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SMART RAPID-DEPLOY MODULAR HOUSING AS URBAN RESILIENCE INFRASTRUCTURE - A PATENT-INFORMED FRAMEWORK FOR CONNECTED SMART CITIES

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Abstract

Rapid urbanization, climate-related disruptions, and increasing socio-economic volatility demand fast, scalable, and resilient housing solutions within smart city ecosystems. This paper proposes a hybrid physical–digital framework for rapid-deploy modular housing, based on a patented prefabricated, foldable, and transportable construction system (Romanian Patent RO 106900 B1), extended through IoT-enabled monitoring, low-power communication protocols (e.g., LoRaWAN, NB-IoT), and cloud-based coordination. To strengthen practical applicability, the study introduces a pilot deployment scenario of a modular housing cluster, illustrating deployment workflows, system interoperability, and real-time data integration within a smart city context. A structured set of Key Performance Indicators (KPIs) is defined and exemplified across operational efficiency, sustainability, service quality, and socio-economic impact, alongside an energy autonomy layer based on photovoltaic generation and local storage. A comparative perspective with conventional temporary housing approaches highlights improvements in deployment speed, scalability, and adaptability. By bridging a historically grounded engineering solution with contemporary digital infrastructures and an applied scenario, the paper contributes a scalable model for resilient and data-driven urban housing within smart cities.

Keywords: Smart cities; rapid-deploy housing; modular prefabrication; urban resilience; IoT integration; cloud data sharing; smart infrastructure

JEL Classification Codes: R11; R58; O18; Q01

1. Introduction

Cities worldwide face increasing pressure from rapid urbanization, climate change, demographic shifts, and socio-economic volatility. These dynamics strain urban infrastructure, especially in domains directly affecting human well-being, such as housing and emergency response. In this context, the smart city paradigm offers a framework for

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improving urban adaptability, efficiency, and resilience through digital technologies and data-driven governance [1].

Despite major advances in mobility, energy, and environmental monitoring, housing remains insufficiently integrated into smart city infrastructures [1]. Traditional housing systems are characterized by long development cycles, high capital requirements, and limited flexibility, making them poorly suited to emergency and transitional contexts. At the same time, modular and prefabricated housing has gained renewed attention because of its speed, transportability, and scalability, yet most existing solutions remain disconnected from sensor networks, cloud platforms, and coordinated governance mechanisms [3].

This paper argues that rapid-deploy modular housing should be reconceptualized as a connected urban infrastructure service within smart city ecosystems. Building upon a patented foldable and transportable construction system developed by Romanian engineer Nicolae Mihoci (RO 106900 B1), it proposes a hybrid physical–digital framework integrating modular units, IoT-based monitoring, low-power communications, and cloud coordination [4]. To strengthen practical applicability, the paper introduces a pilot deployment scenario of a modular housing cluster and operationalizes a set of Key Performance Indicators (KPIs) covering deployment efficiency, sustainability, service quality, and socio-economic impact. The study thus contributes a scalable model for resilient and data-driven urban housing within contemporary smart cities.

2. Smart city context and related work

The concept of the smart city has evolved into a socio-technical framework integrating digital technologies, physical infrastructure, and governance mechanisms to improve urban efficiency, sustainability, and quality of life. More recent research emphasizes resilience as a key dimension of smart cities, focusing on the capacity of urban systems to respond to disruptions while maintaining essential services.

In parallel, a substantial body of work addresses post-disaster housing and emergency sheltering, highlighting the importance of rapid deployment, adaptability, and user-centered design [2]. Prefabricated and modular construction systems are widely recognized for their ability to reduce construction time, improve logistics, and support scalable deployment in crisis contexts. Similarly, contemporary modular housing research emphasizes off-site manufacturing, standardization, and lifecycle efficiency.

However, despite these advances, modular housing solutions are typically treated as isolated construction systems rather than integrated components of smart city infrastructures. Existing approaches rarely incorporate IoT-enabled monitoring, interoperable data platforms, or coordinated governance mechanisms that would enable real-time management and system-level optimization [4].

