses industrial manufacturing logic, which works like the automotive and consumer goods industries, to create multiple product variations within its industrial production system [47]. Across these typologies, a key pattern emerges: higher prefabrication does not automatically produce higher adaptability [44,48]. Volumetric systems maximize delivery efficiency, whereas open-building, plug-in, and kit-of-parts approaches provide the strongest basis for long-term user adaptation. Table 1 provides a comparative overview of these typologies across key characteristics documented in the literature.

Table 1. Comparative Overview of Modular Construction Typologies in Residential Architecture.

Typology	Prefab Level	Flexibility	Materials	Application	Ref
2D Panels	Panel-level prefabrication (walls, slabs, roof)	Medium	Timber, steel, concrete	Walls, floors	[40,42]
3D Modules	Volumetric prefabrication (room-sized units)	Low–Medium	Steel, concrete, timber	Room units	[39,43]
Open Building	Separated structure and infill system	High	Mixed	Adaptable housing	[18,45]
Plug-in/Expandable	Add-on modular units over time	High	Timber, steel	Incremental housing	[46]
Kit-of-Parts	Standardized interchangeable components	High	Mixed	Custom housing	[47]

In terms of material use, the literature identifies four main material types that architects use in their building designs. Cross-laminated timber (CLT) is a lightweight material suited to design-for-disassembly, with the capacity to store biogenic carbon within its structure over the building's lifetime [45,49,50]. Designers prefer steel modular systems as they combine high structural performance with exact manufacturing methods and the ability to be reused [51]. Precast large panel systems and other concrete materials have become the standard building material for large residential projects throughout Eastern Europe [32] and Asia because they provide both strong structural support and fire protection, although they carry a higher embodied carbon footprint during production [50]. Hybrid structural systems combine two or more material types to optimize structural, environmental, and economic performance across different residential contexts [42]. The typological diversity of modular construction systems raises a set of fundamental design questions that cut across all categories, regarding standardization, customization, flexibility, environmental performance, and regulatory compliance. These questions, illustrated in Figure 3, frame the key challenges that the subsequent sections of this review address.

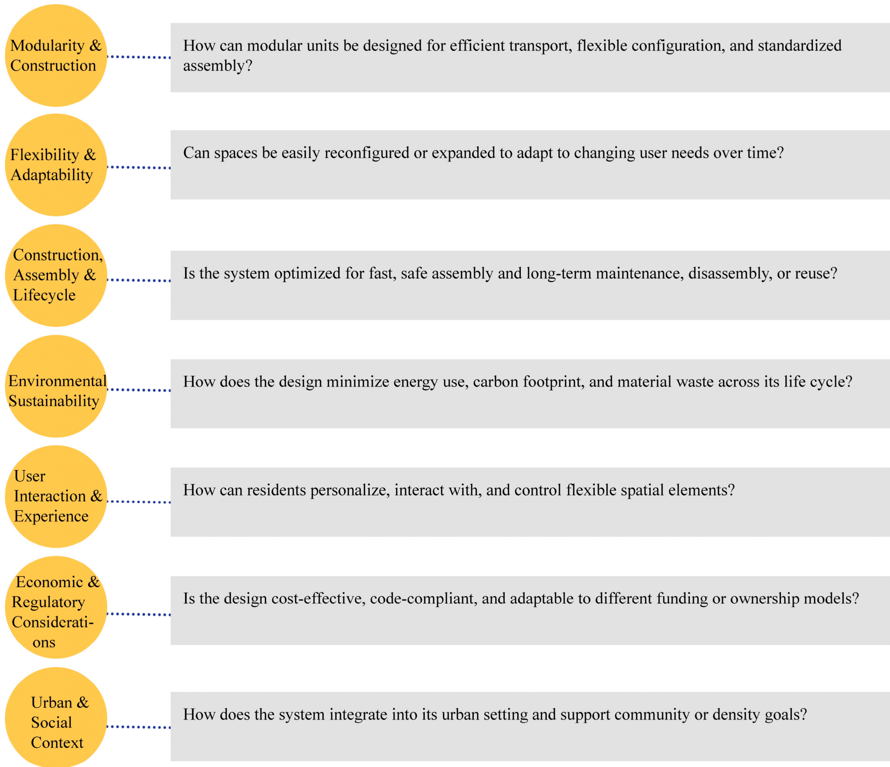

Figure 3. Key questions to consider during the modular residential design process. Authors' own elaboration based on the reviewed literature [9,12,13,17,41–44].

The typological literature reveals several unresolved tensions. First, there is no consensus on performance comparisons between system types: studies comparing volumetric and panelised systems report contradictory findings on cost efficiency depending on context, scale, and regulatory environment [40,43]. Second, the environmental performance of concrete-based systems versus timber or steel alternatives is contested. While CLT is consistently associated with lower embodied carbon [49], its structural performance in multi-storey modular applications remains less documented than steel or concrete alternatives [51]. Third, the literature on hybrid systems is growing but methodologically immature, with most studies reporting single case studies rather than comparative evidence [38,42].

3.3. Flexibility Mechanisms and User Adaptability

The literature documents a range of terms used to describe buildings' capacity to change over time. Notably, "flexibility" here refers to (a) design affordances (e.g., movable internal partitions) versus (b) actual occupant reconfiguration. It was found that the literature discusses both. Table 2 synthesizes the key terms as defined across the reviewed studies.

The Open Building framework, first theorized by Habraken in 1972, provides the foundational conceptual basis for most flexibility strategies documented in the literature [53]. This framework separates the permanent structural support from the adaptable interior infill, allowing occupants or building managers to reconfigure interior layouts independently of the primary structure. The principle supports various modern modular systems that engineers create to enable building transformations for extended periods.

Table 2. Key Definitions Related to Flexibility in Residential Architecture.

