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Earthquake-Oriented, Generative Artificial Intelligence and Voronoi-Assisted Design Approach

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Abstract

In the 21st century, earthquakes occurring in regions with high seismic risk result not only in physical destruction but also in prolonged crises at social, economic, and psychological levels. Post-disaster temporary shelter solutions often evolve into permanent uncertainties, giving rise to issues such as social exclusion, disconnection from productive life, and spatial injustice. This study is grounded in the notion that temporary living environments must be not only rapidly deployable but also adaptable, sustainable, and socially restorative.

In the design approach, the nature-inspired organizational logic of Voronoi diagrams is reinterpreted beyond conventional horizontal sprawl and transformed into a modular vertical structural system. Each module is tailored to specific functions—such as housing, healthcare, education, and production—and designed as an independent unit with its own structural and technical infrastructure. By proliferating vertically, these modules allow for spatial flexibility and evolutionary development over time

Developed through generative artificial intelligence-supported design processes, the proposed system is not merely a structure, but a dynamic living organism capable of reorganizing itself in response to environmental and societal needs. The project presents an innovative model for post-disaster reconstruction by addressing spatial, technological, and social dimensions in an integrated manner, thereby contributing a novel perspective to the field of disaster architecture.

1. INTRODUCTION

In recent years, the increasing frequency and severity of natural disasters, particularly earthquakes, have not only caused large-scale physical destruction but also disrupted social systems, economic continuity, and psychological well-being. Especially in countries like Turkey, located on active fault lines, the post-disaster need for shelter remains a long-standing yet inadequately resolved issue. While emergency solutions such as tents and container cities provide initial relief, they often evolve into unsustainable and socially fragmented settlements that lack infrastructure, community integration, and long-term spatial strategy [1], [2].

Recent assessments highlight that the February 2023 earthquakes in Turkey caused direct physical damage of approximately 34.2 billion USD, while recovery costs are estimated at much higher levels [3]. In response, the World Bank and national housing authorities have initiated large-scale reconstruction programs integrating housing, infrastructure, and community resilience [4], [5]. These policy-driven frameworks underline the urgent need for scalable, adaptable models that move beyond short-term shelters.

In the field of disaster architecture, much of the existing literature focuses on emergency response logistics and the technical aspects of shelter provision [6]. However, there is a growing consensus that temporary settlements should be envisioned not just as stopgap solutions but as the initial phases of future communities [7], [8]. Although research on participatory design and community resilience has increased,

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there is still a gap. Few studies offer design-based proposals that are scalable, transformable, and spatially integrated for long-term recovery [9].

Recent studies emphasize sustainable and reusable temporary housing strategies that can evolve into permanent settlements [10], [11]. Similarly, modular construction has been identified as a promising framework, though significant barriers related to logistics, culture, and scalability remain [12].

Recent advances in computational design and artificial intelligence (AI) have introduced transformative possibilities for post-disaster design scenarios [13], [14]. Generative tools—especially large language models and algorithmic form-finding methods—enable real-time feedback, rapid prototyping, and scenario-based organization. However, their application in disaster-specific architecture is still at an early stage. Existing studies often explore AI in conceptual design or form generation [15], but few projects have tackled post-earthquake housing using AI-based design methodologies in a holistic and systematic way.

Systematic reviews of generative AI in architecture confirm its increasing potential to accelerate early-stage design, particularly through iterative, prompt-based workflows [16], [17]. Such methods demonstrate how AI can act as a partner in shaping adaptive housing strategies, though they remain dependent on human curation.

Similarly, Voronoi diagrams, commonly used in fields such as biology, urban planning, and architecture for spatial partitioning, have shown significant potential in creating flexible, adaptive layouts. While Voronoi logic has been applied in some urban and architectural experiments [18], [19], its combination with modular, vertical, and functionally differentiated housing systems in a post-disaster scenario remains largely unexplored. Recent computational studies extend Voronoi logic toward stress-responsive and lightweight lattice structures [20], [21], offering new directions for earthquake-resilient modular systems.

