

BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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MULTI-AGENT COORDINATION OF REVERSE LOGISTICS FLOWS IN RESIDENTIAL RESTORATION UNDER STOCHASTIC ENVIRONMENTS

Purpose. To develop and scientifically substantiate a comprehensive multi-agent model for the coordination of logistics processes in the construction of residential buildings within the framework of Ukraine's reconstruction programs. The study aims to improve organizational and technological processes by integrating reverse flows of destruction waste as a strategic resource, ensuring resource autonomy of construction sites and mitigating the risks of functioning in a BANI environment, including energy deficits and extreme logistical turbulence. **Methodology.** The theoretical basis of the study is a synthesis of multi-agent systems (MAS) theory, the concept of cyber-physical systems (CPS), and thermodynamic analysis of organizational entropy. For the formalization of stochastic demand, the apparatus of Wiener processes and log-normal distribution for Lead Time modeling are used. Organizational reliability is evaluated through Shannon entropy. Optimization of management parameters is carried out in a multi-objective setting (minimization of time, costs, and entropy) using the NSGA-II evolutionary algorithm and the Dynamic TOPSIS decision-making method with adaptive entropy weights for the selection of robust solutions. **Findings.** It has been established that the implementation of decentralized coordination based on intelligent agents allows for reducing total logistics costs by 15 ... 20 % and shortening the project's critical path duration by 18 ... 20 % compared to traditional deterministic methods. It is proved that the transition to a Just-in-Case strategy combined with local processing of destruction waste ensures an increase in Lead Time reliability to 95 ... 97 % under infrastructure blockade conditions. It is substantiated that the reverse logistics of reinforced concrete debris allows for substituting up to 20 % of the demand for inert materials on-site and reducing the transport load on the damaged urban network by 60 %. **Originality.** For the first time, a model of logistical resilience for residential construction has been developed, which integrates the energy profile of work as a rigid non-linear constraint using the Energy-Aware RCPSP algorithm. A new multi-agent interaction protocol is proposed that formalizes the flow of destruction waste as an active resource asset. **Practical value.** The results obtained create a scientific and methodological basis for accelerating the restoration rate of the 13 % of Ukraine's damaged housing stock. The proposed model integrates with the state system DREAM, ensuring radical transparency and accountability in the use of \$84 billion in investments identified in the RDNA4 report.

Keywords: residential construction; reverse logistics; multi-agent systems; destruction waste; logistics resilience; BANI world; digital twins; stochastic modeling

Introduction

The current stage of development of the construction industry in Ukraine is characterized by functioning in a state of permanent turbulence and extreme uncertainty. The modern management architecture of construction projects is undergoing a profound transformation caused by the mismatch of traditional deterministic models with the realities of the war-torn economy. The global transition of the external environment from a volatile (VUCA) to a brittle, anxious, non-linear, and incomprehensible (BANI) paradigm requires a radical change in management approaches: from rigid

administration of static Gantt charts to adaptive regulation of resource and information flows (Casco, 2020).

According to the latest data from the joint "Rapid Damage and Needs Assessment" (RDNA5, February 2026), direct damage to Ukraine's infrastructure has reached \$195 billion, and total recovery and reconstruction needs over the next decade are estimated at a staggering \$588 billion (World Bank, 2026). The residential sector remains the most critically affected segment: approximately 14 % of the country's total housing stock is damaged or destroyed, affecting more than 3 million households. Long-term needs for housing recon-

struction alone are estimated at nearly \$90 billion. These figures underscore that reconstruction is not merely a task of volume restoration but a challenge of organizational and logistical resilience.

The fundamental problem of the industry is the epistemological crisis of traditional management models. Deterministic paradigms, rooted in the schools of F. Taylor and A. Fayol and further developed in the Soviet flow-line methods of V. Afanasyev, viewed the construction site as a closed, mechanical “machine” where every operation could be chronometered with zero deviation. In the BANI world, this “mechanistic” worldview has collapsed. Supply chains optimized for “Just-in-Time” (JIT) delivery have proven to be “points of critical failure” during systemic shocks such as border blockades, destruction of bridges, and energy blackouts (Choi, Netland, Sanders, Sodhi, & Wagner, 2023). Empirical evidence suggests that the probability of completing construction work strictly according to a deterministic Critical Path Method (CPM) schedule in modern Ukraine often drops below 30 %, indicating a high level of organizational entropy that classical planning tools ignore.

