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INTEGRATING SMART TECHNOLOGIES INTO MODULAR AND FLEXIBLE ARCHITECTURE

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Abstract: *The built environment is undergoing transformation, as integrated smart technologies with modular and flexible architecture enhance sustainability, efficiency and adaptability. These include the Internet of Things (IoT), artificial intelligence (AI), and robotics, which improve modular constructions by prefabrication, scaling, and adaptable spatial configuration. AI-based design can enable real-time customization and accelerate assembly through automation, minimizing costs and errors. This study focuses on modularity, complexity and integration of smart systems, addressing issues of data privacy, interoperability, technology obsolescence, and examining the potential of resilient futures-ready architecture.*

Keywords: *Modular Architecture, Flexible Design, Smart Technologies, IoT in Construction, Responsive Building Systems*

1. INTRODUCTION

In the 21st century, the development of architecture has been positively affected by the rapid technological changes that are constantly being introduced. This is made possible by these modern methods that are used to design, build and monitor buildings in a completely different way. The growing demand for sustainability, efficiency, and adaptability is driving architects, engineers, and urban planners to rethink traditional construction methods [1]. One of the major changes is the appearance of modular construction, which is an innovative building technique that uses prefabricated parts that are assembled on site after being manufactured in a facility under regulated conditions [2].

This approach comes with various advantages, compared to regular constructions, such as the short periods of time needed to erect the structures, cost cuts, and minimal disturbance to the surrounding environment. Above all, modular construction is a solution to the adaptability problem, which consists of the building being easy to adapt with time, for example, by adding new modules, changing the inner configuration, or making it useful for

different purposes. However, the next architectural stage is focused on the integration of smart technologies into these modular systems. Smart technologies such as IoT, AI, automation, and advanced materials embody a wide spectrum of developments. These are technologies that have the potential to revolutionize the relationship of buildings with their environment and the human activities within them [3]. On the one hand, IoT sensors can receive real-time feedback on environmental parameters such as temperature, humidity, air quality, and energy use that, in turn, allow the smart building to respond dynamically. AI algorithms can make building planning more effective, reduce energy consumption, and operating costs. Meanwhile, smart materials, such as self-healing concrete or adaptive building exteriors, could help extend the lifespan of modular structures, improving their ecological and environmental integration.

An important factor in the ongoing change is the close integration of smart technologies into modular and adaptable architecture in a variety of fields, mainly in manufacturing, the management of residential energy and city planning [4]. In manufacturing, a combination of modular design

and intelligent technology can enhance production throughout, allowing for perfect precision and personalization of the part.

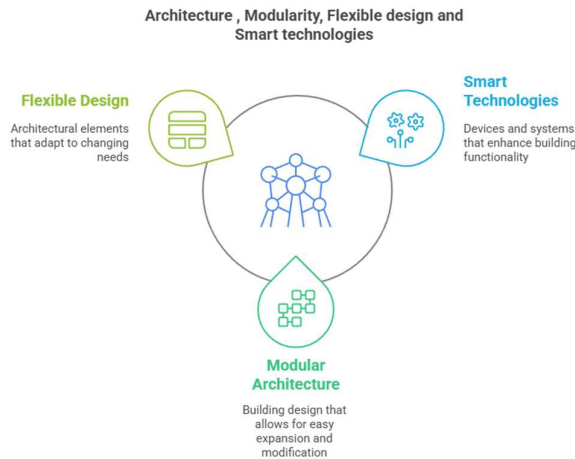


Fig. 1. Comprehensive integration of architecture, modularity, flexible design, and smart technologies to enhance adaptive, sustainable, intelligent built environments for future-ready urban development.

In the context of residential energy management, smart technologies are the technologies that can make buildings energy efficient and hence reduce the carbon footprint of modular buildings by easy continuous real-time adaptation and automation of heating, cooling, lighting, and other things.

The flexibility of these systems will allow cities to transform sustainably, as the buildings comprise them can be easily altered or expanded to adapt to the evolving circumstances within their communities (Fig. 1).

Although there have been many breakthroughs in the two main domains of modular construction and intelligent building systems separately, a profound exploration of the efficient combination of these two fields is still lacking.

Many of the current studies deal only with modular construction or smart technologies separately, rather than how they are combined for the purpose of architectural innovations. However, there is a need for further investigations into the practicability of system interoperability, the adoption of new smart technologies with current construction standards, and the design of universal frameworks that can provide the direction for the implementation of smart modular systems in all

types of climates, locations, and regulatory settings.