Term	Definition	Scale	Reference
Flexibility	Ability to modify internal layouts with minimal intervention	Interior	[17,18]
Adaptability	Capacity to accommodate changing user needs over time	Interior–structural	[9]
Convertibility	Ability to change the building function or use	Functional	[25,45]
Transformability	Capacity for major structural reconfiguration	Structural	[43,44]
Elasticity	Ability to expand or contract spatial capacity	Spatial	[38,46]
Dismantlability	Ability to disassemble components for reuse or relocation	Material	[47,52]

The literature identifies several distinct mechanisms through which flexibility is achieved in residential architecture. The most frequently reported mechanism for spatial reconfiguration involves using movable partitions, demountable partitions, and multipurpose furniture together with open-plan designs, which enable users to rearrange spaces without needing to make structural changes. The building scale application of this principle allows dwellings to expand or shrink according to changing household sizes or operational needs through modular expansion capabilities, permitting the addition or removal of volumetric units [43].

Structural adaptability operates at a deeper level, enabling actual modifications to the building framework. Studies document the use of long-span structural systems, oversized floor-to-ceiling heights, and prefabricated demountable connections as strategies that allow future structural changes without demolition [9,54]. Figure 4 illustrates the levels of flexibility in residential design as synthesized from the reviewed literature. The framework was developed inductively through thematic analysis of the included studies, drawing in particular on the theoretical foundations established by Schmidt and Austin [44], Habraken [53], and Schneider and Till [18], whose work distinguishes flexibility by the scale and permanence of spatial intervention. The five levels (structural, spatial, functional, user-level, and locational) are ordered from the deepest and most permanent form of adaptation (modifications to the primary structure) to the most immediate and reversible (daily user interaction and building relocation), reflecting the spectrum of flexibility strategies documented across the reviewed studies [9,17,18,41,52].

Design-for-disassembly principles, closely linked to circular economy objectives, ensure that modular components can be removed, refurbished, and reused at the end of life, with digital tracking systems increasingly used to manage this process [52]. User interaction with flexible spaces is documented across several studies. Flexibility in use enables both tenants and housing managers to implement spatial changes over time, supported by the design and construction of the dwellings [17].

Residential design integrates diverse flexibility levels, which enable different occupant requirements to be met throughout their residency period [55]. These range from spatial flexibility to structural adaptability, which permits actual changes to the building framework. Flexible housing designs that integrate room layout variability and accessible service runs allow for changes in use without requiring major structural intervention, extending building lifespan and reducing the need for demolition [18].

The literature also documents a financial dimension to flexibility. Preliminary studies indicate that offering limited layout flexibility may result in a space cost increase of approximately 6%, while full flexibility could add up to 26% to construction costs [17,18]. However, studies consistently note that these upfront costs are offset by improved value retention, extended building lifespan, and reduced lifecycle costs [56].

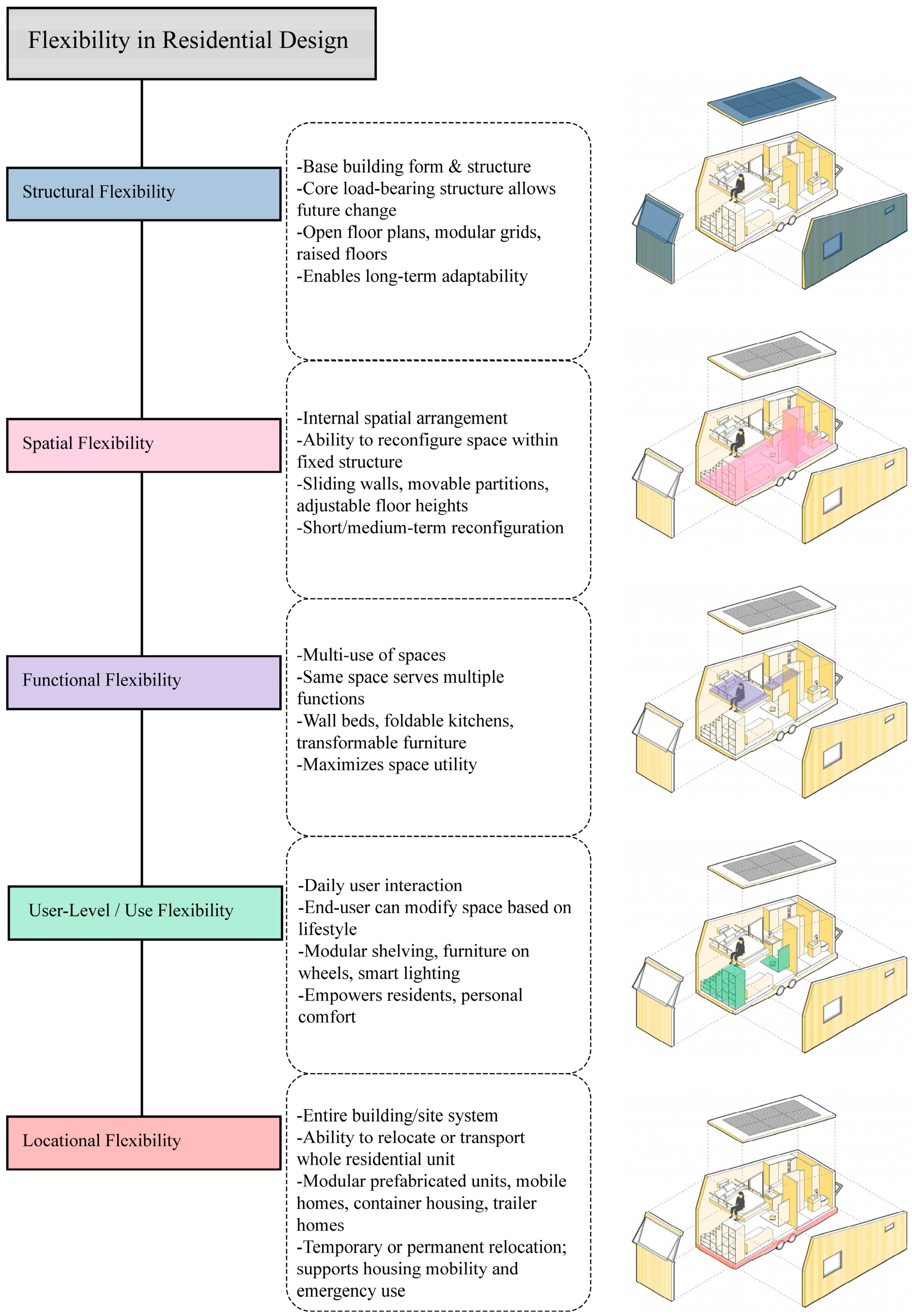

Figure 4. Levels of flexibility in residential design. Authors' own elaboration based on the reviewed literature [9,17,18,41,44,52,53].