This study positions itself at the intersection of generative artificial intelligence, modular architectural design, and mathematically-driven spatial systems [22]. It proposes a vertical, Voronoi-inspired modular housing system developed through AI-assisted workflows, particularly with ChatGPT as a co-designer. Unlike most works in the field, this study does not only evaluate the spatial consequences of disasters, but also introduces a design proposal that can evolve from emergency shelter to permanent living environments, integrating social, structural, and technological dimensions in a single design language. By bridging digital design methodologies with post-disaster spatial planning, the study offers both a conceptual model and a data-driven design process. It contributes to the academic discourse by filling a gap in the literature: the lack of speculative yet structurally rational, AI-generated modular proposals tailored for earthquake resilience. In doing so, it provides a new design paradigm for architects, planners, and researchers working in extreme conditions.

2. METHOD

This study employs a qualitative and speculative design-research methodology centered on the integration of generative artificial intelligence (AI) into architectural design for post-disaster scenarios. The process includes human–AI interaction, modular and algorithmic system development, and the use of mathematical-logical infrastructure (Voronoi diagrams) in vertical spatial organization. The methodology is divided into five primary phases: Role of Artificial Intelligence as Design Partner, Prompt-Driven Iterative Workflow, Modular Logic and System Constraints, Computational Design Approach and Voronoi Diagrams: Conceptual Foundations And Architectural Applications.

2.1. Role of Artificial Intelligence as Design Partner

The generative design process was conducted with the assistance of ChatGPT, an AI model developed by OpenAI. To initiate the process, a design prompt was formulated to frame the AI's role:

- **Prompt 1:** "You are now an architect. You specialize in designing for extreme conditions such as post-earthquake scenarios."

This statement defined the AI's design identity and set the foundation for all subsequent decision-making. From that point onward, ChatGPT was treated as a co-designer capable of understanding complex architectural language, spatial relationships, structural strategies, and post-disaster needs.

2.2. Prompt-Driven Iterative Workflow

The entire process was built on a sequence of human-generated textual prompts and AI-generated design responses. The following are examples of actual prompts used throughout the study:

- **Prompt 2:** "Using Voronoi logic, generate a modular structure that can grow vertically and adapt to user density."
- **Prompt 3:** "Design a post-disaster shelter system composed of prefabricated core modules with expandable secondary units."
- **Prompt 4:** "Create schematic cross-sections that show vertical growth from a central core using modular elements."
- **Prompt 5:** "Visualize bridges and interconnections between modular towers with environmental add-ons like solar panels."

At each step, the outputs were critically reviewed, and feedback was reintroduced into the system, refining the spatial proposal. Instead of a one-time design generation, the workflow evolved through a circular feedback loop of prompting, critique, and refinement.

2.3. Modular Logic and System Constraints

The study process followed a Voronoi-based growth logic, where each module was defined by center–periphery relationships, functional zoning, and user-specific data. Spatial decisions were made with respect to user density, access requirements, service infrastructure, and topographical constraints. Instead of traditional horizontal sprawl, a vertical expansion strategy was adopted—allowing limited land areas to support scalable, adaptable, and space-efficient construction.

Each module was designed to operate as an independent structural unit, capable of withstanding seismic stress without relying on adjacent modules. This independence provides redundancy and enhances earthquake resilience, ensuring localized failure does not lead to systemic collapse. Structural behavior was conceptualized using lightweight steel frameworks, modular connection nodes, and vibration-dampening joints. However, these systems were not validated through engineering simulations and remain conceptual at this stage.

Generative AI tools were employed not only for spatial organization but also for functional detailing. In the later stages of the working process, ChatGPT began to integrate environmental features such as solar panels, cable cars, and vertical gardens—even though these elements were not explicitly requested. This demonstrated the system's evolving "design memory" based on previous prompt-response cycles. While such creativity can accelerate conceptualization, it also introduces challenges of control and coherence, particularly when multiple layers of spatial logic are generated without strict parametric constraints.