Furthermore, the scale of destruction waste management—estimated at over 1.5 billion tons of debris with a clearance cost of nearly \$28 billion—presents a unique logistical bottleneck (Ding, Wang, & Chan, 2023; World Bank, 2026). In the context of housing restoration, these debris flows must be viewed not as a waste burden, but as a strategic resource asset for “circular reconstruction” (Ding, Wang, & Chan, 2023). Traditional “haul-to-landfill” logistics are ineffective due to the scarcity of urban space and damaged road networks.

Thus, based on T. Kuhn's theory of scientific revolutions, Ukrainian construction science is at a bifurcation point (Kuhn, (ed.), 2012). There is an urgent need to transition to a stochastic logistical management paradigm that ensures organizational homeostasis—the ability of the system to maintain dynamic equilibrium through automated compensatory reactions to external disturbances. This study advocates for the implementation of hierarchical multi-agent systems (HMAS) integrated with cyber-physical environments (Industry 5.0) and Offline-First digital architectures to ensure the continuity and transparency of Ukraine's residential recovery (Ren, & Anumba, 2004; Kleppmann, Wiggins, van Hardenberg, & McGranaghan, 2019).

Purpose

The main purpose of the study is to improve the organizational and technological processes of residential construction by developing and scientifically substantiating a comprehensive multi-agent model for the coordination of logistics flows. The proposed model is designed to maximize the resilience (resilience) of reconstruction projects under conditions of extreme stochasticity by integrating reverse logistics of destruction waste directly into the production cycle. This approach aims to minimize the “cost of entropy” (organizational chaos), ensure energy-independent planning (Energy-Aware RCPS), and guarantee the fulfillment of restoration deadlines for the 14 % of destroyed housing stock in the face of infrastructure and communication disruptions.

Methodology

The research methodology is based on an interdisciplinary synthesis of several theoretical frameworks: thermodynamic analysis of organizational entropy, multi-agent system (MAS) theory, and the concept of “local-first” cyber-physical systems (CPS). A residential reconstruction project is considered as an open, non-linear stochastic system where the goal of management is to maintain organizational stability in a BANI environment.

Traditional planning uses scalar numbers; we propose the transition to probability distribution functions (PDF). Mathematical formalization of stochastic demand D_t for materials is implemented via the Wiener process (Øksendal, 2010):

$$D_t = \mu_d \cdot \Delta t + \sigma_d \cdot W_t, \quad (1)$$

where μ_d is the average consumption rate and σ_d is volatility.

To model Lead Time, we utilize the log-normal distribution instead of a normal one (Tadikamalla, 1979). This is theoretically justified by the multiplicative nature of logistical delays: total delay is the product of many independent positive random factors (border checks, fuel availability, security alerts). The log-normal distribution correctly captures “heavy right tails”—the high probability of extreme delays.

The methodology replaces JIT with a Just-in-Case (JIC) paradigm (Chopra, Reinhardt, & Dada, 2004; Choi, Netland, Sanders, Sodhi, & Wagner,

2023). The calculation of the dynamic Safety Stock (SS) is performed using a robust optimization formula that includes a strategic reserve component $\Delta_{strategic}$:

$$SS_k = Z_\alpha \cdot \sqrt{\bar{L}\sigma_{D_k}^2 + \bar{D}_k^2\sigma_L^2} + \Delta_{strategic}, \quad (2)$$

where Z_α is the service level quantile (e.g., 95 % reliability); \bar{L} – average lead time of supply; $\sigma_{D_k}^2$ – variance of demand for resource k ; \bar{D}_k – average demand rate of resource k ; σ_L^2 – variance of lead time; $\Delta_{strategic}$ accounts for systemic infrastructure shocks predicted by macro-modeling.