From a user well-being perspective, flexible housing is documented as improving occupant satisfaction by offering individualized spaces that respond to residents' changing needs, contributing to both psychological well-being and social sustainability [57,58].

The literature shows that flexibility mechanisms are most effective when integrated from the earliest design stages [17,51], particularly when structural, spatial, and service strategies are coordinated within a coherent framework rather than applied as isolated features.

The flexibility literature contains several significant methodological limitations. Most studies measure flexibility as a design affordance rather than as an outcome of actual occupant behaviour [59]. The gap between designed flexibility and realized flexibility remains one of the most consistently acknowledged but least empirically addressed problems in the field [18,57]. Additionally, the cost premium figures cited in the literature derive from a small number of European studies and have not been validated across different regulatory, labour market, or material cost contexts.

3.4. Digital Technologies Supporting Modularity and Flexibility

The adoption of digital technologies in modular construction has transformed design workflows, manufacturing operations, and on-site assembly methods. Building Information Modelling (BIM), 3D printing, robotics, digital twin technology, Internet of Things (IoT) sensors, and augmented/virtual reality (AR/VR) systems collectively contribute to greater accuracy, efficiency, and environmental sustainability across construction processes [20,60]. Table 3 provides a structured overview of these technologies, their functions, documented benefits, and reported challenges. These technologies operate across different phases of the building lifecycle: BIM and digital twins primarily support the design and manufacturing phase, robotics and 3D printing apply during production and assembly, while IoT sensors enable performance monitoring and post-occupancy adaptability [61].

Table 3. Overview of digital technologies in modular construction: functions, benefits, and challenges.

Technology	Purpose	Benefits	Challenges
BIM (Building Information Modelling)	Shared data environment for design, fabrication and assembly coordination	Reduced errors; improved stakeholder collaboration; supports design-for-disassembly integration from the early design stage	High upfront infrastructure cost; software licensing; interoperability gaps; staff training requirements
Digital Twins	Real-time virtual replica of physical building systems updated via IoT sensors	Enables monitoring of structural behaviour, energy consumption and spatial use patterns; supports data driven maintenance and reconfiguration decisions	Requires continuous IoT infrastructure; cybersecurity management; significant ongoing operational costs
3D Printing	Fabrication of geometrically complex building components	Reduced material waste; shorter production schedules; greater design freedom	Limited structural performance of printable materials; slow production speed; absence of regulatory frameworks for printed structural elements
Robotics and Automation	Automated factory based modular production	Improved manufacturing precision; reduced variability; enables higher customization within standardized frameworks	High capital cost; designed for standardized geometries, limiting flexibility for design variation in hybrid systems
IoT Sensors	Real-time data collection across building systems	Supports energy efficiency; occupancy monitoring; post-occupancy adaptability	Requires infrastructure investment; raises privacy and data security concerns
AR/VR	Design visualization and on-site training	Supports design communication; stakeholder engagement; construction training	High hardware cost; software integration complexity; skills gap for effective deployment

The research studies examined in the literature review show that BIM constitutes the most commonly used digital tool for architectural engineering purposes. The system enables design, fabrication, and assembly process coordination through its shared data environment, resulting in decreased errors and improved stakeholder collaboration, and can support design-for-disassembly methods when such strategies are integrated from the early design stage [62]. BIM-based modular workflows enable precise tracking of prefabrication tolerances and monitoring of component reuse throughout the building's entire lifecycle [60,62].

Digital twins create virtual replicas of physical building systems which receive real-time updates through Internet of Things (IoT) sensors. Studies report their application in tracking structural behaviour, energy consumption, and spatial use patterns, supporting data-driven decisions about maintenance and reconfiguration [63].

Additive manufacturing (3D printing) is documented in the context of component fabrication and experimental housing prototypes. Studies report its capacity to produce geometrically complex building components with reduced material waste and shorter construction schedules, though full-scale residential application remains largely experimental [64]. The sustainability implications and limitations of digital personalization in modular housing are illustrated in Figure 5.