This gap between physical modular housing systems and digital smart city infrastructures motivates the present study, which proposes an integrated framework positioning rapid-deploy modular housing as a connected and adaptive urban infrastructure layer.

3. Patent-informed modular housing system

The proposed framework builds upon a patented prefabricated modular construction solution developed by Romanian engineer Nicolae Mihoci (Romanian Patent RO 106900 B1), designed to enable rapid deployment, efficient transport, and scalable housing delivery. The concept was further extended through a patent application initiated in Germany in 1989 for a “transportable house made of prefabricated elements” (Transportfähiges Haus aus vorgefertigten Elementen), reflecting its early international development trajectory. This study focuses on the system’s engineering logic and operational advantages within smart city environments.

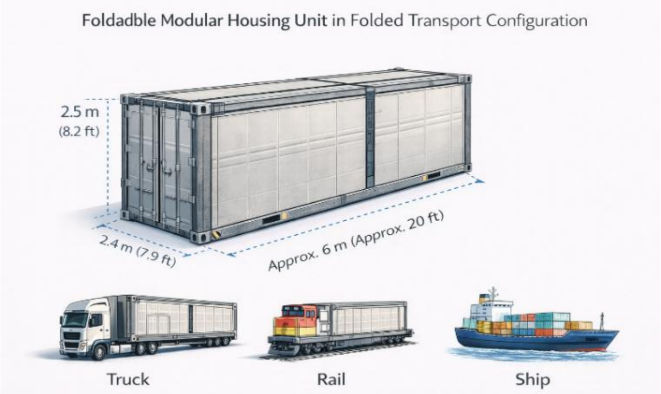

Figure 1 - Modular housing unit in its folded configuration

The core innovation lies in a foldable structural configuration that allows each unit to be transported in a compact form and deployed on-site through a controlled mechanical unfolding process. The module integrates structural elements, enclosure components, and preconfigured functional zones into a single transportable unit, minimizing on-site construction requirements.

This folding mechanism significantly reduces transport volume compared to conventional prefabricated modules, enabling multiple units to be delivered using standard logistics infrastructure. As a result, deployment efficiency is improved both in terms of time and cost [1]. Once on-site, the unit can be unfolded and stabilized with minimal equipment, allowing rapid transition from transport to operational use.

From an operational perspective, the system supports a full lifecycle model including prefabrication, transport, rapid deployment, relocation, and reuse [3]. This transforms housing from a fixed asset into a mobile infrastructure resource, suitable for dynamic allocation in emergency or high-variability contexts.

In addition, the modular design incorporates standardized interfaces for connection to external systems such as energy supply, water, sanitation, and communication networks. This ensures interoperability with both temporary and permanent infrastructure, facilitating integration into broader urban systems.

Figure 1 illustrates the modular housing unit in its folded configuration, highlighting the compact transport form and structural arrangement that enables efficient logistics and rapid deployment.

4. System architecture: physical–digital integration

4.1 Physical and Functional Layer

Within the proposed framework, the modular housing unit is reconceptualized as a deployable urban infrastructure component rather than a standalone construction element. Each unit functions as a standardized, reusable module designed for rapid installation, relocation, and integration into diverse urban contexts, including emergency settlements and temporary extensions of existing urban areas.

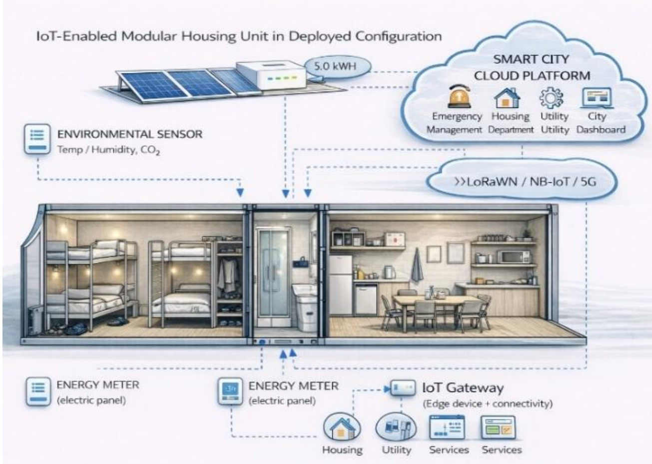

Figure 2 - Modular housing unit in its deployed configuration

Figure 2 illustrates the modular housing unit in its deployed configuration, highlighting both spatial organization and functional layout.