The human designer acted as both facilitator and curator throughout the workflow. AI-generated options were continuously filtered, modified, and redirected according to aesthetic, structural, ethical, and cultural criteria. The process was non-linear, with decision-making emerging through iterative dialogue between human and machine. This hybrid method allowed for rapid ideation, but it also revealed several limitations and constraints:

- **Geometric Irregularity:** While Voronoi cells provide flexible spatial layouts, their irregular forms often resulted in inefficient connections between modules, especially in vertical configurations.
- **Prompt Sensitivity:** The quality and relevance of AI output was highly dependent on precise prompt language. Ambiguous instructions led to abstract or impractical solutions.
- **Structural Assumptions:** AI-generated designs suggested complex geometries and overhangs without considering real-world load paths, material behavior, or construction techniques.
- **Environmental Adaptability:** The AI-generated designs did not automatically adapt to site-specific data (e.g., climate, orientation, solar exposure), unless explicitly defined in the prompt.

2.4. Computatıonal Design Approach

While traditional design methods are mostly based on static, linear, and predictable scenarios, they fall short in situations characterized by high levels of uncertainty, such as post-disaster contexts. The physical, social, and logistical complexities that emerge particularly after earthquakes demand rapid, flexible, and replicable solutions. In this context, computational design — with its rule-based, algorithmic, and parametric approaches — introduces adaptive flexibility into the design process.

Computational design is a process in which numerous variations can be rapidly generated through defined rules and algorithms based on specific inputs [23]. For post-disaster conditions, this approach enables scenario-based system generation for both temporary and permanent shelter solutions, accelerating and diversifying the process. The modular system developed in this study is fundamentally based on computational design. Each module consists of units that can be reshaped according to their function and context. Variables such as user density, functional requirements, access, and service infrastructure have been integrated into the system as parameters that determine the size, location, and connection forms of the modules. Additionally, a Voronoi-based logic of proliferation has been incorporated into the computational framework to enable a systematically organized expansion from the center outward. Through this method, each new module adapts to environmental conditions while maintaining the integrity of the overall system.

2.5. Voronoi Diagrams: Conceptual Foundations And Architectural Applications

Voronoi diagrams are a mathematical concept first developed by Georgy Fedoseevich Voronoi in 1908. These diagrams are formed by determining the areas closest to each of the points (seed points) distributed on a plane. These structures define the competitive relationships between points on a plane and provide effective tools for spatial partitioning [18].

Voronoi diagrams are used in modeling natural organizational processes across many disciplines, from biology to astronomy, urban planning to architecture. In the context of architecture and urban design, Voronoi diagrams are typically used to establish spatial organization, functional separation, and spatial relationships. These diagrams play an important role in creating complex spatial configurations and organic forms, particularly in parametric design processes [18].

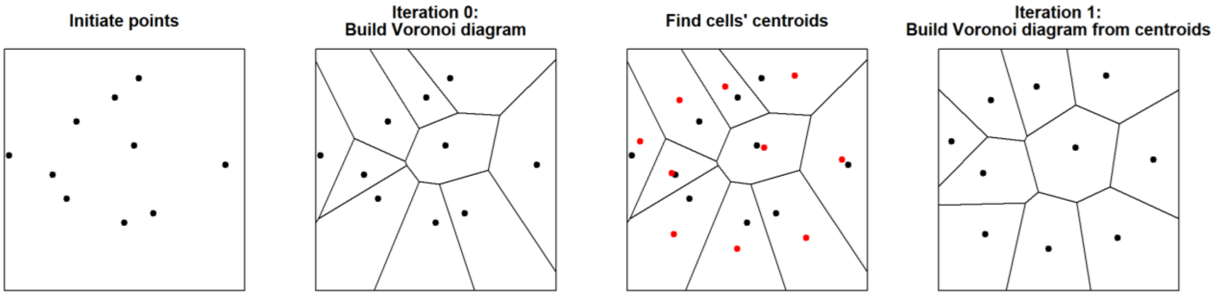

Figure 1. *Voronoi Diagrams [24]*

One of the most powerful aspects of these diagrams is their ability to establish both flexibility and hierarchy. Voronoi cells function as independent units while maintaining their relationship with central seed points. This makes them a suitable infrastructure for modular systems, adaptable architectural solutions, and scalable structures [19].