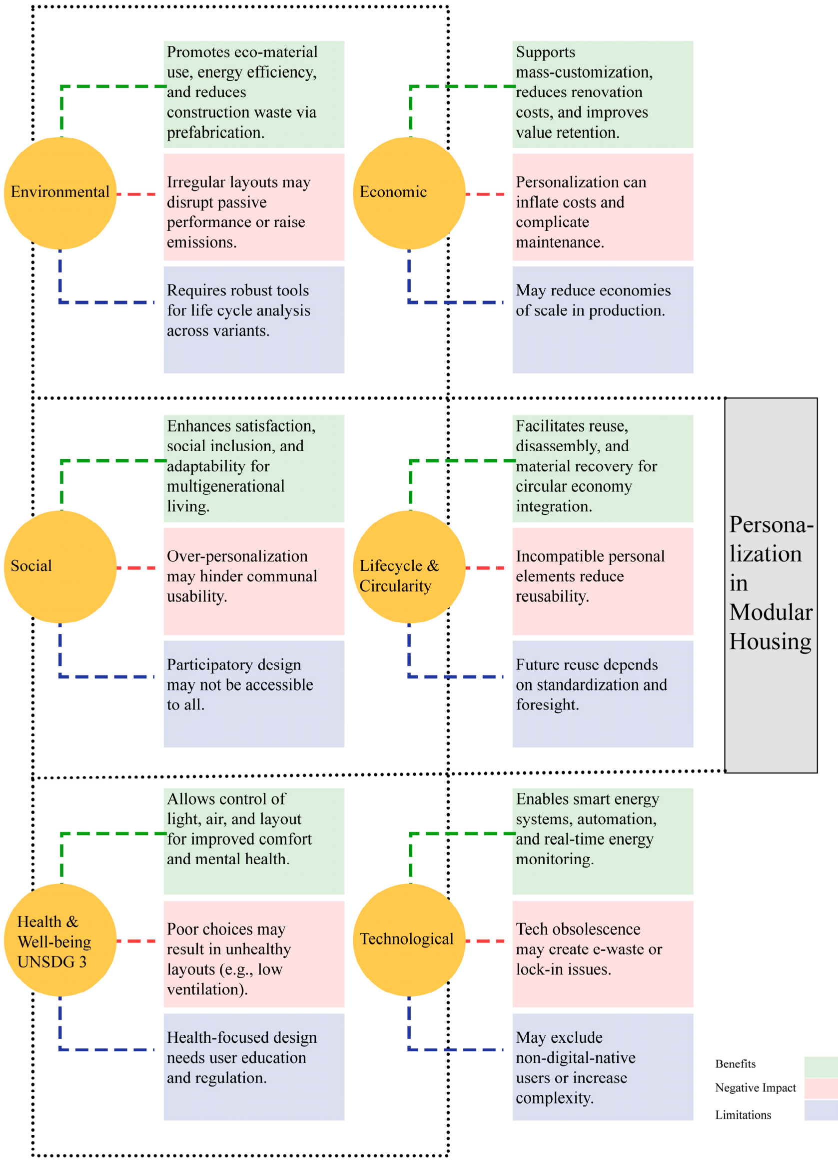

Figure 5. Sustainability benefits, impacts, and limitations of personalization in modular housing.

Robotics and automation are documented in factory-based modular production, improving manufacturing precision, reducing variability, and enabling higher degrees of customization within standardized production frameworks [65]. Studies using artificial intelligence and computer vision techniques further document their emerging role in automating inspection and quality control in offsite fabrication [61]. AR/VR technologies are reported as supporting design communication, stakeholder engagement, and on-site training [66].

The literature notes that BIM adoption is well documented across multiple contexts and is increasingly integrated into standard prefabrication workflows [62]. However, the remaining technologies like digital twins, robotics, 3D printing, and AR/VR, are predominantly reported in research prototypes and pilot projects rather than mainstream residential production, and their reported benefits should therefore be interpreted as promising rather than uniformly mature [67].

Several practical barriers constrain broader adoption. Implementation costs represent the most consistently documented challenge: BIM infrastructure, software licences, staff training, and interoperability upgrades impose significant upfront investment that is difficult to justify in small- and medium-scale residential projects [62]. Digital twin systems require continuous IoT sensor networks, real-time data infrastructure, and cybersecurity management, creating ongoing operational costs that many housing developers cannot absorb [63]. Additive manufacturing at the full building scale remains constrained by material limitations as well as slow production speeds and the absence of regulatory frameworks governing printed structural elements [64]. Robotic assembly systems, while highly precise in factory settings, are designed for standardized component geometries and lack the flexibility to adapt to design variation, limiting their applicability in customized or hybrid modular systems [65]. AR/VR technologies face barriers related to hardware cost, software integration with existing BIM environments, and the skills required for effective deployment on construction sites [66].

Geographic and sectoral disparities further compound these constraints. The evidence base for digital technologies in modular residential construction is concentrated in highly industrialized contexts where regulatory environments and industry capacity support adoption. In developing regions, where modular construction could have the greatest social impact, digital technology integration remains largely unreported in the literature [20,68].

While digital technologies play a critical role in enabling modular and flexible design and construction processes, their broader value is ultimately reflected in the environmental, economic, and social performance of residential systems [56,69].

The digital technologies literature is characterized by a pronounced optimism bias: most studies report potential benefits under controlled or pilot conditions rather than measured outcomes in mainstream residential production [67]. Comparative studies that evaluate digital technology adoption across different scales, contexts, or regulatory environments are rare. Furthermore, the environmental footprint of digital infrastructure itself is almost absent from the reviewed literature, representing a significant blind spot in the sustainability narrative [60].

3.5. Environmental, Economic, and Social Performance Indicators

The reviewed literature documents quantitative and qualitative evidence on the environmental, economic, and social performance of modular and flexible residential systems; however, the included studies vary considerably in their evaluation indicators, system boundaries, geographic contexts, and analytical scales, which limits direct cross-study comparability. To address this, a structured synthesis framework was applied during data extraction and analysis. Performance indicators were grouped into three dimensions (environmental, economic, and social) following established sustainability assessment practice [11,13]. Within each dimension, findings were classified according to their evidence type: quantitative metrics supported by measured or modelled data were distinguished from qualitative assessments based on expert judgment or descriptive reporting. Where multiple studies reported the same indicator using different units or system boundaries findings were normalized thematically rather than numerically, and ranges rather than point estimates are reported where appropriate. Studies reporting context-specific findings, such as the Hong Kong MiC analysis [69] or the South Korean embodied carbon comparison [4], are presented as documented case evidence rather than generalizable benchmarks. This approach acknowledges that the heterogeneity of the evidence base precludes meta-analytic aggregation and that the performance ranges reported in Table 4 should be interpreted as indicative of documented trends rather than universal values.

Table 4. Summary of documented performance indicators for modular and flexible residential systems.

Performance Dimension	Indicator	Finding	Key Sources
Environmental	Material waste reduction	Up to 80% less waste	[23,70]
Environmental	GHG emissions reduction, embodied carbon	~20.7% (MiC, Hong Kong)	[69]
Environmental	Embodied carbon reduction	Up to 20% (circular design)	[8,49,50]
Economic	Construction time	30–50% reduction	[11,13]
Economic	Construction cost	Up to 20% reduction	[13,71]
Economic	Flexibility cost premium	+6% to +26% upfront	[17,18]
Social	Occupant satisfaction	Increased with flexibility	[57,58]
Social	SDG alignment	SDG 11, 12, 13	[12,72]
Social	Post-occupancy evidence	Limited	[21,58]

- Environmental Performance

Modular construction is consistently documented as producing lower environmental impacts than traditional on-site construction across several metrics. Studies report reductions in material waste of up to 80% in factory-based production environments compared to conventional construction [70]. A lifecycle analysis of the Kai Tak Community Isolation Facility in Hong Kong showed that modular integrated construction (MiC) achieved a 20.7% reduction in embodied carbon compared to a hypothetical equivalent conventional reinforced concrete construction approach, primarily attributable to shortened construction timelines, reduced waste generation, and optimized material usage [69]. In 2019, the built environment was responsible for approximately 21% of global greenhouse gas emissions, of which 18% originated specifically from the production of cement and steel used in construction and refurbishment [6]. Global greenhouse gas emissions from residential and commercial building materials present a significant decarbonization challenge. Modelling across mitigation scenarios shows that combining material efficiency strategies could substantially reduce emissions from the building materials sector through to mid-century, though ambitious action across all strategies simultaneously is required to approach climate targets [73,74].

