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Engineering Smart Infrastructure For In-Building Logistics: Innovative Approaches To Safe Delivery In Dense Urbanization Conditions

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Abstract: This article presents a theoretical and analytical overview of the prospects for implementing a vertical-horizontal logistics architecture for automated parcel delivery within buildings in high-density urban environments. The study is conducted within a multidisciplinary framework that integrates principles of systems engineering, architectural adaptation, digital logistics, and urban planning. Special attention is given to the comparative analysis of three architectural models of vertical delivery in terms of their compatibility with existing building stock, energy efficiency, level of digital integration, and implementation costs. The research theoretically reconstructs and substantiates a combined model of logistics infrastructure that includes an entry node, a vertical transport shaft, and distributed floor-level storage lockers. This model is compared to the engineering solution developed by Skyscraper Parcels, which is considered an applied projection of the theoretical concept. A structural and functional analysis of system components is conducted, along with an assessment of operational efficiency based on key metrics such as delivery time, failure resistance, parcel loss rate, and user satisfaction. The study finds that integrating logistics infrastructure into building architecture contributes to reduced operational risks, enhanced delivery security, and improved scalability of the system. At the same time, it emphasizes the need for regulatory standardization, architectural adaptability,

and the development of universal IoT platforms to enable broader implementation of such systems in urban settings. The findings will be valuable to professionals in smart construction, digital logistics, architectural design, and urban infrastructure management.

Keywords: Smart building, internal logistics, vertical delivery, shaft infrastructure, automated lockers, urban development, IoT systems, drones, digital architecture, smart logistics.

Introduction

Global urbanization processes in the early 21st century are radically transforming the requirements for intra-city logistics. According to UN-Habitat forecasts, by 2030, more than 60% of the world's population will reside in urbanized areas, which will lead to a sharp increase in demand for compact, automated, and sustainable solutions for delivering goods within urban developments [12]. These challenges are particularly acute in the final stage of the logistics chain, the so-called "last mile," which includes delivery inside residential and commercial buildings.

Modern high-density developments are limited in their capacity to accommodate new logistics systems. Architectural and regulatory barriers, a lack of available space, and a high level of operational risks (including theft, delays, and damage to parcels) require a rethinking of engineering approaches. As indicated by Andreas K. et al. [1], annual losses from theft and misplacement in unsecured residential building lobbies amount to tens of millions of dollars even in developed countries. This actualizes the task of developing an intelligent infrastructure that is integrated into buildings and adapted to the specifics of the urban environment.

One of the most indicative examples of the technical implementation of the in-building delivery concept is the solution developed by the company Skyscraper Parcels. This system involves the use of a vertical transport shaft, distributed floor-level reception modules, and a digital platform for managing the movement of parcels. The architectural-engineering model realized by Skyscraper Parcels is of interest as an applied case study for verifying the theoretical principles of digital logistics in high-density development conditions.

The objective of this study is to conduct a structural analysis of the engineering, architectural, and operational aspects of implementing intelligent in-building logistics, using the Skyscraper Parcels system as an example. Special attention is paid to assessing the applicability of such solutions in the context of the existing housing stock, energy efficiency, digital integration, and scalability within modern urban planning constraints.

Materials and Methods

The methodological foundation of this theoretical study is formed at the intersection of engineering sciences, architectural modeling, and digital logistics. The interdisciplinary approach is necessitated by the need for a comprehensive analysis of in-building delivery systems in dense urban environments, taking into account technical, regulatory, and architectural limitations.

The analytical framework is built on the principles of systems engineering, the theory of architectural adaptation of buildings, and the concept of an intelligent logistics infrastructure. The key areas of content analysis are:

- "last-mile" delivery scenarios in an urbanized environment;
- vertical logistics architectures;
- models for integrating digital devices into building infrastructure;
- prospects of IoT infrastructures for managing internal logistics.

The primary analytical tool is a critical review of publications covering both the theoretical aspects of vertical delivery (including concepts of shaft systems, digital lockers, and lifting modules) and applied engineering models presented in open sources. Data from the official website, patent publications, and presentation materials available in the public domain are used, with the company not being the object of an empirical study in the narrow sense.

Thus, the methodological strategy of the study is based on a reconstructive-comparative approach, which allows for the assessment of the applicability of theoretical solutions in the context of modern urban planning challenges. The analysis of the Skyscraper Parcels model in this context serves as a conditionally applied element, used for the illustration and critical verification of theoretical engineering hypotheses.

Results

Within the framework of theoretical modeling, a concept of a vertical-horizontal logistics architecture adapted to the conditions of dense urban development was formulated. To confirm the practical applicability of this model, the study includes a case study of the innovative Skyscraper Parcels system, proposed as a solution for automated parcel delivery inside multi-story residential buildings. This system demonstrates the integration of key components of a logistics infrastructure into the building's architecture and serves as a validated example of transferring a theoretical concept to the level of engineering implementation.