The ongoing integration of these technologies is the critical determinant of the future trajectory of architectural design development. The progression of modular construction techniques creates an increasing need for the implementation of data-driven design methods alongside automated construction processes and innovative materials to satisfy the growing demand for intelligent and sustainable buildings.

Over many years, the idea of modular architecture eventually attracted interest in the 1950s as a way to simplify building technologies, leading to the design of more uniform, repeatable structures. In its early days, modular architecture was mostly concerned with prefabricated houses and temporary buildings, most often used for post-war housing shortages. With advances in time, the concept progressed towards more advanced and more resilient applications for modular constructions [5].

Today's modular architecture is the product of prefabricated components and modules that can be combined and built on-site, thereby accelerating the pace of building and improving flexibility and resource efficiency [6]. A major principle of modular design is that standardized parts can be used in different configurations to achieve various design requirements. This flexibility is fundamental to modular success, meaning that modular structures may be appropriate for any type of building, from homes to large commercial and industrial developments [7].

In addition to the principles of modular architecture, it is also sustainable in the sense that modules can be reused to minimize waste materials and further reduce the footprint of a construction project. Modular parts disassembled and reassembled, allow extensions or alterations in the future to maximize the life of buildings [8].

Smart architecture includes all modern systems and devices that incorporate automation to detect functionality with real-time data to improve building performance, comfort of use, and energy efficiency [7]. On the contrary, it allows buildings to adapt to conditions of environmental change, occupancy, and user needs. Hence, smart technologies are becoming ever more important in architecture as we

progress toward more intelligent and connected spaces [9].

2. INTEGRATION OF SMART TECHNOLOGIES WITH MODULAR ARCHITECTURE

2.1 Internet of Things (IoT)

Dynamic in reconfiguring architectural spaces through smart sensors and actuators, IoT-enabled systems allow modular movable walls, automated lighting, and climate control systems to adjust in real-time with occupancy patterns, environmental states, or user needs. IoT, in lighting and shading systems, optimizes how HVAC systems operate so that reduced energy consumption is achieved and building practices become more sustainable. IoT also enhances predictive maintenance applications, which continuously monitor structural integrity, air quality, and resource use of modular architectural components to enable timely interventions with the minimum possible downtime and material waste. IoT scalability applies to modular architecture, which will suit any possible future need for changing technology or function within a building, especially relevant in applications of smart cities, co-working environments, or disaster response infrastructure. Sensors offer live data to automate systems, increase efficiency, and optimize comfort for building occupants. For example, in modular architecture, the IoT can support the supervision of separate modular units or total modular buildings using a central system that observes all elements [10].

The data from such sensors can provide real-time tracking of people's presence, temperature, and lighting in space, adjusting it at will in between.

2.2 Artificial Intelligence (AI)

Artificial intelligence integrates well with operations in modular construction. AI programs may filter through all data transmitted by IoT devices and even manage pattern matching and decision-making using predictive models [11]. In the case of a modular structure, it assists predictive maintenance through which HVAC and lighting systems would ensure that such

systems are functioning correctly before any failures occur. AI, on the other hand, could reduce energy consumption through optimizing building systems based on occupancy trends, time of day, or outside weather [12].

AI is able to personalize the building environment according to the behavior of the occupant [13]. For example, an AI algorithm would create a room environment by changing room temperature or lighting conditions as per the individual's preferences, thereby giving a modular building an individualized feel and more efficient use.

2.3 Smart sensors

Incorporating smart sensors into modular units allows tracking of environmental parameters such as humidity and movement. It could also automatically change building systems without human touch. In modular construction, such automation can be convenient since centralized control will allow distance management [14].

For example, motion sensors switch lights off in empty spaces, while temperature sensors will turn on or off heating or cooling, depending on the presence of humans in the space. Automation in modular buildings may be distributed throughout an entire unit or specific to certain modular sections, thus better-managing energy use while improving occupant comfort [15].

2.4 Smart Materials

The intersection of adaptive facades, self-healing concrete, phase change materials (PCMs), and other kinds of intelligent materials may maximally enhance the sustainable functionality of modular architecture. For example, a dynamic facade that reacts to changes in light or temperature has the potential to reduce the dependency of HVAC and energy costs. Self-healing materials used into the design of modular units can improve the life of structures and reduce maintenance costs, among which are significant savings in modular architecture planned for reshaping or relocation [16].