3. GENERATIVE ARTIFICIAL INTELLIGENCE AND VORONOI-ASSISTED DESIGN PROCESS

This study is based on a modular building system that began with meeting temporary shelter needs after an earthquake and can be transformed into a permanent, flexible, sustainable settlement in the long term. At the heart of the design is a vertically expanding structure based on the organizational logic of Voronoi diagrams. This system offers a structural organization in which each module is structurally and functionally independent but integrated with the entire system. Post-disaster architectural design processes are of great importance not only for the reconstruction of physical structures but also for the reconstruction of communities and the support of psychosocial recovery processes. In this context, a community-based and participatory approach to architecture is one of the most effective ways to produce lasting and sustainable solutions in disaster areas. This approach ensures that users are not merely recipients but active participants in the design and production processes.

Participatory architecture strengthens users' sense of belonging to the spaces they inhabit; it also makes it possible for designs to be more appropriate to local needs, cultural codes, and social dynamics. This participation is particularly important in post-disaster reconstruction processes, as communities need collaborative production processes to recover not only physically but also socially and culturally.

3.1. Defining the Identity and Role of Artificial Intelligence

In the first step of the design process, the role assigned to ChatGPT, one of the artificial intelligence tools, was clearly defined. "You are now an architect. You specialize in designing for extreme conditions." Work began with this prompt. This statement signifies the designer's transformation into an expert who not only produces spatial solutions but also systematically considers post-disaster reconstruction processes. This identity has determined the direction of the entire design process and has been the fundamental determinant in decision-making stages. Here, the designer is not only designing structural elements but also a living fabric: An approach that interprets the process from the initial response to a disaster to the creation of permanent living spaces within the time-space-function triangle.

3.2. Disaster Scenario and Fictional Setting

The basic extreme scenario of the design is a disaster environment following a large-scale earthquake. A two-stage systematic solution has been developed in line with this scenario. Since the first 24-72 hours after a disaster are critical, core modules that can be set up within this timeframe have been designed. These modules offer a compact yet effective spatial solution to meet basic living needs (shelter, heating, access to clean water, security). These units, which are transported to the site as prefabricated structures, are designed to be assembled with minimal technical equipment and can be modified by the user. After the crisis phase has passed, the system's second phase is activated: Modules with different functions are added around the existing core module. These modules consist of units aimed at rebuilding social life, such as housing, healthcare, education, production, and logistics. Each module has a functional identity, and the system as a whole is formed by the collaboration of these identities.

3.3. Visualizing Post-Disaster Architecture through Generative AI

First, design formation schemes were studied. Key decisions were made for these schemes using keywords such as "voronoi" and "modular design."