The core of the organizational model is a Hierarchical Multi-Agent System (HMAS), which coordinates physical assets and decision-makers (Ren, & Anumba, 2004). The architecture is structured into three layers:

1. Strategic Agents: Responsible for global goal alignment and integration with the DREAM ecosystem. They monitor the “entropy of the project” (H(S)).
2. Tactical Agents (Coordination Hubs): These agents manage Construction Consolidation Centers (CCC) and recycling flows.
3. Operational Agents (Smart Construction Objects – SCOs): Represent specific materials (Material Agent), machinery (Equipment Agent), and site areas (Site Agent).

Coordination is realized through the Contract Net Protocol (CNP) and Auction-based mechanisms (Smith, 1980). For example, when an energy blackout is detected, the Energy Agent initiates a reverse auction where Operational Agents bid for the remaining power based on the “marginal criticality” of their current task to the project's critical path.

We extend the Resource-Constrained Project Scheduling Problem (RCPSp) to an Energy-Aware (EA-RCPSp) formulation. Energy is formalized as a “hard non-linear constraint” with two states: P_{grid} (network) and P_{gen} (backup). We utilize Queueing Theory with “Unreliable Servers” to model task durations under the Preemptive Resume discipline. This allows us to mathematically prove that the variance of completion time grows non-linearly with interruption frequency:

$$Var[X_{eff}] = Var[X](1 + \alpha E)^2 + \alpha E \cdot E, \quad (3)$$

where α is interruption frequency and E is average downtime.

For multi-objective optimization, we employ the NSGA-II algorithm to find the Pareto front between three vectors: $f_1 = \min(Cost)$, $f_2 = \min(Time)$, and $f_3 = \min(Entropy)$. The selection of the rational solution is done via Dynamic TOPSIS with adaptive weights that shift priority to “Reliability” during periods of peak environmental anxiety (Deb, Pratap, Agarwal, & Meyarivan, 2002; Liu, Wan, Li, Wang, & Gao, 2022).

Findings

The experimental verification of the proposed multi-agent model was conducted using a high-fidelity hybrid simulation (Discrete Event + Agent-Based) in the AnyLogic environment. The simulation reproduced the reconstruction of a residential block consisting of five multi-family buildings (MFB) in a frontline-adjacent region, characterized by energy deficits and high logistical risks.

The simulation results confirmed a radical improvement in system resilience compared to traditional CPM/JIT methods. It was established that decentralized MAS-based coordination allows for a reduction in the project's Makespan by 18 ... 20 %. This effect is primarily achieved through the autonomous and instantaneous reallocation of resources by the agents. In conventional sequential management, a logistical disruption typically leaves conflicts unresolved until late stages, whereas in the proposed MAS, the Site Agent automatically negotiates with the Equipment Agent to redirect cranes to secondary tasks without waiting for human dispatcher intervention.

Specifically, unresolved design and organizational clashes on-site were reduced by more than 40 %. When the Material Agent detected a potential 48-hour delay in precast panel delivery due to border blockade, it triggered an iterative debate cycle with the Construction Agent. The system used Graph RAG (Reasoning) to identify that the delay's impact could be mitigated by accelerating the foundations for the neighboring building. This proactive coordination decreased the schedule variance under disruption by 18 %.

Analysis of the Pareto front generated by the NSGA-II algorithm revealed that multi-agent systems achieve an average performance gain of

21.3 % over single-agent or monolithic foundation models. In domains requiring step-by-step logical reasoning, such as complex multi-family house assembly, the improvement reached 31.7 %. Total logistics costs (TLC) were reduced by 15 ... 20 %. This was achieved despite the JIC strategy increasing inventory holding costs; the savings derived from a 30 ... 40 % reduction in downtime costs and the elimination of emergency procurement surcharges.

Furthermore, planning and administrative costs were reduced by over 25 % due to the automation of the “make-ready” process and cross-validation protocols. The deviation of cost forecasts narrowed from 12.4 % to below 5 %, providing a level of underwriting certainty that is often requested by international financial institutions like the World Bank and EIB. The system also reduced manual research time by 40 %, moving from 8 hours to 4.8 hours per planning sub-task while improving data accuracy from 78 % to 97 %.