The modular configuration supports clustering, enabling the formation of adaptable micro-communities that can scale according to demand. Internally, the unit is organized into compact functional zones supporting essential activities such as sleeping, hygiene, storage, and basic domestic use. Space optimization is achieved through multifunctional elements, including bunk beds, foldable furniture, and integrated storage systems, allowing multiple occupants to be accommodated efficiently within a limited footprint [3].

4.2 Digital and IoT Architecture

To enable integration within smart city ecosystems, each modular unit is equipped with an IoT-based monitoring system that captures key operational and environmental parameters. Typical sensor configurations include temperature and humidity sensors (e.g., BME280), air quality sensors (e.g., CO_2 monitoring), smart energy meters, and occupancy detection through PIR sensors.

Data is collected locally and transmitted through a hybrid communication architecture combining low-power wide-area technologies such as LoRaWAN or NB-IoT with higher-bandwidth solutions (4G/5G), depending on infrastructure availability (ITU, 2017). A local gateway aggregates data from multiple units and ensures secure transmission to cloud-based platforms.

At the platform level, data is processed and visualized through dashboards that support real-time monitoring, predictive maintenance, and coordinated resource management across the housing cluster. This architecture enables operational visibility and data-driven decision-making at both local and municipal levels (Chichernea, 2011; Chichernea, 2015; NIST, 2022).

4.3 Energy, Governance, and Security Integration

To enhance resilience, the system incorporates decentralized energy generation through photovoltaic panels (typically 1.5–3 kW per unit) combined with local storage (approximately 5 kWh). This configuration enables partial energy autonomy, particularly in off-grid or infrastructure-constrained environments, while also supporting hybrid operation in grid-connected contexts (Ceranic et al., 2018).

From a governance perspective, the system is designed to operate within a multi-stakeholder environment involving municipal authorities, emergency services, and infrastructure providers. Interoperability is ensured through standardized data formats and communication interfaces, enabling integration with existing smart city platforms (ITU, 2017; NIST, 2022).

Security and privacy considerations are addressed through a security-by-design approach, including encrypted communication, device authentication, and controlled data access. Particular attention is given to data protection in emergency contexts, where sensitive information related to vulnerable populations must be handled through anonymization and strict access policies in compliance with regulatory frameworks such as GDPR.

5. PILOT CASE STUDY: MODULAR HOUSING CLUSTER DEPLOYMENT

5.1 Scenario overview: modular micro-community deployment

To demonstrate practical applicability, a pilot deployment scenario is defined based on a modular housing cluster composed of ten units. The scenario simulates a rapid-response intervention in a post-disaster context requiring the establishment of a temporary yet functional living environment within a short timeframe (UNDRR, 2015; Ginigaddara et al., 2023).

Six units are allocated for residential use, accommodating approximately 3–4 occupants per unit (total capacity: 18–24 individuals), while four units serve support functions, including a medical point, a childcare or educational space, a shared social/dining unit, and an administrative coordination unit. Each unit provides an estimated usable area of 18–25 m^2, optimized through compact design solutions such as bunk beds, foldable furniture, and integrated storage systems.

5.2 Deployment workflow and logistics

The foldable configuration enables efficient transport and rapid installation [3]. Approximately 4–6 units can be transported per standard flatbed truck, depending on configuration and regulations. On-site deployment involves mechanical unfolding, positioning, and stabilization, requiring approximately 2–4 hours per unit.

Connection to essential utilities, including temporary power, water, and sanitation, can be completed within an additional 1–2 hours per unit through standardized interfaces. As a result, a full cluster of ten units can become operational within 24–48 hours, significantly faster than conventional temporary housing solutions.