- Economic Performance

The reviewed studies provide comprehensive documentation of established economic benefits that modular construction delivers to the construction industry. The construction time for volumetric modular systems shows a 30 to 50% reduction when compared to traditional construction methods [11,13]. Cost reductions of up to 20% are documented in studies examining factory-based prefabrication, attributed primarily to reduced on-site labour, fewer weather-related delays, and improved material efficiency [13,71].

Flexible housing designs carry documented upfront cost premiums. Preliminary studies indicate that limited layout flexibility adds approximately 6% to construction costs, while full flexibility can increase costs by up to 26% [17,18]. However, these upfront costs are reported to be partially offset by improved value retention, reduced lifecycle maintenance costs, and extended building lifespan [71,75]. Modular housing systems deliver affordable housing solutions to high-demand urban markets at a faster rate through their capacity to accelerate construction delivery [76].

- Social Performance

Social performance indicators in the reviewed literature focus primarily on user satisfaction, well-being, and equity. Flexible housing is consistently associated with higher occupant satisfaction, attributed to its capacity to accommodate changing household needs and personal preferences over time [57,58]. Studies document that spatial flexibility contributes to psychological well-being and a sense of agency among residents [58].

The alignment of modular and circular construction with the UN Sustainable Development Goals is documented in the literature, with contributions to SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) reported in relation to construction-and-demolition waste reduction, lower whole-life/embodied carbon, and affordable housing provision [10,72,77].

The performance literature is fragmented across three dimensions that are rarely integrated within a single study. Environmental studies tend to focus on embodied carbon at the construction stage while excluding operational energy and end-of-life scenarios. Economic studies focus on upfront construction costs while providing limited evidence on lifecycle value retention or resale performance of flexible housing. Social studies focus on short-term satisfaction metrics while providing almost no longitudinal evidence on how occupant wellbeing evolves with flexible spaces over time [21,58]. The absence of integrated whole-life assessments represents the most significant methodological gap in the current performance literature.

While these findings highlight overall performance trends, important gaps remain in the current body of evidence, particularly regarding long-term evaluation and geographic representation; these are discussed further in Section 4.3.

4. Discussion

The synthesis of evidence across the 98 included studies supports the development of a cross-scale conceptual framework that connects three interdependent levels of analysis: production logic, occupant adaptation, and sustainability outcomes (Figure 6). At the first level, production logic encompasses the design, manufacturing, and assembly decisions that define a modular residential system, including its typological classification, material composition, and integration of digital technologies. At the second level, occupant adaptation describes how residents interact with, modify, and inhabit their spatial environments over time, encompassing flexibility mechanisms, user satisfaction, and reconfiguration across the building lifecycle. At the third level, sustainability outcomes capture the environmental, economic, and social performance generated by the combined effect of production decisions and occupant behaviour across the building's full lifecycle.

The three levels are structurally interdependent: production constraints shape the range of adaptation possibilities available to occupants; user needs and behaviours, in turn, drive design innovation at the production level; and together, these levels determine the sustainability outcomes realized over time. A feedback loop from sustainability outcomes back to production logic reflects the growing influence of lifecycle performance evidence on design and manufacturing decisions. The cross-scale framework draws on six established theoretical traditions that collectively provide its conceptual grounding. Open Building Theory, first formulated by Habraken [53] and subsequently extended through empirical research [55], provides the foundational separation between permanent structural support and adaptable infill that underpins the framework's second level. Adaptability Theory, as synthesized by

Schmidt and Austin [44], supplies the taxonomic structure for distinguishing flexibility by scale and permanence of intervention informing the typological classification in Table 1 and the levels of flexibility in Figure 4. The Circular Economy Framework [7,10] grounds the environmental dimension of the third level, linking design-for-disassembly principles [9] and material reuse strategies to embodied carbon reduction and whole-life performance.