The architectural scheme of Skyscraper Parcels is based on a modular approach and includes three key links: an entry delivery gateway, a vertical transport shaft, and floor-level digital storage cells. The system operates autonomously, ensuring delivery from the point of parcel reception to the recipient without human involvement, with all operations being tracked and controlled via IoT interfaces. Special attention in the case study is given to the analysis of the structural, functional, and operational characteristics of the system's components. This allows for their comparison with the theoretically substantiated model and an assessment of the compliance of the declared parameters with the requirements of modern urban logistics. Table 1 presents a systematized characterization of the components and parameters of the Skyscraper Parcels system, reflecting its architectural structure, digital integration, and operational efficiency.

Table 1 – Architecture and operational characteristics of the Skyscraper Parcels system as a case study of intelligent in-building logistics (Compiled based on source: [13])

Component/Indicator	Description / Value	Comment
Entry Delivery Gateway	Automated reception with digital identification	Eliminates manual handoff, minimizes delays and contact risks
Vertical Transport Module	Electromechanical lift with two-way movement	Up to 50–60 deliveries per hour with minimal energy load
Floor-level Storage Modules	Digital cells with authorization and notification	Contactless access, API support, and integration with building systems
Average Delivery Time	1–2 minutes per floor	Operations do not require the participation of residents or service personnel
Loss Rate	< 0.3%	Achieved through automation and a secure route

Component/Indicator	Description / Value	Comment
Compatibility with Existing Buildings	Medium	Requires analysis of load-bearing structures and modernization of digital infrastructure
Scalability	High	Suitable for individual buildings and residential complexes with unified logistics
User Satisfaction	High	Confirmed in surveys within pilot implementations

The Skyscraper Parcels case study confirms the effectiveness of the proposed vertical-horizontal logistics model and demonstrates its feasibility in real-world conditions. The application of this system allows for a significant increase in the reliability and security of delivery, a reduction in operational risks, and ensures the scalability of solutions for various forms of urban development.

Table 2. Functional effects of implementing the Skyscraper Parcels system in dense urban environments (Compiled based on source: [13])

Effect Category	Specific Manifestation	Explanation
Operational Efficiency	Reduction of delivery time to 1–2 min/floor	Eliminates the need to call the resident or involve personnel
Architectural Compatibility	Low invasiveness during installation	Modular design allows for adaptation to new and existing buildings
Social Security	Reduction in the risk of theft and conflicts in the lobby	Fully automated parcel transfer, no intermediaries
Digital Integration	Compatibility with the building's IoT platforms	Synchronization with video surveillance, access control, and BMS is possible
Environmental Sustainability	Energy efficiency and elimination of paper notifications	Operates on demand, without constant energy consumption

Effect Category	Specific Manifestation	Explanation
Scalability	Expansion to residential and mixed-use complexes	Creation of a unified logistics network between buildings

The system under review demonstrates a high degree of compliance with the tasks of the post-pandemic transformation of urban logistics, as it eliminates crowds in entry areas and completely removes human contact with couriers. In terms of digital maturity and scalability, Skyscraper Parcels can be integrated into multi-building residential complexes with a unified logistics infrastructure, making it a potential core for so-called intelligent logistics clusters.

The system's ability to adapt to buildings of various heights without changing the operating algorithm and logistics procedures deserves special attention. This confirms the universality of the proposed engineering solution and its relevance for an urban environment with limited opportunities for horizontal expansion.

Discussion

The vertical-horizontal in-building logistics architecture developed within the framework of theoretical modeling demonstrates a set of sustainable advantages arising from the systemic integration of three levels: the architectural structure of the building, the engineering transport nodes, and the digital management interfaces. One of the key effects of the proposed scheme is an increase in the security of logistics operations and a reduction in the load on traditional entry zones—such as lobbies, reception areas, and concierge services. Thanks to autonomous delivery directly to floor-level digital cells, the need for intermediaries is eliminated, the risk of theft and distribution errors is minimized, and the density of crowds at reception points is reduced.

A significant advantage is the scalability of the concept. The two-level structure (entry module – vertical shaft – local floor nodes) allows the model to be adapted to both individual buildings and multi-building complexes with a common logistics infrastructure. This creates the prerequisites for the formation of so-called intelligent logistics clusters, uniting residential and commercial buildings into a single system managed through a central digital gateway. This approach is particularly relevant in the context of the growth of mixed-use complexes (MUCs), where the logistics load is comparable to that of small distribution centers [1]. Nevertheless, the theoretical implementation of this architecture is associated with a number of limitations, which are taken into account in its modeling. First, the placement of vertical shafts and digital nodes requires an analysis of the load-bearing capacity of structures and an assessment of the permissible loads on inter-floor slabs, especially in buildings not originally designed for such infrastructure [6]. In older housing stock, this can conflict with historical-architectural restrictions and current building regulations. Difficulties arise when integrating systems into buildings not equipped with digital communications. Connecting digital storage cells, managing access, and synchronizing with existing video surveillance and BMS systems require the modernization of low-voltage networks, retraining of personnel, and changes to operational regulations.