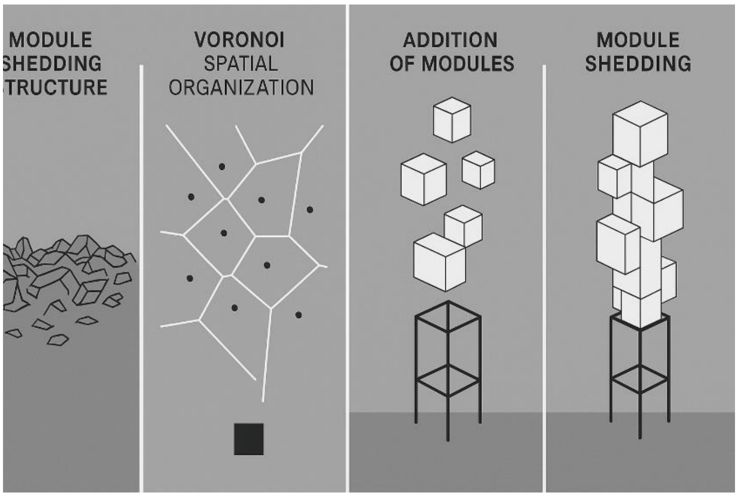

Figure 2. *Formation Diagram Visualized with ChatGPT*

The spatial structure of the design is based on the logical structure of Voronoi diagrams. Unlike common applications, this project focuses on vertical expansion rather than horizontal expansion. This choice, especially in areas with post-earthquake soil deformation, minimizes ground intervention and maximizes space efficiency through stacked modulation. The aim here is to use Voronoi not merely as a formal aesthetic tool but as an organizing and relational system logic [Figure 2]. Each module is treated as a cell growing from the center outward. The fundamental principle of Voronoi—the shortest-distance center-cell relationship—is combined here with functional optimization, ease of access, and structural efficiency.

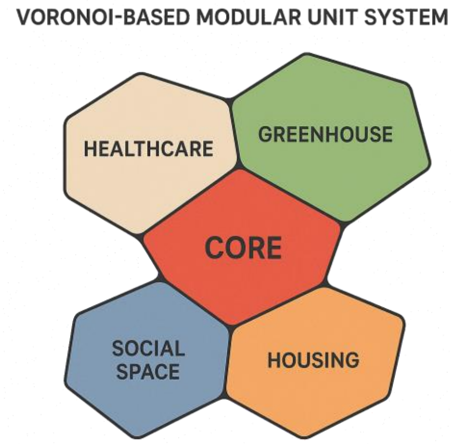

Figure 3. *Center-Spreading Schemes Visualized with ChatGPT*

The system is based on the principle of proliferation according to the functions of peripheral modules, starting from a central module. This central module is considered not only a structural core but also a “collective core” through which the community can carry out its decision-making processes. Each module radiating from the center can be shaped according to the suggestions and needs of different user groups; thus, the structure becomes flexible and adaptable not only physically but also socially. Community participation also continues during the use phase of the structures. For example, while one module may serve as a health unit, another module may function as an education or production area. This flexibility allows the structure to respond to different needs at different times. The post-disaster first response module represents the central cell of the Voronoi system. The entire system develops from this core. Just like in Voronoi diagrams, each new module creates its own “neighborhood boundary.” These boundaries are determined based on user needs, accessibility, and functional density. Module sizes are scaled according to usage time, user density, and functional requirements. For example, a residential unit may be 24 m², while a health module may be 60 m². Modules not only touch each other but also become physically interconnected. These connections are provided through both vertical and horizontal links.

After the design schemes and general principles were determined, the visual representation of the design was generated using the information previously stored in the artificial intelligence memory.

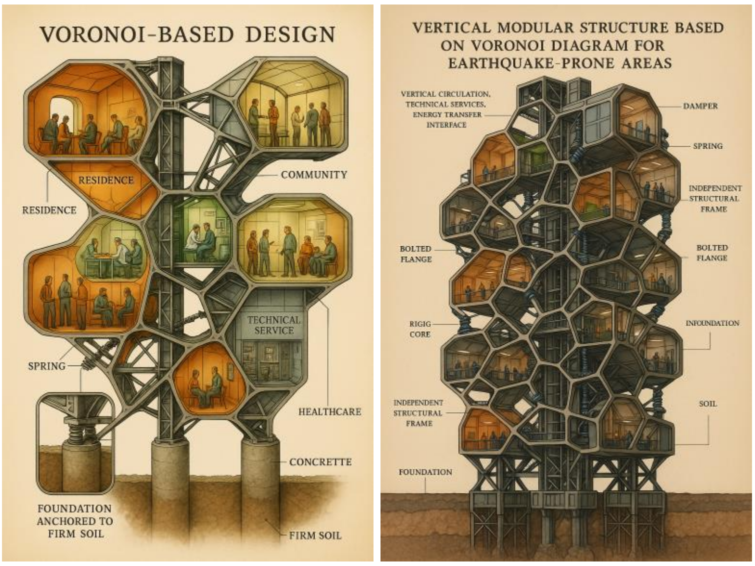

Figure 4-5. *First-Phase Design Visualized with ChatGPT*

However, in the initial stage, ChatGPT used the Voronoi concept in a very formal way and directly reflected it in the design.