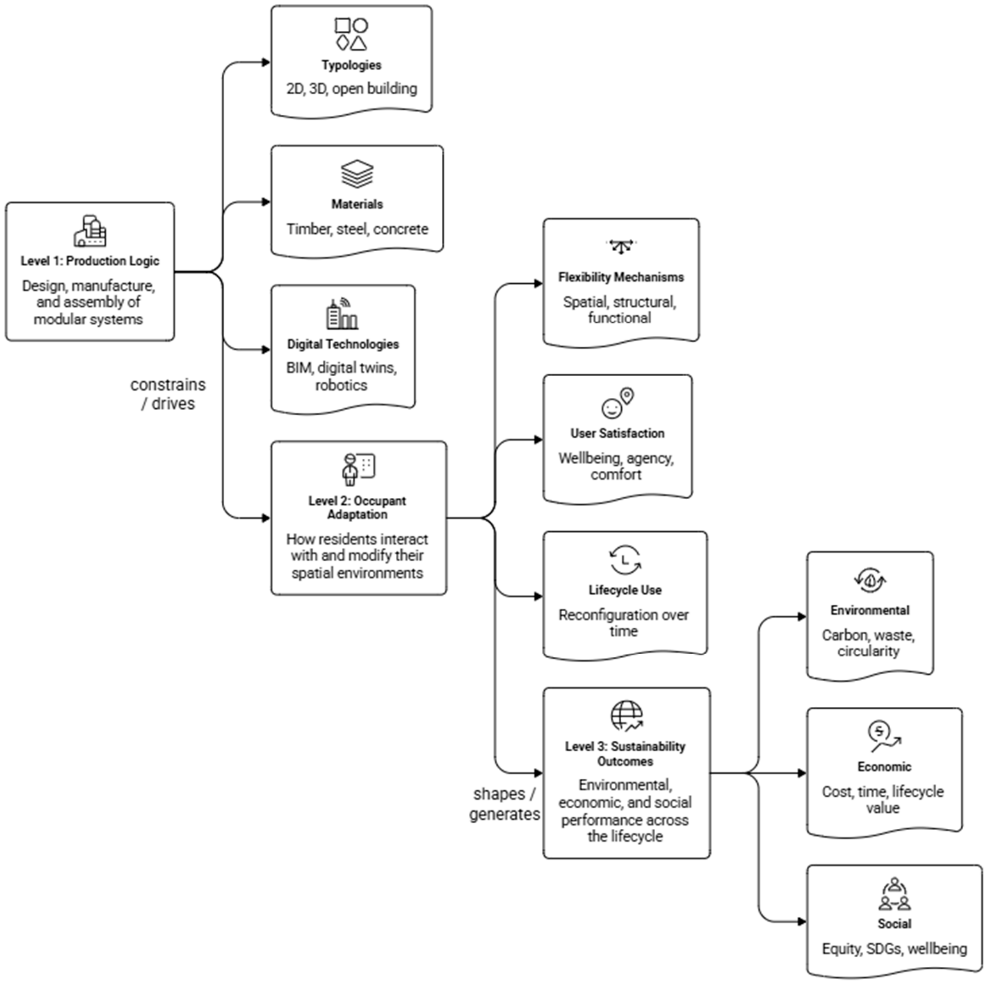

Figure 6. Cross-scale conceptual framework linking production logic, occupant adaptation, and sustainability outcomes in modular and flexible residential architecture.

Life Cycle Assessment methodology [49,50,69] provides the quantitative basis for evaluating sustainability outcomes across the environmental performance indicators in Table 4. Design for Disassembly principles [9,52] connect the production logic of the first level to the circular economy objectives of the third, establishing the pathway through which construction decisions affect end-of-life outcomes. Finally, Sustainable Building Frameworks anchor the social performance dimension of the third level within a globally recognized normative structure [3,7,12]. Together, these six theoretical traditions are not merely cited as background but are structurally embedded in the framework: each level and each sub-dimension maps to at least one established theory, ensuring that the framework is grounded in existing scholarship rather than constructed ad hoc.

4.1. Hybrid Approaches: Integrating Modularity and Flexibility

The convergence of modular construction and flexible architectural strategies has given rise to hybrid systems that represent the most advanced documented response to contemporary residential challenges [38,78]. The system implements the rapid production and large-scale manufacturing capabilities of prefabrication together with its quality assurance system, while using architectural designs that permit building redesign throughout its operational period to meet market demands and occupant requirements.

The most widely documented hybrid model consists of a permanent structural support system hosting interchangeable living modules. This configuration enables quick reconfiguration in response to change household needs while preserving foundational infrastructure, making it relevant for urban professionals, migrant populations, and households experiencing demographic change [38].

Successful hybrid systems need designers to balance standardization requirements with adaptation needs. The standardized dimensions together with module connections and structural interfaces have been documented as essential requirements that enable efficient assembly and future modifications of prefabricated components [79]. The international coordination standard system, including ISO 2848, serves as the regulatory framework that governs this standardization process to achieve module interoperability among different manufacturers in various operational settings [80].

Modular systems combined with traditional construction methods create extra difficulties for construction projects. The modular unit interfaces need precise coordination with site-built elements, which include foundations, utilities, and external cladding systems, to achieve smooth operational transitions [79,81]. The research demonstrates that modular systems combining prefabricated volumetric units with adaptable design strategies have been used in disaster relief and humanitarian contexts, where rapid assembly, portability, and adaptability are critical requirements [82].

Computational design tools are increasingly documented as enabling the optimization of hybrid systems. These tools use parametric and algorithm-based workflows to evaluate multiple design options against predefined criteria (such as spatial layout, structural constraints, and user preferences), allowing designers to balance flexibility, customization, and production efficiency within modular frameworks [81].

The practical feasibility of hybrid modular–flexible systems varies considerably across economic, regulatory, and cultural contexts. In high-income, highly regulated markets such as Hong Kong and Singapore, hybrid systems have been successfully implemented at scale, supported by government mandates, standardized connection systems, and well-developed supply chains [69,83]. In middle-income contexts such as Egypt and parts of Eastern Europe, the evidence suggests that simpler hybrid configurations offer the most feasible pathway, given cost constraints and the limited availability of specialized modular components [32,57]. In low-income and informal housing contexts, the literature provides almost no documented evidence of hybrid system implementation, representing both the most significant gap in the evidence base and the context where adaptable housing could have the greatest social impact [68]. Cultural dimensions further shape feasibility: studies from Northern Europe document high occupant engagement with flexible spaces [56,59], while evidence from Middle Eastern and Asian contexts suggests that cultural norms around spatial privacy and household configuration may require adaptation of flexibility mechanisms to local residential typologies [57]. These contextual differences underscore that hybrid modular–flexible systems are not a single universal solution but a design and production logic that must be adapted to local conditions to achieve its potential.

4.2. Trade-Offs, Tensions, and Challenges

Despite the well-documented advantages of modular and flexible residential systems, the literature consistently identifies a set of practical barriers that limit broader adoption. Table 5 synthesizes the key strategies, their documented strengths, weaknesses, and unresolved issues as identified across the reviewed studies.

Table 5. Critical Synthesis of Modular and Flexible Residential Strategies.

Strategy	Strength	Weakness	Unresolved Issue
Volumetric modular	Fast delivery, high quality control	Spatially rigid, transport constraints	User adaptation to fixed layouts
Panelised systems	Design flexibility, efficient production	Lower prefabrication level	Integration with services
Open building/infill	High long-term flexibility	Complex coordination, higher cost	Standardization of infill components
Hybrid modular-flexible	Balanced efficiency and adaptability	Design and coordination complexity	Long-term cost evidence
Digitalized/BIM driven	Precise, coordinated, data-rich	High carbon footprint of digital infrastructure, implementation cost	Scalability in developing contexts
Kit-of-parts	Mass customization potential	Limited structural span options	Regulatory acceptance

The most consistently documented tension in the literature is between standardization, which is required for production efficiency, and customization, which is required for user satisfaction and long-term flexibility [59,84]. Highly standardized systems reduce costs and accelerate delivery but restrict spatial variety, whereas highly customized systems enable better alignment with user needs but result in increased production complexity and cost.