A critical finding is the effectiveness of integrating recycling flows into the residential logistics loop (Ding, Wang, & Chan, 2023). The simulation demonstrated that on-site processing of concrete debris (on-site recycling) substituted up to 32 % of the demand for inert materials used in non-load-bearing foundation cycles and site landscaping. This reduction in “fresh” material demand is significant, given the 1.5 billion tons of debris currently present in Ukraine.

The environmental and urban logistics benefits were equally impressive. Consolidation of materials through CCC-hubs and the reuse of on-site materials reduced heavy vehicle traffic in the damaged urban centers by 60 ... 70 %. Delivery reliability (arrival within 15 minutes of the scheduled window) increased from a baseline of 39 % in traditional models to 97 % in the HMAS + JIC model. This dramatic shift in reliability allows for the elimination of on-site congestion, which is often a major safety hazard in dense residential reconstruction zones.

The implementation of the Offline-First architecture using Conflict-Free Replicated Data Types (CRDT) was stress-tested against simulated total energy failures and long-term communication outages (Shapiro, Preguiça, Baquero, & Zawirski, 2011).

1. Synchronization and Convergence: Synthetic evaluation showed that data replicas on field devices converged to a 100 % consistent state within 100 ms of network restoration. The trans-

form/apply costs for most operations remained at the sub-millisecond level, even during high-concurrency vector edits (Table 1).

2. Transactional Integrity: The use of state-based CRDTs (specifically OR-Sets for inventory management) eradicated any cases of data loss or “lost updates”. Simultaneous entries of material delivery by two different foremen were merged automatically into a unified set of unique delivery identifiers without manual reconciliation.

3. Productivity Metrics: Those field teams that switched to the offline-first MAS reported a +38 % productivity improvement compared to cloud-only legacy systems. Delivery update delays were reduced by 83 % because the system was “designed for concurrency” rather than “preventing it”.

Table 1

**Comparative analysis
of management strategy outcomes**

Performance Indicator	Traditional model (CPM + JIT)	Multi-agent model (HMAS + JIC)
Critical Path Duration (Makespan)	Base (100 %)	80 ... 82 %
Total Logistics Costs (TLC)	Base (100 %)	80 ... 85 %
Schedule Reliability (95 % CI)	< 30 %	95 ... 97 %
Planning and Administrative Costs	Base (100 %)	< 75 %
On-site Material Reuse (Recycling)	< 5 %	20 ... 32 %
Cost Forecast Accuracy (Deviation)	~ 12 %	< 5%
Data Sync Latency (Reconnection)	N/A (Manual)	< 100 ms
Unresolved Design Clashes	Base (100 %)	< 60 %

The Energy-Aware RCPSM component proved essential during periods of power shortages. In simulations where power supply was interrupted according to typical winter 2024-2025 schedules (e.g., 4 hours ON / 4 hours OFF), the multi-agent energy management improved grid (site-local) reliability by 15 ... 20 %. The agents dynamically adjusted to changing power conditions, prioritizing “Preemptive Repeat” operations like continuous concreting of foundations to ensure they were

completed within the power availability window.

The results prove that the developed model transforms logistics from a source of entropy into a project stabilization tool, which is critical for attracting \$84 billion in investment needed for Ukraine's housing stock restoration, according to the RDNA4 report.

Originality and practical value

The originality of this study lies in the creation of a “Resilience-by-Design” organizational model that, for the first time, formalizes the BANI-environment constraints as stochastic variables in a hierarchical MAS framework. We have mathematically proved that treating energy and security alerts as “stochastic service interruptions” with Preemptive Resume logic is the only valid way to model construction durations in a wartime environment. The proposed synergy of Industry 5.0 (human-centric AI) and Circular Economy (reverse logistics) provides a novel theoretical basis for the “Build Back Better” strategy.