Then, starting from the beginning, schematic cross-sections and isometric visual studies were carried out for the structure to be created. Instead of providing all the information and creating visuals for the design at once, the artificial intelligence memory was updated in detail at each step, resulting in healthier design inputs.

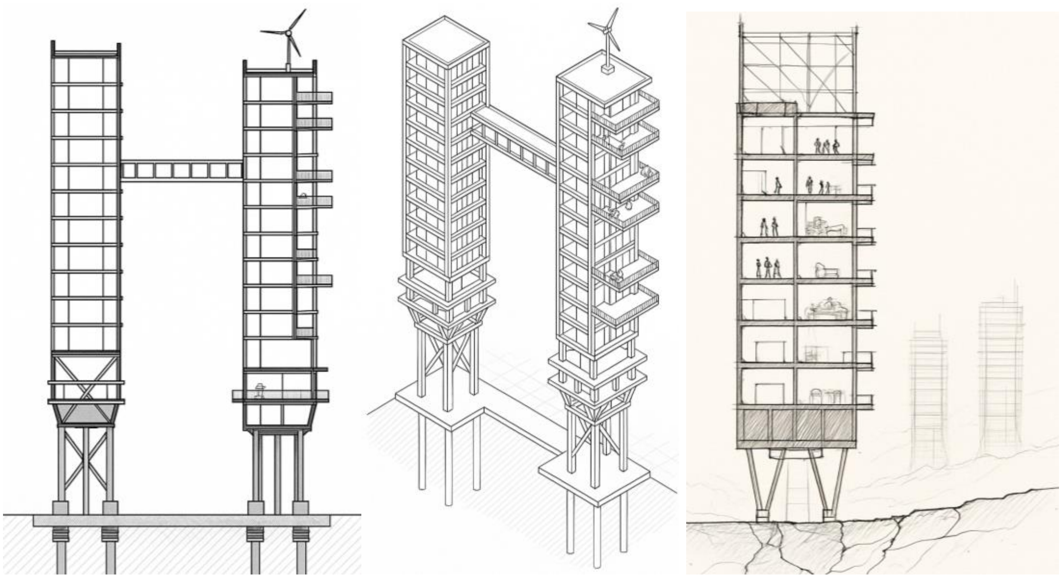
Figure 6-7-8. *Section and Isometric Drawing Works Visualized with ChatGPT*

Following the section studies, the work continued with the addition of new design inputs to the colored section study. As environmental characteristics, it was determined that there were ruins left over from the earthquake and that people remained in the first modules created after the earthquake.

Figure 9. *Post-Disaster Initial Living Modules Visualized with ChatGPT*

Inter-building bridges have been added to the post-disaster initial living modules that have been created. The modules have been raised off the ground to mitigate the risk of continued seismic activity. As a result of all these inputs, ChatGPT has added solar panels and transition elements such as cable cars on its own, even though they were not specified in the prompt, using its own memory.
The next step involves adding modules that can be used for different purposes on top of the existing modules. Each structure has a different number of floors and size depending on its purpose and user density.

Figure 10. *Functionally Diverse Modules Visualized with ChatGPT*

Lightweight steel systems, connection details, and damping elements have been used for wind and earthquake loads. To ensure self-sufficiency, each structural unit is equipped with green gardens, solar panels, wind turbines, and water collection systems. Vertical transition elements are used to facilitate movement between modules. Flexible transitions and semi-open spaces (terraces, balconies, inner courtyards) are available between modules. The safety, flexibility, and sustainability of housing units under extreme conditions such as earthquakes are directly related to the structure's load-bearing system and the materials used. In this context, the proposed modular and reconfigurable structural system within the project has been designed to perform at a high level both in terms of the load-bearing system and the materials used. As suggested by ChatGPT, each module functions as an independent structure within itself. This ensures that the entire system is not affected in the event of local damage. This structural independence enables rapid, low-cost, and modular post-earthquake interventions.