Integrating smart materials into modular components enhances building performance with minimal manual work, resulting in more energy-efficient spaces with low maintenance.

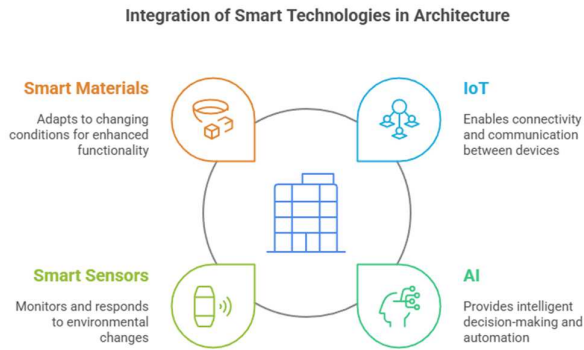


Fig. 2. Advanced integration of smart technologies in architecture for sustainable, adaptive, and high-performance built environment.

Real-time monitoring, automation, and energy optimization are seamlessly integrated by IoT, AI, smart materials, and sensors to benefit from adaptive, high-performance, and sustainable built environments that respond dynamically and responsively to user needs and environmental conditions (see Figure 2).

3. BENEFITS AND CHALLENGES OF INTEGRATING SMART TECHNOLOGIES WITH MODULAR ARCHITECTURE

The integration of smart technologies within modular architecture is expected to yield significant energy efficiency. Constant improvements in energy usage could be achieved with IoT sensors, AI, and smart materials. For instance, real-time occupancy information accessed by automated lighting, HVAC change management systems provide guarantees of efficient energy use. Intelligent systems can also be used to optimize renewable energy resources such as solar panels to make a building achieve the maximum use of sustainable energy [17].

Modular architecture has the inherent attribute of being able to flexibly add, remove, or rearrange independent units. This flexibility becomes even more pronounced when it is combined with smart technologies. Building systems can easily alter functions to accommodate the needs of end users, while modular components can be configured to meet changing user conditions or environmental factors. This flexibility allows the building to

change over time without the need for large-scale renovations.

Smart systems within modular buildings, for example, will set heating or lighting differently based on actual usage patterns of a particular module or unit. Since modular buildings are mostly built for multi-use or short-term purposes, this would add a considerable advantage to the apparent flexibility to change their functionality [18].

This further creates avenues for smart technologies to continuously track building performance. Sources of information, such as IoT sensors, AI technologies, and materials that become intelligent, can be instantaneously analyzed and produce valuable information on building operation and improvement measures. For example, trends in energy consumption can lead to opportunities for improvement, and predictive maintenance becomes possible, thus reducing the risk [19].

The effective use of data analytics could enable building managers to make informed decisions about physical efficiency, energy consumption, and the satisfaction of tenants in a building. In particular, this is useful for modular buildings, because each modular unit can be separately monitored and controlled to facilitate defined improvements over that of the whole building.

Both modular architecture and smart technologies are focused on sustainability. Modular construction minimizes the waste of material and energy. However, intelligent technologies also contribute much more to the objective. Automated energy control, the use of renewable energy sources, and intelligent materials contribute to improving the environmental sustainability of buildings [20].

Modular construction uses prefabricated components from different manufacturers, so interoperability must be ensured using intelligent technology equipment [21]. Ideally, it shall therefore be possible to harmonize communication protocols or to implement universal systems to solve the challenge.

The capital costs of smart technologies are quite high for modular buildings based on the assumption that these need sophisticated sensors, automation systems, and intelligent materials.



Fig. 3. Exploring the opportunities and weaknesses of integrating smart technologies in modern architecture.

This type of technology incurs huge initial investments but pays off later during reduced energy and maintenance costs. Moreover, they tend to become obsolete sooner than normal buildings due to rapid changes in technology. Their current job is to ensure that these modular systems can be upgraded or modified to receive new technologies without entire renovation requirements [22]. Integrating smart technologies into modular architecture by stakeholder participation is required to meet environmental, social, economic, and regulatory objectives (Fig. 3).

