

## APPLICATION OF MODULAR CONSTRUCTION TECHNOLOGIES AND OPEN BUILDING PRINCIPLES TO THE FORMATION OF AN ADAPTIVE RESIDENTIAL ENVIRONMENT

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### **Abstract.**

This paper explores the discrepancy between the extended lifespan of load-bearing building frameworks and the swift functional aging of interior layouts and technical systems. The research seeks to validate an architectural and structural concept for an adaptable housing setting, founded on merging Open Building concepts with modern modular assembly methods. The research material encompasses analyses of Open Building theory, literature on modular building, structural connections, plug-and-play technical apparatus, and building codes for seismic construction in Uzbekistan. The research approach integrates comparative scrutiny, examination of finished projects, structural-logical synthesis, a life-cycle viewpoint as an evaluative structure for assessing efficacy, and the contrasting of structural designs based on dismantlability, maintainability, seismic response, and hardness. The analysis shows that pairing a long-lasting Support framework with a mutable Infill section allows shifting from a fixed design paradigm to an asynchronous pattern of building updating without complete dismantling. It is determined that modular and composite systems employing reversible mechanical fastenings, encompassing bolted links with vibration-dampening inserts and components utilizing shape memory materials, present the highest adaptive capability. Furthermore, relocating utility conduits to designated distribution areas and employing BIM/BEMS platforms enhances spatial adaptability and boost whole-life management. The practical relevance of these findings resides in the utility of the suggested methodology for residential planning in earthquake-prone zones of Uzbekistan, where flexibility, robustness, and lowered costs over the building's service period need to be attained concurrently.

### **Keywords**

adaptive residential environment; Open Building; modular construction; Support and Infill; design for disassembly; plug-and-play engineering systems; seismic performance; building life cycle.

## 1. Introduction

Current architectural and building methods confront a fundamental paradox: the actual operational lifespan of major supporting frameworks considerably surpasses the duration for which interior arrangements, technical installations, and usage patterns stay pertinent. Under the established design model, a structure is regarded as a uniform and functionally static entity. Consequently, frameworks that could safely function for a hundred years or longer become outdated after merely 15-25 years and are then subject to refurbishment involving partial ruin or total teardown. [1; 3; 8].

This structure causes considerable ecological and financial reductions. The forfeit of embedded carbon gathered in the structural framework and the increase of demolition debris are direct results of altering a structure's purpose via the dismantling of sturdy elements instead of through the regulated substitution of adaptable ones. Fundamentally, the issue is not solely technical but procedural: current methods for design and structure administration inadequately separate between structure strata that deteriorate at varying speeds. [1; 8].

In this context, the Open Building concept, proposed by N. J. Habraken and subsequently developed in later studies as a model that separates the building into a durable base structure and changeable internal infill, is of particular importance [3]. In conjunction with contemporary modular technologies, BIM modelling, design for disassembly, and reversible joints, this concept makes it possible to move toward an adaptive architecture designed for repeated modernisation without loss of load-bearing capacity and without radical dismantling [1; 5; 6; 10].

For Uzbekistan, the importance of this subject is determined by the convergence of two factors: the necessity to broaden housing development and the considerable seismic intensity across a large portion of the national territory. Under these circumstances, flexibility cannot be handled just at the level of planning variance; it demands a structural and engineering framework able to sustain strength and ease of repair following severe impacts. [2; 10].

The research seeks to validate an architectural and structural framework for an adaptable housing environment, founded on merging Open Building concepts with modular building methods, and to ascertain the prerequisites for its deployment in earthquake-prone zones. To accomplish this goal, the subsequent aims were established: (1) to organize the conceptual basis of the Open Building notion; (2) to recognize the capability of modern modular assemblies and substances for flexible housing; (3) to contrast connection types and technical designs based on ease of

disassembly, seismic response, and lifespan benchmarks; and (4) to define the constraints and foreseen opportunities for applying this strategy in Uzbekistan.

The research hypothesis is that the combination of a durable Support structure, a changeable Infill layer, reversible mechanical joints, and independent engineering networks makes it possible to create a residential environment that is simultaneously adaptable, structurally reliable, and economically efficient throughout the building life cycle.

## 2. Materials and Methods

The research is analytical and review-oriented in nature and draws upon an interdisciplinary comparison of conceptual, design, and engineering literature. The material examined encompasses writings on the Open Building notion [1; 3; 8], publications concerning infill frameworks and modular standardization [5; 6], figures regarding construction substances and encased carbon [9], investigations into the seismic response of self-aligning connections utilizing shape memory constituents [10], intelligence on OpenADR frameworks and electronic building administration [4], and the stipulations of the regulatory text KMK 2.01.03-96 directing building in quake zones[2].