Flexible housing designs carry documented cost premiums that vary considerably depending on the degree of flexibility integrated into the design, ranging from modest increases for limited layout options to substantially higher costs when full structural adaptability is pursued [17]. While lifecycle benefits are frequently cited, long-term empirical cost data remain limited [56]. The business case for flexibility in developer-driven housing markets gets undermined by the gap between short-term cost visibility and long-term value. A further underdeveloped issue is delivery logic: the literature rarely compares manufacturer-led platform models, developer-led project procurement, and public-sector commissioning pathways, even though these structures shape how the cost premium of flexibility is distributed across actors and over time. Business models (e.g., manufacturer-owned platforms vs. developer projects) influence these trade-offs [11,16].

The research identifies different types of barriers, which include regulatory and policy obstacles. Existing building codes together with zoning regulations, taxation frameworks, and property assessment systems base their operations on fixed residential models that do not allow for housing solutions that can be modified or transformed throughout their operational life [85]. The existing regulatory system fails to support modular and adaptive design principles, which creates an obstacle that prevents the adoption of these design principles in practice.

Geographic context shapes both the nature and severity of the barriers documented in the literature. In East Asian contexts, regulatory frameworks have actively supported modular construction adoption through standardization mandates and government procurement incentives, resulting in well-documented performance gains in construction time and embodied carbon reduction [69,83]. In contrast, Western European contexts show a more fragmented picture: while flexible housing principles are relatively well established in the Netherlands, Finland, and Scandinavia [55,56], modular construction adoption remains lower than in Asia, constrained by preservation regulations, labour market structures, and conservative procurement practices [85]. In North American contexts, modular construction is predominantly driven by private sector cost efficiency rather than sustainability or flexibility objectives, with limited policy integration. In developing country contexts, the barriers are qualitatively different: financial constraints, skills gaps, limited supply chains, and the absence of modular-specific regulatory frameworks represent the primary obstacles [48,68]. The tendency in the literature to treat modular and flexible housing as a universal solution, without adequately accounting for these geographic and institutional differences, represents one of the field's most significant methodological limitations.

Technical barriers include the challenge of integrating flexible spatial strategies with building services. The HVAC, plumbing, and electrical systems lack necessary adaptive features, which create problems for implementing flexible design solutions that need extensive design planning before execution [17].

Cultural and behavioural dynamics create additional obstacles for implementation. Studies document that residents do not always fully utilize available flexibility features, either due to unfamiliarity with reconfigurable systems or a preference for stable, defined living environments [59]. This gap between designed flexibility and actual use raises important questions about how flexibility should be communicated and supported at the occupant level [59].

4.3. Gaps in Knowledge and Research Priorities

The reviewed literature reveals several significant gaps that limit the current understanding of modular and flexible residential architecture. Rather than presenting these as isolated issues, this section analyses their structural relationships and proposes a prioritized research agenda organized around three interconnected clusters.

Cluster 1—Evidence depth: the absence of longitudinal data

The most fundamental gap in the current literature is the near-total absence of long-term post-occupancy evidence. Most studies report short-term construction-phase metrics (time, cost, and material waste) rather than longitudinal assessments of how buildings and their occupants perform over extended periods [21]. This gap is not independent of the others: without long-term post-occupancy data, it is impossible to verify whether the economic benefits of modular construction materialize in practice [19,56]. Similarly, claims about occupant satisfaction with flexible housing [57,58,86] and about the effectiveness of flexibility mechanisms [17] cannot be validated without evidence of how residents actually use and adapt their spaces over time. This cluster represents the highest research priority because it underpins the credibility of almost every performance claim in the current literature. Future research should prioritize longitudinal case studies of at least five to ten years, tracking both building performance and occupant behaviour across the full range of modular and flexible system types documented in this review.

Cluster 2—Evidence breadth: geographic and contextual concentration

The second cluster concerns the geographic concentration of the reviewed literature in Western Europe, North America, East Asia, and Australia [19,83]. This concentration is not merely a bibliometric imbalance; it reflects a genuine gap in knowledge about the transferability of modular and flexible strategies to contexts with different regulatory frameworks, material supply chains, labour markets, and cultural housing norms [87]. Studies addressing modular construction in developing nations consistently identify barriers that differ substantially from those documented in high-income contexts [48,68]. This matters because the regions most underrepresented in the literature are also those where modular construction could have the greatest social impact in terms of affordable housing delivery and disaster-resilient construction [82,85]. The geographic gap and the post-occupancy gap are structurally linked: without studies conducted in diverse contexts over extended periods, the field cannot determine whether the performance advantages documented in Hong Kong [69] or South Korea [4] are transferable to Sub-Saharan Africa, Latin America, or South and Southeast Asia [4,68,83]. Future research should prioritize multi-context comparative studies that explicitly examine how regulatory, cultural, and economic conditions moderate the performance of modular and flexible systems.

Cluster 3—Evidence scope: whole-life carbon and regulatory frameworks

The third cluster concerns two related gaps in evidence scope. First, while embodied carbon at the construction stage is increasingly documented [50,69], whole-life carbon assessments that integrate operational energy, maintenance, adaptation cycles, and end-of-life scenarios remain rare and methodologically inconsistent [49]. As regulatory frameworks increasingly require whole-life carbon reporting (notably through the EU's Level(s) framework and emerging national building regulations), this gap will become a critical barrier to policy uptake. Second, the literature engages very little with which specific regulatory obstacles prevent the adoption of modular and flexible housing, or with how policy interventions could address them [56,85]. These two gaps are connected: without whole-life carbon evidence, policymakers lack the quantitative basis to design performance-based regulations that incentivize modular and flexible strategies. Future research should prioritize whole-life carbon assessments of hybrid modular–flexible systems across multiple contexts, combined with regulatory mapping studies that identify jurisdiction-specific barriers and propose evidence-based policy pathways.