Another area of limitation is regulatory. Current legislation in most countries does not yet contain unified requirements for the architecture of digital logistics in residential buildings [7]. The absence of standard solutions, certified data exchange interfaces between IoT devices, and the heterogeneity of requirements across regions significantly complicate the scaling and implementation of theoretically substantiated models in practice.

A promising direction for the development of theoretical engineering solutions is the integration of autonomous transport platforms and the development of drone logistics. A number of studies [2], [4], [5] describe scenarios in which delivery is carried out by unmanned aerial vehicles landing on the roofs of buildings, after which the cargo is automatically transferred to distribution shafts and then to floor-level cells using manipulators. Such a model appears technically feasible and opens up new opportunities for synergy between aerial and in-building logistics.

In the long term, the focus is shifting towards the formation of ecosystems of intelligent buildings as digital organisms, in which all engineering and logistics processes are managed through a single digital platform.

As emphasized by Hong F. [4] and Ożadowicz A. [11], the decisive factor will be the creation of universal, standardized IoT infrastructures capable of ensuring compatibility between the subsystems of delivery, storage, access, and energy efficiency. The most important challenges here are related to the harmonization of protocols, the management of data traffic, and ensuring cybersecurity. According to Heidary R. et al. [10], it is the development of open architectures for digital interaction that will determine the possibility of large-scale implementation of intelligent logistics in an urbanized environment.

For a visual assessment of the operational potential of the proposed architectural model, Table 3 presents key metrics for automated in-building delivery, calculated based on data from scientific literature and the logic of theoretical design.

Table 3. Assessment of the operational efficiency of automated in-building delivery (Compiled by the author based on sources: [3], [8], [9], [13])

Metric	Value with an automated system	Comment
Average delivery time (per floor)	1.5–2.0 min	Excluding external delivery delays
Shaft throughput	up to 60 parcels/hour	With dual flow (up/down)
Loss rate	less than 0.3%	By eliminating the human factor
Resilience to failures (redundant paths)	high	Support for autonomous mode and diagnostics
Flexibility of integration into the building	medium	Requires calculations of loads and communication channels
User satisfaction	high	According to surveys in pilot projects

As theoretical estimates show, the automation of processes allows for a reduction in the physical load on personnel and an increase in the resilience of the logistics system to external failures. Despite the high implementation cost, the integration of digital logistics demonstrates a positive operational effect upon reaching a critical volume of deliveries. Promising directions for further development include the implementation of predictive routing algorithms, self-learning management systems, and adaptive logistics depending on the time of day, traffic, and seasonal load.

Conclusion

The study conducted has revealed the methodological viability of the vertical-horizontal logistics architecture concept as a tool for the engineering adaptation of buildings to the challenges of digital urbanization. It has been established that such models provide a sustainable integration of logistics processes into the architectural fabric of properties, increasing the security, autonomy, and scalability of in-building delivery without the need to transform the organizational logic of the urban infrastructure.

The analysis of the structural and digital characteristics of the Skyscraper Parcels engineering solution has confirmed the applicability of the proposed architectural scheme for operation in high-density development conditions, which actualizes the development of universal logistics modules with IoT coordination and modular compatibility. It has been shown that it is the architectural-digital symbiosis that becomes the critical condition for the successful implementation of intelligent logistics systems in residential and mixed-use developments.

Special attention in the work was paid to the regulatory and structural constraints that limit the scalability of solutions, which underscores the need for interdisciplinary design involving engineers, architects, and specialists in digital transformation. The prospect of creating a new type of logistics cluster—distributed and self-organizing based on a single digital core with a high degree of adaptability to building morphology—has been substantiated.

It has been proven that the key factor of operational resilience is not so much the physical infrastructure as the architecture of digital management and the system's ability for functional self-service and interaction with other engineering subsystems. These propositions find support in current research in the field of intelligent buildings, the synergy of IoT and logistics, and in projects implementing autonomous logistics platforms.

Thus, the proposed theoretical model, confirmed by the analysis of the Skyscraper Parcels case study, forms the basis for rethinking last-mile logistics in the urban environment. It opens the way for the development of intelligent buildings as active participants in logistics processes. Prospects for further research are related to the development of regulatory standards for digital logistics, the empirical verification of models in various architectural contexts, and the integration of aerial and shaft-based delivery into a unified ecosystem of smart urban logistics.

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