The methodological structure includes several linked procedures. Initially, a comparative study was held between the conventional monolithic building approach and the flexible Open Building paradigm based on lifespan metrics, choice loci, technical incorporation, and maintainability. Following that, a case-example examination was carried out on completed endeavors - Solid Oud West, NEXT21, and Patch22 - as typical instances of the concrete application of spatial latitude, component standardization, and robust foundational frameworks [5].

Third, structural-logical synthesis was utilized to craft a unified model of an adaptive dwelling environment where the architectural, structural, engineering, and digital aspects are viewed as linked yet distinct strata. Fourth, the building's lifespan served as a framework for analysis: solutions were evaluated not solely by initial capital investments but also by their potential to lower operational expenses, modification needs, repair costs following an event, and final disposal [7].

A constraint of this investigation is that it omits full-scale trials or numerical modeling of a definite building archetype. The findings are thus theoretical and analytical in character and aim to aid the creation of a design approach that can later be confirmed through empirical and computational study.

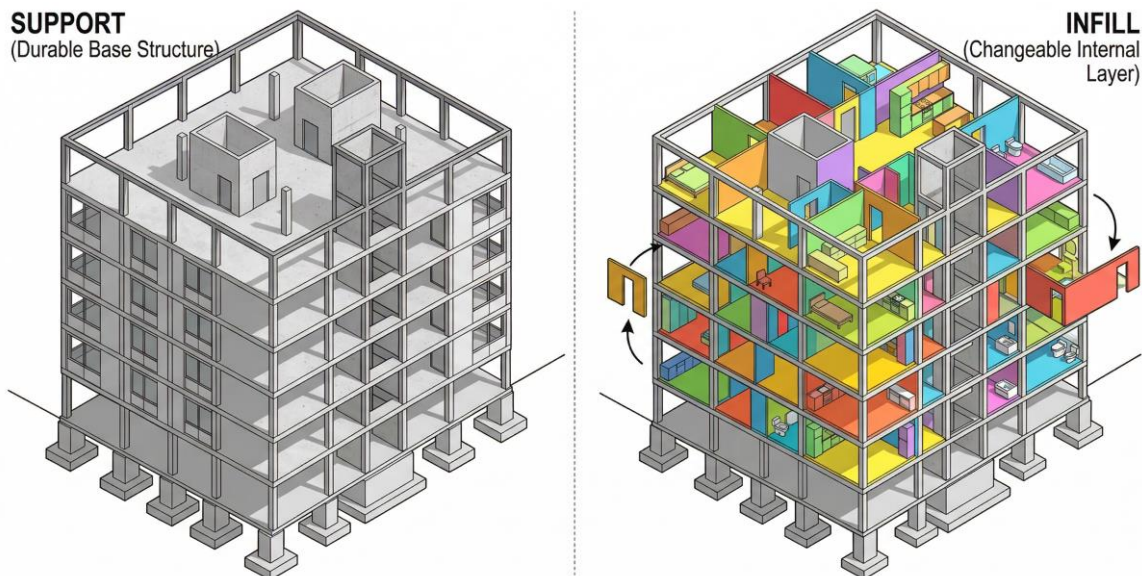
## 3. Results

### 3.1. Theoretical model of an adaptive residential environment

The review indicates that the core concept of an adaptable housing setting is established via segmenting the structure into two tiers with varying operational

durations: Support and Infill. Support encompasses the base, bearing structure, vertical transit shafts, exterior cladding, and main utility conduits. These parts are engineered for extended service and offer the spatial and foundational structure of the edifice. Infill involves interior divisions, surface treatments, plumbing fixtures, cooking areas, localized distribution of utility lines, and other aspects prone to regular alteration driven by occupant demands [3; 8].

The division of Support and Infill alters the fundamental principle of architectural conception. In the standard framework, building shape, the load-bearing structure, and technical systems are closely linked; thus, updating any single component necessitates modification in the others. In the Open Building concept, this reliance is lessened via the spatial, statutory, and technical separation of building strata (Figure 1). The outcome is the potential for staggered revision: lasting components stay in use, while the interior arrangement can be altered numerous times without compromising the structural foundation [1; 3].



**Figure 1 Open Building Concept: Separation of Durable Support and Changeable Infill.**

The practical analysis of realised projects confirms the viability of this approach. Solid Oud West employs a large structural grid and increased storey height, enabling the user to receive an 'empty shell' with the possibility of free internal zoning. In NEXT21, the independence of engineering layers was achieved through the placement of services in raised floors and ceiling voids, together with the strict coordination of dimensions and positions of technical elements. Patch22 demonstrates that structural flexibility can be combined with the transformation of the functional use of floors over the building life cycle [5].