Smart governance involves a greater provision of public services and improves the response to crises, making communities adaptable. Economically, modular smart technologies reduce lifespan costs but require greater initial investments that require collaborative funding models. However, regulatory complexities remain unarticulated, needing unified sustainability standards to make compliance a straightforward issue [23]. International standards such as ISO/IEC 30141 - an IoT reference architecture- and ISO 19650, which governs the management of all information with the aid of Building Information Modelling (BIM), serve as the groundwork for seamless communication between IoT devices [24,25]. ISO 37120 would ensure that smart cities become sustainable, and ISO 55000 is necessary for effective asset management in smart buildings [26]. ISO 22301 gives a

framework or template regarding business continuity in terms of data security and resilience. All these challenges become more easily standardized for the actual practice of courtesy of smart modular solutions.

4. REAL-WORLD APPLICATIONS

Modular and flexible architecture has embraced intelligent technology in the recent past, creating a revolution in the adaptability, efficiency, and sustainability of buildings. The use of Building Information Modeling (BIM) in modular construction improves project execution massively, with completions reduced by a 50% minimum down to 20% in cost. BIM enhances design, construction, and operational processes through an integrated and unified virtual model, therefore minimizing resource intensity as well as maximizing the overall efficiency of the project [27]. Similarly, the amounts by which it can make improvements in smart cities through the adoption of digital twin technology are 15% and 25% of improving energy efficiency and reduction of maintenance costs, respectively, making cities more resilient and ultimately sustainable [28].

Prefabricated modular components have reduced construction time by nearly 50% therefore building solutions are created faster and cheaper, also being environmentally friendly [29]. AI-driven HVAC systems also claimed energy reductions of 15.8%, as demonstrated in projects such as 45 Broadway in Manhattan, which helped to prove the economic and environmental impacts of smart energy management systems [30]. Similarly, EDGE Amsterdam, one of the greenest office buildings, uses IoT and AI for real-time energy optimization [31].

Households will save £1,341 each year at current costs with the new low-carbon homes that incorporate solar panels, heat pumps, high-grade insulation, and battery storage, bringing total savings to £46,612 for the 25-year term of a mortgage [32]. Very importantly, changes in AI in building management systems can contribute to a reduction in global energy consumption and carbon emissions [33]. In the end, the statistics may be between 8-19% in

terms of savings in costs incurred in energy consumption and due to gas emissions, thus having long-term sustainable goals.

5. FUTURE DIRECTIONS

The concept that replaces the future architectural scenario is the hybridization of modular construction with intelligent technologies, which is being established as a new model of design focusing on flexibility, efficacy, and intelligence. As cities expand, the need for environmentally friendly and highly efficient buildings becomes essential. Intelligent modular systems are emerging as the ideal solution, seamlessly combining rapid construction with advanced technology integration. These evolving systems are transforming not only how buildings are designed and constructed but also how they function, interact with occupants, and continuously adapt over time [34].

Modular buildings are solid structures that require huge changes to meet new requirements or use while affording adaptability, as these types of units may be reconfigured, extended, or relocated with minimal disturbance [35]. Intelligent technology takes adaptability even further by allowing buildings to dynamically adjust to occupancy patterns, climate conditions, and energy needs. Smart modular systems make building performance improvement easy and effective by using self-learning algorithms that study and use patterns for instantaneous management recommendations while increasing comfort levels [36].

In fact, advances in artificial intelligence and automation are pivotal for the future of intelligent modular systems. Advanced AI design tools that enable architects and engineers to design optimized modular configurations that maximize space usage have made this possible. When it comes to construction, automated manufacturing methods and robotics will be useful to improve accuracy, quantify material waste, and speed up the construction of modular pieces [37].

Robotic assembly lines guarantee that every module meets strict quality standards, leading to buildings that can be erected more quickly and that can last for many years.

The current state of changes within the modular systems has been shaped and molded into intelligent, self-managing ecosystems through an Internet of Things (IoT) incorporation. Furthermore, security would be enhanced through IoT connectivity in intelligent surveillance systems, along with biometric access controls and remote monitoring, which guarantee that modular buildings remain safe and secure [38]. They would be manufactured with sustainable materials such as engineered wood, recycled steel, and prefabricated modular components of bio-based insulation, significantly reducing carbon footprints during construction. Energy efficient systems, such as solar panels, green roofs, and passive cooling systems, will be integrated into modular designs, successfully increasing the self-sufficiency and eco-friendliness of these buildings [39].