Figure 11-12. *Render Section Works Visualized with ChatGPT*

The images created were shared again with Chatgpt, and it was requested that the design be developed further. This prevented the design from being developed in different directions or unwanted inputs from being added. It was requested that a more detailed cross-section be created based on the latest images. A cross-section image was created that shows all living units and connections [Figure 13].

Figure 13. *Detailed Section Work Visualized with Chatgpt*

Based on this detailed cross-section study, a design concept was requested in which structures were replicated on different floors and connected to each other by bridges.

Figure 14-15-16. *Interconnected Structure Modules Visualized with ChatGPT*

4. EVALUATION

The design proposal developed in this study introduces a vertically expandable, modular system shaped by Voronoi logic and enhanced through the use of generative artificial intelligence (AI). The system seeks not only to address urgent shelter needs in the immediate aftermath of an earthquake but also to offer a pathway toward the establishment of socially integrated, functionally diverse, and spatially adaptive communities. This aligns with recent disaster recovery literature that stresses functional recovery as a staged, adaptive process, where rapid deployment must be directly linked with long-term resilience metrics [25]. Empirical analyses of large-scale post-earthquake housing in Turkey also reveal the challenges of scaling modular approaches under resource constraints [26]. The two-phase structure—composed of rapidly deployable core modules followed by the gradual addition of secondary, function-specific units—supports a transformative process that shifts the focus from emergency response to long-term recovery and urban resilience. In this respect, the proposal extends beyond conventional approaches to disaster architecture by framing temporary shelter as the foundation for regenerative urban strategies [27].

One of the primary strengths of the proposed model lies in its transformability. Enabled by a Voronoi-based spatial logic, each module operates as an independent yet interrelated unit, capable of evolving in response to shifting user needs, functional demands, and environmental constraints. This bottom-up adaptability ensures not only spatial flexibility but also social inclusivity, as the design allows communities to reconfigure and repurpose modules over time. In addition, the emphasis on vertical scalability makes efficient use of land and offers structural advantages in high-density or geotechnically unstable urban contexts. Modules may expand both upward and outward, maintaining structural autonomy through their individual support systems.

Another notable aspect of the design is its potential for self-sufficiency and environmental integration. During the iterative process, the AI system suggested solar panels, green gardens, wind turbines, and suspended cable systems. These contributions enhanced the environmental performance and sustainability of the proposal. Comparable approaches in recent modular housing research emphasize not only the adaptability of units but also their integration with sustainable energy and water systems, reinforcing the importance of ecological self-sufficiency [28]. These features, while speculative in nature, reflect a growing interest in combining modularity with ecological sensitivity in disaster-prone environments [28].

Despite these strengths, the design remains largely conceptual and carries a number of limitations that must be acknowledged. Most notably, the system's structural performance has not yet been validated through engineering simulation or physical prototyping. Emerging computational approaches suggest that Voronoi-based lattice and micro-architectures can improve energy absorption and stress distribution under dynamic loads [29], [30]. However, these remain primarily experimental at material scale and require architectural-scale validation. The feasibility of the proposed vertical connections, intermodular links, and material systems under seismic conditions remains untested. Additionally, economic considerations such as prefabrication logistics, material availability, and cost-efficiency have not been analyzed within the scope of this study, making the design more of a visionary framework than an immediately actionable solution [31].

Another critical limitation relates to the reliance on prompt quality and human intervention in the AI-assisted design process. While ChatGPT provided generative support throughout the workflow, the quality, relevance, and depth of its responses were highly dependent on the clarity and specificity of the user's inputs. This indicates that such systems cannot operate independently but require skilled human curation, interpretation, and decision-making. Furthermore, ethical, cultural, and contextual parameters—critical in any architectural design—were not inherently addressed by the AI, highlighting the continued necessity of human agency in design authorship [32].