### 3.2. *The role of modular construction in ensuring adaptability*

Modular technologies operate not solely as a method for industrializing building but also as the physical apparatus via which Open Building can be achieved. Modern modular fabrication encompasses volumetric three-dimensional sections, two-dimensional panel setups, and mixed approaches integrating a structure with pre-made enclosure parts. Their main benefit stems from shifting a considerable portion of production tasks to plant environments, which enhances fabrication accuracy, quality assurance, and the control of junctions [5; 6].

Regarding flexibility, the most beneficial modular designs are those allowing repeated construction, individual part swapping, and readjustment without harming neighboring elements. Therefore, assessing modular frameworks must not be confined to metrics like setup swiftness or debris reduction; it also requires evaluating junction reversibility, the level of interface standardization, and the appropriateness of modules for subsequent dismantling and recycling. In this scenario, the Design for Disassembly notion becomes an essential complement to Open Building since it transfers the concept of adaptability into the structural and material realm [6].

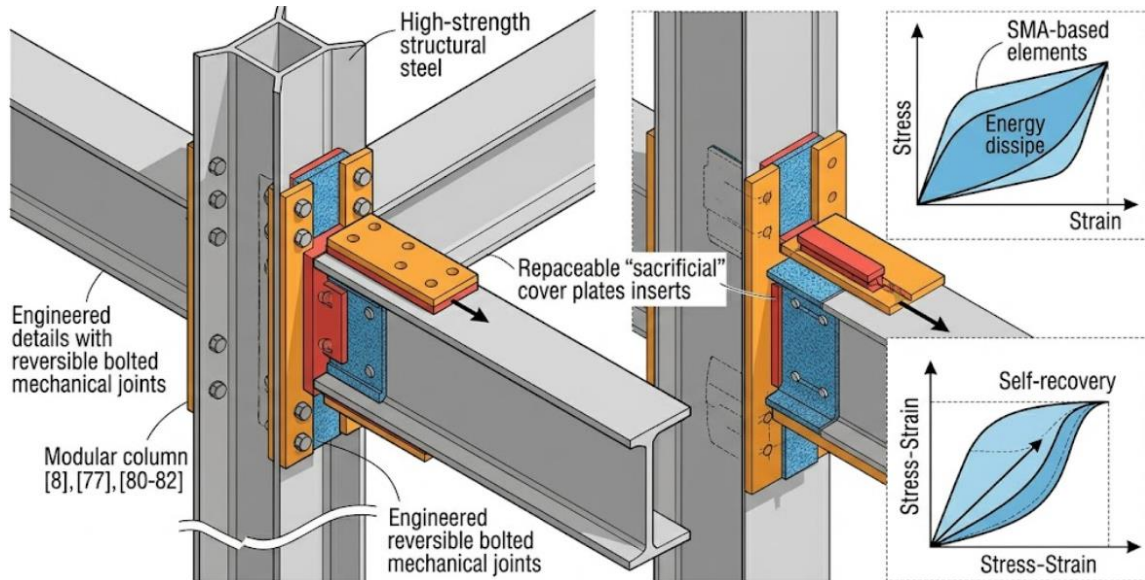
The materials-science aspect also directly influences adaptability. Besides steel and reinforced concrete, engineered timber, composites, and light multilayer boards are gaining importance. These substances lessen component weight, enhance assembly manageability, and decrease embodied carbon. Simultaneously, material choice should be evaluated not just for low-carbon output but also regarding compatibility with reversible connections, longevity, and performance under repeated erection [9].

3.3. Structural joints and the preservation of load-bearing capacity during reconfiguration

A principal outcome of the research is the determination that the structural dependability of a responsive structure is governed mainly not by modularity per se but by the standard of intermodule connections. Connections emerge as the most fragile spots during dynamic and seismic occurrences. Fused connections offer considerable stiffness; nevertheless, they conflict with disassembly concepts, impede element substitution, and render post-failure restoration more demanding of resources. Typical fastened joints are undoable, yet during severe actions, they might transmit crucial stresses to the primary load-bearing members [10].