Sophisticated battery storage systems should be included in modular designs that can enable the retention of surplus energy from solar sources, thus minimizing the dependence on external power networks by using the energy during high-demand times. The decentralized integration of modular structures into energy networks that share surplus energy with adjacent buildings or neighborhoods will be made possible through intelligent grids and blockchain-driven energy trading systems [40]. Smart modular systems will integrate seamlessly into the design of smart cities, as cities become digitized. Therefore, they will become integrated future-linked modular structures connecting with transport and civic infrastructures.

Advanced mobility solutions will be incorporated into modular housing projects, such as smart parking systems, allowing residents to benefit from a seamless urban experience. Intelligent modular systems will improve industry and commerce by customizing flexible working environments with space configurations that are adaptable to user needs, remote collaboration tools, and automated logistics oversight, as shown in Figure 4.

Smart modular buildings will provide users with well-being in unique environments dedicated to individual preferences and life patterns. Within the home environment, AI-enabled home automation systems will monitor user habits [41].

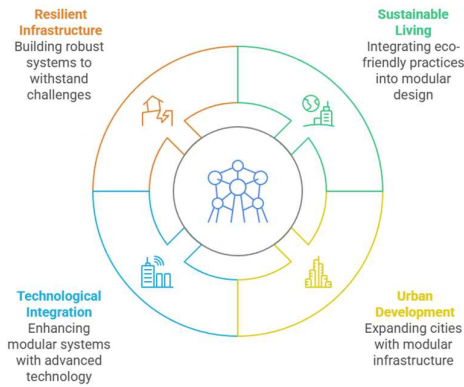


Fig. 4. Evolution of smart modular systems. Advancing resilient infrastructure, sustainable living, technological integration, and urban development.

Although voice-activated assistants and augmented reality interfaces would allow residents to seamlessly configure their environments, all aspects of health and wellness will include indoor air quality monitoring, circadian lighting, and biophilic design features that would ensure a much more pleasant, livable, and productive environment. The construction industry is on the verge of a major leap, ready to embrace fully autonomous and self-sustaining modular systems (Fig. 5).

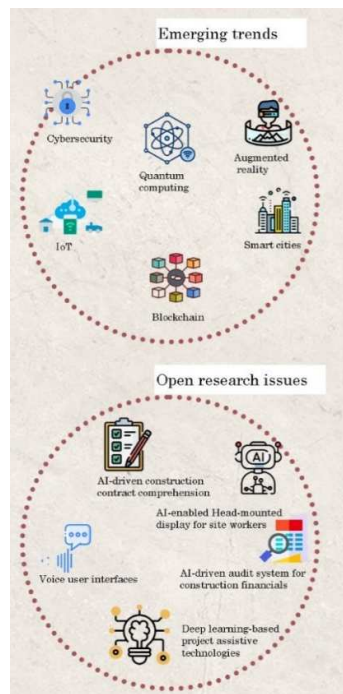


Fig. 5. Digital and computing technologies in construction. Emerging trends and open research challenges.

Self-sufficient construction sites, where modules are built and assembled on-site entirely using standard components under the management of artificial intelligence and robots, will radically change efficiency within the built space [42]. Buildings will cease to be physical but unmovable structures and evolve into intelligent living entities that will learn, adapt, and continuously improve their performance as time goes on. By incorporating blocks of technology, self-executing smart contracts could ensure transparent transactions for the construction, operation, and maintenance of modular buildings, thereby eliminating processes such as leasing, maintaining, and distributing resources from manual activity [43].

As cities expand and environmental issues become increasingly imperative, the incorporation of smart modular systems will become an important aspect of a more resilient, sustainable, and tech-savvy future for city life.

Future research will focus on: (1) gaps in current research (e.g., lack of standardization in AI-driven modular systems); (2) emerging technologies (e.g., blockchain-enabled construction, AI for design optimization) and (3) policy implications (e.g., regulations for AI-integrated modular buildings).

6. CONCLUSION

The integration of smart technologies into adaptable and modular architectures marks a significant change in the way buildings are conceived, designed, and occupied. This development is initiated due to the growing demands for sustainable, energy-efficient, and flexible designs that can meet the needs of a world that is becoming more urbanized and technologically advanced. Modular construction, which was previously appreciated primarily for its cost-effectiveness and speed of construction, is now at the forefront of incorporating smart systems to optimize functionality, energy efficiency, and user experience.