5.3 IoT ecosystem and inter-unit connectivity

Each unit is equipped with an IoT monitoring system including environmental sensors (temperature, humidity, CO_2), smart energy meters, and occupancy detection (PIR sensors), with optional extensions such as door/window sensors and leak detection [2].

Figure 3 - Modular housing cluster

Data is transmitted through a hybrid communication architecture combining LoRaWAN for low-power, long-range connectivity with NB-IoT or 4G/5G where available. A local gateway aggregates data at cluster level and transmits it to a cloud platform, where it is processed and visualized through dashboards.

This enables real-time monitoring of key parameters, including indoor environmental conditions (18–26°C; $CO_2 < 1000$ ppm), energy consumption (kWh/day), and occupancy patterns, transforming the cluster into a coordinated digital system supporting data-driven management.

Figure 3 illustrates the deployment scenario, including units in different operational stages and the associated data communication flows.

5.4 Energy layer and comparative performance

Each unit can integrate a photovoltaic system with an installed capacity of approximately 1.5–3 kW and a local battery storage of around 5 kWh. This enables partial energy autonomy, supporting essential loads such as lighting, ventilation, and device charging, with autonomy of approximately 12–24 hours depending on usage [1].

Compared to conventional temporary housing, the system offers significant advantages (Ginigaddara et al., 2023; Nguyen et al., 2022), including deployment time reduction (from weeks to 24–48 hours), improved transport efficiency (4–6 units per truck), reusability across multiple cycles, real-time monitoring capabilities, and enhanced resilience through decentralized energy systems.

5.5 KPI operationalization within the pilot scenario

The pilot scenario enables direct mapping of KPIs to measurable variables (ISO 37120, 2018; ITU, 2017; NIST, 2022), including deployment time (<4 hours/unit), total cluster readiness (<48 hours), energy consumption (3–6 kWh/day per unit), environmental conditions (18–26°C; $CO_2 < 1000$ ppm), occupancy rate, and system uptime.

These indicators are continuously monitored through the IoT infrastructure, providing a structured basis for performance evaluation and future empirical validation.

6. Performance evaluation framework and scalability

6.1 KPI framework and evaluation dimensions

To support systematic assessment, the proposed system is evaluated through a structured set of Key Performance Indicators (KPIs) covering four core dimensions: deployment efficiency, environmental performance, service quality, and socio-economic impact (ISO 37120, 2018; NIST, 2022; ITU, 2017).

Deployment efficiency focuses on rapid installation and operational readiness, including metrics such as deployment time per unit (<4 hours) and full cluster activation (<48 hours). Environmental performance evaluates energy consumption (3–6 kWh/day per unit), indoor conditions (18–26°C; $CO_2 < 1000$ ppm), and integration of renewable energy sources.

Service quality addresses occupant-related parameters, including occupancy rate, perceived comfort, and system uptime, while socio-economic impact considers cost efficiency, reusability across multiple deployment cycles, and local economic integration.

The KPIs are operationalized through measurable variables collected via the IoT infrastructure, enabling continuous monitoring and real-time evaluation.

Table 1 presents the operationalized KPI framework, including measurement methods, frequency, target benchmarks, and responsible entities, ensuring alignment with SMART performance criteria.

TABLE 1. KPI FRAMEWORK FOR MODULAR SMART HOUSING SYSTEM

Category	KPI	Measurement Method / Data Source	Frequency	Target / Benchmark	Responsible Entity
Deployment Efficiency	Time to install per unit	Manual log / deployment records	Per deployment	< 4 hours / unit	Deployment team / Site operator
	Total cluster deployment time	Project timeline tracking	Per deployment	< 48 hours (10 units)	Project coordinator
	Transport efficiency	Units per transport cycle	Per deployment	4–6 units / truck	Logistics operator
Energy & Environment	Daily energy consumption	Smart meter (Modbus / IoT)	Daily	3–6 kWh / unit	Energy operator
	Renewable energy contribution	PV production vs consumption	Daily	> 50% (context-dependent)	Energy operator