The most prospective approaches involve hybrid and undoable mechanical connections where harm is confined within deliberately replaceable components – flange plates, shock-absorption plates, inlays, or friction parts. This rationale aligns with the concept of damage displacement: under excessive load, energy is absorbed in the expendable connection, while the primary framework maintains its

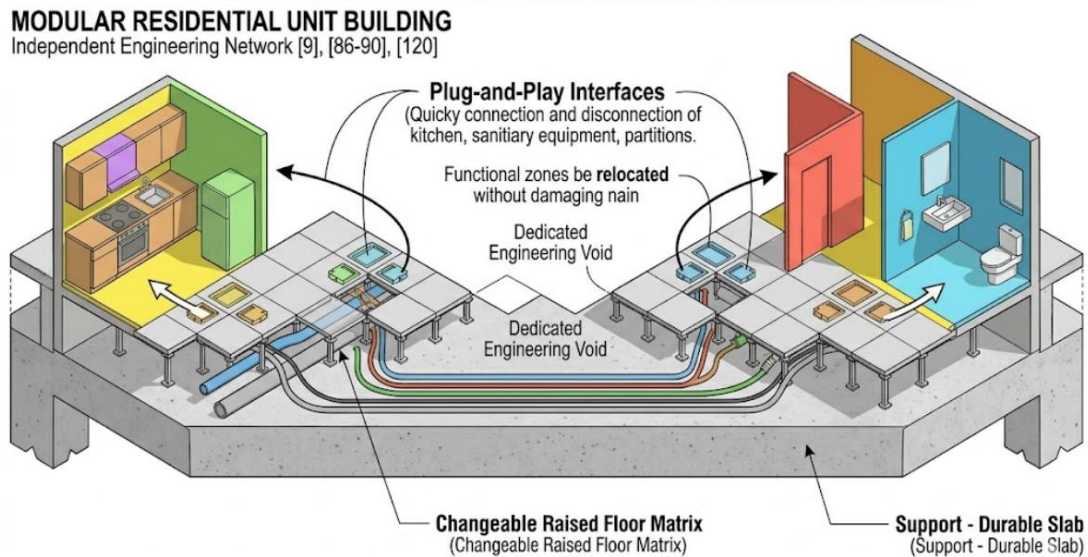
soundness and spatial steadfastness. For adaptive architecture, this is vital because mending following a severe incident ought to be confined to swapping out a standard joint instead of the major rehabilitation of the whole structure (Figure 2) [10].



**Figure 2** adaptive Seismic-Resilient Joint: Damage Localization in Replaceable Elements and Self-Centering Effect of Shape Memory Alloys (SMA).

Particular interest attaches to joints incorporating shape memory alloys. Their use expands the functionality of connections through two effects: energy dissipation and self-centring. Once the load has ceased, SMA-based elements can return to their original shape, thereby reducing residual deformations in the frame. This ensures not only the building's stability during a seismic event but also its continued suitability for operation and reconfiguration afterwards [10]. Under the conditions of Uzbekistan, where seismic resilience must be ensured simultaneously with an increase in housing adaptability, this group of solutions is of particular practical value [2].

*3.4. Independent engineering networks as a condition of spatial flexibility*



**Figure 3 Independent Engineering Networks: Use of Raised Floors and Plug-and-Play Interfaces to Ensure Spatial Flexibility.**

The study shows that even a structurally flexible building does not become genuinely adaptive if its engineering systems remain rigidly embedded in load-bearing components. Consequently, the second fundamental component of an adaptive environment is an independent layer of engineering infrastructure. In practice, this is achieved by relocating service distribution to dedicated zones such as raised floors, suspended ceilings, technical underfloor spaces, service shafts, and distribution galleries (Figure 3) [5; 6].

SlimLine and Matura demonstrate two complementary approaches. In the first case, service channels are integrated into the floor structure without compromising the performance of the load-bearing elements; in the second, a lightweight distribution matrix for pipes and cable routes is formed above the base slab. For adaptive housing, this means that sanitary and functional zones can be relocated without damaging the main frame and without dependence on fixed connection points [5; 6].

The digital dimension of this model is provided by BIM and building management systems based on open protocols. When a digital twin is available, each module and each engineering component receives an identifier, while the BEMS platform records performance, loading, and maintenance parameters. Adaptability thus ceases to be merely an architectural property and becomes a manageable characteristic of the building life cycle [4].

### 3.5. Environmental and economic effects of the adaptive model

The contrast between conventional and flexible building methodologies reveals that the crucial metric is not the reduction of upfront capital outlays but the

reshaping of the spending framework throughout the complete structure lifespan. The greater initial expense for intricate reversible connections, elevated flooring, and spread-out technical apparatus is balanced by lesser expenses for alteration, fault correction, subsequent incident mending, and demolition [7].