Prioritized research agenda

Based on this cluster analysis, future research priorities are proposed in the following order: (1) longitudinal post-occupancy studies of modular and flexible residential buildings across diverse geographic contexts, with minimum five-year observation periods; (2) multi-context comparative studies examining performance transferability across regulatory, cultural, and economic settings; (3) whole-life carbon assessments of hybrid modular-flexible systems using consistent system boundaries and lifecycle stages; and (4) regulatory mapping studies identifying jurisdiction-specific barriers and proposing evidence-based policy solutions. Addressing these priorities in sequence would progressively close the most critical gaps in the current evidence base and enable more robust and generalizable conclusions about the long-term value of modular and flexible residential architecture.

4.4. Limitations of the Review

This review has several limitations that should be considered when interpreting its findings. First, the search was conducted across Web of Science, Scopus, and ScienceDirect only, and may not capture all relevant studies indexed elsewhere. Second, the review is restricted to English-language peer-reviewed publications, which may systematically exclude relevant research published in other languages, particularly from regions where modular construction is rapidly developing, and grey literature was not included. Third, of the 197 records sought for full-text retrieval, 88 (45%) could not be accessed despite retrieval attempts through institutional access, open-access repositories, and direct author contact, primarily due to paywall restrictions not covered by the institutional subscription. This non-retrieval rate represents a potential source of selection bias that may partly contribute to the geographic concentration and temporal distribution of the included evidence noted in Section 4.3. Fourth, duplicate removal was performed by the lead author using reference management software without independent verification by a second reviewer, which may have resulted in the retention of undetected duplicates or the erroneous removal of distinct records. Fifth, because the included evidence comprised heterogeneous study types, a formal risk-of-bias tool was not applied; instead, a four-criterion quality assessment framework was used, and variation in study quality among the included publications means that some performance claims rest on stronger evidentiary foundations than others. Sixth, the rapid pace of technological development in modular construction means that some findings may become outdated relatively quickly, and this review should be read as a snapshot of the evidence base as of early 2026. Finally, there is a tendency for positive findings to be published more frequently than null or negative results, which may contribute to an overrepresentation of studies reporting the benefits of modular and flexible systems relative to those documenting failures or limitations.

5. Conclusions

This systematic literature review examined modular and flexible design strategies in residential architecture, drawing on 98 studies identified through a PRISMA-based search across Web of Science, Scopus, and Science Direct. The review addressed a gap in the existing literature by synthesizing modularity with flexibility within a unified framework that links design decisions, user adaptation, and environmental performance.

Beyond synthesizing existing knowledge, this review makes three distinct theoretical contributions to the field:

(i) An integrated cross-scale framework that connects production logic, occupant adaptation, and sustainability performance, three levels of analysis rarely addressed together in prior reviews, which have tended to focus on either construction efficiency or user adaptability in isolation.
(ii) A typological classification system that extends conventional distinctions between volumetric and panelised construction to incorporate flexibility potential, lifecycle adaptability, and sustainability profile across five system types, formalizing for the first time the structural tension between prefabrication level and adaptability potential.
(iii) A critical synthesis of trade-offs that maps three structurally unresolved tensions (between standardization and customization, between upfront cost and lifecycle value, and between designed flexibility and actual occupant use) across six documented strategy types, providing a structured basis for future comparative research.

The evidence reviewed confirms that modular construction offers measurable advantages over traditional on-site methods, including construction time reductions of 30 to 50%, material waste reductions of up to 80%, and cost savings of up to 20%. These gains are achieved through factory-based prefabrication, standardized component production, and parallel site and manufacturing workflows. Flexible residential design extends building lifespan, improves occupant satisfaction, and supports circular economy goals through design-for-disassembly and material reuse, with evidence suggesting partial offsetting of upfront cost premiums through improved value retention and reduced maintenance costs over time, though long-term empirical validation of lifecycle cost savings remains limited.

The review finds that neither modularity nor flexibility alone is sufficient to address the full complexity of contemporary housing challenges. Hybrid systems that integrate the efficiency of modular construction with the adaptability of flexible design represent the most promising documented pathway, combining prefabrication speed with long-term capacity to support reconfiguration, multiple usage scenarios, and evolving spatial needs across the building's lifecycle. Digital technologies, particularly BIM and digital twins, are increasingly enabling the design, coordination, and monitoring of these hybrid systems, though their adoption in mainstream residential production remains uneven.

The ongoing dispute between standardization and customization remains unresolved, with highly standardized systems constraining spatial variety and highly customized systems increasing production complexity and cost. Regulatory frameworks continue to assume static residential configurations, creating systemic barriers to the adoption of adaptive housing. Building services integration, upfront cost premiums, and low occupant awareness of flexibility features further limit practical implementation.

Critical gaps in the literature include the absence of long-term post-occupancy evaluations, limited whole-life carbon assessments, and insufficient regulatory analysis. While embodied carbon at the construction stage is increasingly documented, whole-life carbon assessments that integrate operational energy, maintenance, adaptation, and end-of-life scenarios are still emerging, with current studies mostly based on preliminary estimations rather than fully established long-term evaluations. While research is concentrated in Western Europe, North America, East Asia, and Australia, large parts of the Global South, including Sub-Saharan Africa, Latin America, and South and Southeast Asia, remain underrepresented [21,68,88].

This review offers structured guidance for practitioners and policymakers engaged in the development of resilient, adaptable, and environmentally responsible residential environments. At the policy level, the findings support three priority actions: first, the development of performance-based building regulations that explicitly accommodate modular and adaptable residential systems, moving beyond static building codes designed for conventional construction; second, the introduction of fiscal and procurement incentives for circular construction practices to accelerate the transition from linear to circular housing production; and third, the establishment of standardized modular design guidelines that enable interoperability between manufacturers and regulatory acceptance across jurisdictions. At the industry level, greater integration of BIM and digital manufacturing technologies across the full supply chain represents the most immediately actionable pathway toward improving both efficiency and sustainability performance. At the research level, longitudinal evaluation of occupant satisfaction and housing adaptability over extended periods remains the most critical unmet need, as it underpins the credibility of virtually every performance claim in the current literature. Future research should also prioritize empirical validation of the proposed cross-scale framework through comparative international case studies, and interdisciplinary collaboration between architecture, engineering, environmental science, social science, and housing policy will be essential to advancing the field toward more comprehensive and transferable solutions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings16153052/s1, Table S1: PRISMA 2020 Checklist; Table S2: references.

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