Table 1. *Evaluation Table*

Transformability	The ability of the design to evolve from the post-disaster first response phase into a permanent settlement over time.	-Two-phase structural system: The first module starts as a "core," gradually surrounded by functional modules. -Modules can be rearranged according to user needs. -With Voronoi logic, each module can be adapted to its surroundings and reconfigured.
Scalability	The capacity of the modular system to expand horizontally or vertically over time.	-"Vertical expansion" is emphasized; each new module can be added to the existing structure from above. -Each module has an independent support structure, allowing growth at both functional and physical levels. -Module sizes can be scaled according to user density.
Becoming Permanent	The transformation of temporary living spaces into permanent neighborhood structures in the long term.	-Permanent social spaces (health, education, production) that support community life over time. -Modules are made permanent with legs connected to solid ground. -Socio-cultural sustainability is targeted: collective core, community participation.
Artificial Intelligence Contributions	Contributions to the design process such as decision support systems, visualization, and suggestion generation.	-ChatGPT assumed the role of designer: started with the prompt "You are now an architect..." -ChatGPT integrated sustainable elements such as solar panels, cable cars, wind turbines, and green gardens into the design without being specifically requested by the user. -Distribution of Voronoi seed points and module dimensions were optimized with artificial intelligence. -AI-supported material and connection recommendations were provided for wind and earthquake loads.

In summary, the proposed system presents a promising and innovative approach to post-disaster architectural intervention, particularly in its ability to synthesize modularity, generative intelligence, and adaptive spatial strategies. However, its long-term applicability will depend on future work involving structural validation, real-world prototyping, and the development of ethical and methodological frameworks for AI-supported co-creation in architecture.

5. CONCLUSION

This study introduced a speculative yet structured design approach that integrates generative artificial intelligence (AI) and Voronoi-based modular logic into a post-earthquake housing model. Through the iterative co-creation process between human and AI, the research proposed a vertically expandable, functionally differentiated, and socially integrative system that rethinks the transition from emergency shelter to permanent settlement.

The findings demonstrate that AI can support early-stage design processes by generating formal, spatial, and functional ideas in response to well-structured prompts. In particular, ChatGPT's ability to suggest modular relationships, vertical connections, environmental elements (e.g., solar panels, cable systems), and public program distributions proved beneficial to conceptual exploration. However, the process also revealed key limitations: AI struggled with issues requiring engineering judgment, cultural nuance, or ethical reasoning unless these parameters were explicitly encoded into the prompts. Furthermore, AI responses often lacked critical reflection, leading to outputs that required continuous human interpretation and validation.

The role of the human user was central to curating, refining, and steering the AI-generated content. While the system was able to produce design directions, the final articulation of spatial quality, hierarchy, and feasibility depended entirely on human decision-making. Although the prompt-response cycle allowed for a high degree of ideation, the creative agency, contextual sensitivity, and structural logic were ultimately shaped by the designer's intervention. This confirms that the current state of AI-supported design remains dependent on hybrid intelligence rather than full autonomy.

If the proposed system were to be prototyped, several practical challenges would emerge. Structurally, the vertical modular logic requires rigorous validation under seismic loading through simulations or physical testing. Connection strategies between modules, load transfer behavior, and site-specific foundation systems would need to be engineered. Additionally, issues such as transportation of prefabricated parts, on-site assembly logistics, and material durability under long-term use would also require careful consideration. Socially, real-world acceptance of such a system would depend on cultural appropriateness, user participation, and flexibility in post-disaster contexts.

For future research, multiple trajectories can be pursued. Comparative studies may explore how generative design outputs from ChatGPT differ from those produced by visual-based platforms such as Midjourney, Rhino AI, or Revit plugins—each of which offers different representational and parametric capabilities [33]. Usability studies with real users, particularly those who have experienced disaster conditions, would provide invaluable insight into the adaptability and livability of the proposed system. In addition, the structural performance of modular units could be tested through digital simulations (e.g., finite element analysis) to ensure safety and durability. Lastly, the system could be extended beyond earthquakes and adapted to other types of disaster scenarios, such as floods, wildfires, or climate-induced displacement, thereby enhancing its versatility and relevance.

In conclusion, this research contributes not only a design proposal but also a methodological lens for integrating AI into disaster-resilient architectural thinking. By identifying both opportunities and constraints within the human–AI partnership, the study offers a roadmap for future innovation in computational architecture under extreme conditions.

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