The adaptive model also reduces environmental costs because it preserves the durable structural frame and decreases the volume of construction waste. When the 'demolition - new construction' scenario is replaced by a scenario of deep modernisation or phased module replacement, a substantial share of the previously invested material and energy resources is retained. Adaptive residential environments may therefore be understood as an architectural form of the circular economy, in which the building is designed not as a final product but as a durable platform for successive transformations [6; 7; 9].

#### 4. Discussion

The findings gathered suggest that flexibility in building design should not be narrowed to just the variation of layouts. It necessitates the synchronization of a minimum of four tiers: the conceptual tier (distinguishing Support from Infill), the structural tier (reversible connections and a logic for redeemable damage), the engineering tier (separate plug-and-play systems), and the digital tier (BIM/BEMS serving as tools for lifetime maintenance). Lacking any single one of these tiers significantly diminishes the potency of the entire framework. From a scholarly standpoint, the significance of the study lies in the integration of previously fragmented fields - Open Building, modular construction, Design for Disassembly, seismic self-centring joints, and digital building management - into a single framework for assessing adaptive residential environments. This synthesis makes it possible to explain more precisely why not every modular building is adaptive: modularity without disassemblable interfaces, service independence, and a life-cycle strategy may accelerate assembly, but it does not create the conditions for long-term transformation.

For practice in Uzbekistan, the key point is that the proposed model reconciles the requirements of flexibility and seismic resilience, which in mass housing are often treated as competing priorities. On the contrary, the analysis shows that localising damage in replaceable joints and reducing residual frame deformation after earthquakes makes it possible not only to preserve safety but also to accelerate building recovery without long-term withdrawal from use [2; 10].

At the same time, there are significant implementation constraints. These include the conservatism of industry practice focused on reducing initial CAPEX, insufficient regulatory detail regarding disassemblable joints and module reuse, the need to standardise interfaces across manufacturers, and the lack of local

experimental data on the performance of adaptive modular systems under the normative loads of Uzbekistan. Accordingly, further research should include numerical modelling, full-scale testing of joints, the development of standard modular coordination grids, and the economic assessment of pilot projects.

The discussion therefore confirms the initial hypothesis: provided that architectural, structural, engineering, and digital solutions are integrated comprehensively, the adaptive residential environment becomes not a marginal innovative technique but a new model of building design and management.

### 5. Conclusion

The study makes it possible to formulate the following conclusions.

1. The Open Building concept provides the theoretical basis for moving from a static building model to a model of asynchronous renewal, in which durable Support elements are separated from changeable Infill components.

2. Contemporary modular and hybrid construction systems acquire their greatest value when they are designed with Design for Disassembly, standardised interfaces, and the possibility of repeated assembly in mind.

3. A critical condition for preserving the load-bearing capacity and repairability of an adaptive building is the use of reversible mechanical joints, including connections with damping components and shape memory alloys, which localise damage and reduce residual deformation after seismic actions.

4. An independent layer of engineering infrastructure, implemented through raised floors, service zones, matrix distribution systems, and BIM/BEMS-based digital management, provides genuine spatial flexibility and turns adaptability into a manageable life-cycle characteristic.

5. For the seismically active regions of Uzbekistan, the integration of Open Building principles and modular technologies represents a promising direction for housing development capable of increasing transformability, reducing environmental losses, and lowering total life-cycle costs simultaneously.

Overall, the adaptive residential environment should be regarded not as an optional architectural feature but as a strategic model for the sustainable development of housing construction in the twenty-first century.

Table 1. Comparison of traditional and adaptive construction models

Criterion	Traditional model	Adaptive model (Open Building + modular construction)
Decision-making centre	Primarily the developer and the designer	Responsibility is divided between the base structure and the user/operator

Criterion	Traditional model	Adaptive model (Open Building + modular construction)
Life cycle of elements	Synchronous; renewal leads to the destruction of durable components	Asynchronous; Support and Infill are renewed at different intervals
Engineering networks	Integrated into load-bearing structures	Relocated to service zones and plug-and-play interfaces
Reconfiguration	Labour-intensive and associated with dismantling	Phased, with replacement of individual modules and joints
Economic logic	Focused on initial CAPEX	Focused on life-cycle cost

Table 2. Comparison of intermodular joint types

Characteristic	Welded	Standard bolted	Reversible damping with	Joints with SMA
Disassemblability	Low	Moderate	High	High
Damage localisation	Predominantly in primary elements	Partly in the joint	In replaceable joint components	In the joint with a self-recovery effect
Residual deformations	High	Moderate	Reduced	Minimal
Post-seismic repairability	Low	Moderate	High	Very high
Compliance with DfD	Non-compliant	Limited compliance	Compliant	Fully compliant

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