In this study, we have analyzed how the integration of modular architecture with intelligent technologies such as Internet of Things (IoT), Artificial Intelligence (AI), smart materials and automation creates a new

paradigm in the built environment. These developments have allowed the building to be transformed into self-managed, data-informed structures that make the best use of resources, increase comfort levels for building occupants, and, in general, sustainability. The ability of modular buildings to house intelligent energy management systems, predictive maintenance, and real-time monitoring makes modularity a plausible answer to most of today's urgent issues regarding modern architecture and urban development.

Above all the advantages, this integration boasts of flexibility as well as scalability in modular intelligent systems. Unlike traditional static buildings, these are smart modular structures that can adapt themselves to varied needs, either by alterations of layouts or by mechanisms such as automated climate controls, or even with smooth integration into smart city systems. Modular systems can definitely be repurposed, extended, or moved and this is a form of flexibility that is not matched by any conventional construction technique, thus making these systems extremely attractive for fast-growing urban populations, disaster relief housing, and for changing business and industrial needs. Sustainability is becoming an increasingly important factor in developing intelligent modular architectures. As the world talks about climate change and environmental issues, pressure is on the construction industry to reduce its carbon footprint and promote sustainable practices. Renewable energy solutions, sustainable materials, and energy-saving design approaches further establish modular smart buildings as an important building block for sustainable development. Intelligent grids, AI-driven energy management, and autonomous modular communities lead to the future, where buildings act as environmental preservation participants and the energy economy, not just passive constructions.

There are numerous benefits in incorporating smart technologies into modular architecture; however, barriers remain. Initial costs for high-end smart systems are usually very high, and their rampant adoption calls for the joint effort of architects, engineers, policymakers, and technology developers. In this sense, the intervention must focus on the standardisation of

smart modular construction methods, data security issues, and interoperability of diverse smart systems to facilitate smooth operation in particular settings. Furthermore, it is being emphasised that even though productivity is enhanced with the automated and AI-based high-tech systems, talented professionals are mandatory to operate and maintain such advanced setups, in which case, the accent is being laid on workforce training and education in this domain. The coming years promise that continued development on intelligent modular systems will revolutionise the construction sector and in particular the city environment. Innovative robotics, digital twin technologies, smart contracts on a blockchain basis, as well as future competitive materials, will be the force behind the modular construction potential. Intelligent cities will feature modular buildings that are critical for the construction of connected, adaptive, and intelligent urban spaces. Enhanced digital transformation and modular architecture will be effective in improving construction process efficiency and improving the resilience, adaptability, and sustainability of the built environment.

The future research should emphasise the implementation of AI for optimising its use through Digital Twin technology as well as smart grids of the Internet of Things to acquire so much efficiency and durability. With sustainable materials, 3D printing, and the circular economy model, long-lasting improvements are to be made. Additionally, adaptability will be enhanced by autonomous construction and climate-responsive designs, whereas feasibility and policy incentives will drive large-scale usage. Barriers to investment can be mitigated through research into financial mechanism options, such as public-private partnerships, while the standardisation of sustainability metrics will ensure compliance. The assessment of AI-led collaborative tools will help in better coordinate stakeholder for smart, resilient, and sustainable modular architecture.

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Integrarea tehnologiilor inteligente într-o arhitectură modulară și flexibilă

Mediul construit trece printr-o transformare semnificativă, pe măsură ce tehnologiile inteligente integrate, alături de o arhitectură modulară și flexibilă, îmbunătățesc sustenabilitatea, eficiența și adaptabilitatea. Aceste tehnologii includ Internetul Lucrurilor (IoT), inteligența artificială (AI) și robotica, care contribuie la îmbunătățirea construcției modulare prin prefabricare, scalabilitate și configurare spațială adaptabilă. Proiectarea bazată pe AI permite personalizarea în timp real și accelerează procesul de asamblare în cadrul automatizării, reducând astfel costurile și erorile. Acest studiu analizează modularitatea, complexitatea și integrarea sistemelor inteligente, abordând probleme legate de confidențialitatea datelor, interoperabilitate, obsolescența tehnologică și examinând potențialul unei arhitecturi reziliente, pregătite pentru viitor.

Keywords: Arhitectură modulară, design flexibil, tehnologii inteligente, IoT în construcții, sisteme de construcții responsive

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