Category	KPI	Measurement Method / Data Source	Frequency	Target / Benchmark	Responsible Entity
	Indoor temperature	Environmental sensors (BME280)	Continuous	18–26°C	System monitoring unit
	CO_2 concentration	CO_2 sensors (MH-Z19)	Continuous	< 1000 ppm	System monitoring unit
Service Quality	Occupancy rate	PIR sensors / manual input	Daily	70–100% (optimal usage)	Site administrator
	Service availability (power, water, sanitation)	System status logs	Continuous	> 95% uptime	Infrastructure operator
	IoT system uptime	Network & platform monitoring	Continuous	> 98% uptime	IT / platform operator
Socio-Economic Impact	Cost per unit (deployment)	Financial estimation / project data	Per deployment	Lower than conventional solutions (order-of-magnitude)	Project manager
	Scalability rate	Units deployed per day	Per deployment	5–10 units/day (cluster scale)	Deployment coordinator
	Reusability index	Number of reuse cycles per unit	Lifecycle tracking	≥ 3 deployment cycles	Asset manager

6.2 Data integration and monitoring workflow

All KPI-related data is collected through distributed sensors at unit level and aggregated at cluster level via local gateways. The data is transmitted to cloud-based platforms where it is processed, stored, and visualized through interactive dashboards (Li et al., 2021; Chichernea, 2011; Chichernea, 2015).

This architecture supports both real-time operational monitoring and historical analysis, enabling predictive maintenance, anomaly detection, and optimization of resource allocation. The integration of IoT data with decision-support systems allows stakeholders to dynamically adjust deployment strategies and improve system performance over time.

6.3 Scalability and replicability

The proposed system is inherently scalable [5], allowing incremental expansion from small clusters (5–10 units) to larger deployments (50–100+ units) depending on demand. Standardized modular design, interoperable communication protocols, and cloud-based coordination enable replication across different urban contexts, including post-disaster environments, temporary workforce housing, and infrastructure-constrained areas.

From a logistical perspective, scalability is supported by transport efficiency (4–6 units per truck), rapid deployment capabilities, and reusability across multiple operational cycles. From a digital perspective, the architecture supports horizontal scaling of IoT devices and cloud resources without significant structural modifications (Li et al., 2021; Parracho et al., 2025).

6.4 Limitations and future work

Despite its advantages, the proposed framework requires further validation through real-world deployment. Future work will focus on large-scale pilot implementations, integration with municipal smart city platforms, and refinement of KPI benchmarks based on empirical data.

Additional research directions include optimization of energy autonomy, enhancement of user-centric service indicators, and exploration of AI-driven predictive models for deployment planning and resource management.

7. Conclusions

This paper has proposed a novel framework for reconceptualizing rapid-deploy modular housing as an integrated urban infrastructure service within smart city ecosystems. By combining a patented foldable construction system with IoT-enabled monitoring, decentralized energy solutions, and cloud-based coordination, the study advances a hybrid physical–digital approach to resilient urban housing.

The pilot deployment scenario demonstrates the practical feasibility of the system, highlighting significant improvements in deployment speed (24–48 hours for a functional cluster), transport efficiency (4–6 units per truck), and operational adaptability. The integration of IoT technologies enables continuous monitoring of environmental conditions, energy consumption, and occupancy, supporting data-driven decision-making and improved service quality.

Furthermore, the proposed KPI framework provides a structured method for evaluating system performance across multiple dimensions, including efficiency, sustainability, and socio-economic impact. This contributes to bridging the gap between conceptual smart city models and deployable, measurable infrastructure solutions [1] [5].

From a broader perspective, the study positions modular housing not as a temporary or isolated solution, but as a scalable and replicable component of future urban systems. Its applicability extends beyond post-disaster scenarios to include temporary workforce housing, rapid urban expansion, and infrastructure-constrained environments.

Future research will focus on large-scale pilot implementations, integration with municipal digital platforms, and the development of AI-driven optimization models for deployment planning and resource management.

Overall, the proposed framework contributes to the advancement of adaptive, resilient, and data-driven urban infrastructure, aligning with the evolving needs of contemporary smart cities.

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