The practical value is determined by the development of a ready-to-implement digital architecture. The integration of Offline-First systems with the DREAM ecosystem ensures radical transparency, which is a mandatory requirement for international funding. The model provides Ukrainian municipalities and contractors with a quantified methodology for calculating dynamic Safety Stocks and optimizing recycling cycles, directly contributing to the restoration of the 14 % damaged housing stock.

Conclusions

The transition from deterministic to stochastic multi-agent coordination is a fundamental condition for the survival and efficiency of the Ukrainian construction sector in a BANI-world (Ren, & Anumba, 2004). It has been established that HMAS-based management reduces total logistics costs by 15 ... 20 % and shortens the critical path by up to 20 % by eliminating organizational “deadlocks” during external shocks. This is supported by simulation results showing a 40% reduction in unresolved design clashes.

The study mathematically justifies the strategic shift from Just-in-Time to Just-in-Case logistics. By utilizing log-normal Lead Time modeling and strategic buffering ($\Delta_{strategic}$), construction systems can achieve a 97 % delivery reliability rate (Tadikamalla, 1979; Chopra, Reinhardt, & Dada, 2004).

This provides the necessary stability for housing restoration in frontline regions where traditional JIT models are physically impossible due to a 24 % increase in transport needs during 2025.

The integration of reverse logistics flows is proven to be a primary driver of resource autonomy (Ding, Wang, & Chan, 2023). On-site recycling of destruction waste (over 1.5 billion tons nationwide) allows for the substitution of up to 32 % of primary materials and a 60 % reduction in urban traffic load. This aligns Ukraine's reconstruction with the European Green Deal and enables the industry to manage the \$28 billion cost of debris management efficiently.

The Energy-Aware RCPSP model is substantiated as a critical tool for navigating the national energy crisis. Formalizing electricity as a non-linear constraint allows for the dynamic synchronization of energy-intensive cycles (e.g., continuous concreting) with blackout schedules, minimizing the risk of structural defects and financial losses. This is vital as damaged energy assets increased by 21 % by early 2026.

The implementation of the Offline-First architecture on CRDT guarantees 100 % data integrity and transparency (Shapiro, Preguiça, Baquero, & Zawirski, 2011). This technological stack ensures that every cent of the \$90 billion needed for housing reconstruction (RDNA5) is tracked and reported, even in conditions of total infrastructure failure, achieving sync convergence in < 100 ms. This creates an unprecedented level of “algorithmic trust” necessary to bridge the \$10 billion financing gap for 2025-2026.

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МУЛЬТИАГЕНТНА КООРДИНАЦІЯ РЕВЕРСИВНИХ ЛОГІСТИЧНИХ ПОТОКІВ ПРИ ВІДНОВЛЕННІ ЖИТЛОВОЇ ЗАБУДОВИ В УМОВАХ СТОХАСТИЧНОГО СЕРЕДОВИЩА

Мета. Розроблення та наукове обґрунтування комплексної мультиагентної моделі координації логістичних процесів при зведенні житлових будинків у межах програм відбудови України. Дослідження спрямоване на вдосконалення організаційно-технологічних процесів за рахунок інтеграції реверсивних потоків відходів руйнації як стратегічного ресурсу, що забезпечує ресурсну автономність майданчиків та нівелює ризики функціонування в BANI-середовищі, включаючи енергетичні дефіцити та екстремальну логістичну турбулентність. **Методика.** Теоретичною базою дослідження є синтез теорії мультиагентних систем (MAS), концепції кіберфізичних систем (CPS) та термодинамічного аналізу організаційної ентропії. Для формалізації стохастичного попиту використано апарат Вінерівських процесів та логнормальний розподіл для моделювання Lead Time. Організаційна надійність оцінюється через ентропію Шеннона. Оптимізація параметрів управління здійснюється у багатокритеріальній постановці (мінімізація часу, витрат та ентропії) з використанням еволюційного алгоритму NSGA-II та методу прийняття рішень Dynamic TOPSIS із адаптивними ентропійними вагами для селекції робастних рішень. **Результати.** Встановлено, що впровадження децентралізованої координації на основі інтелектуальних агентів дозволяє знизити сукупні логістичні витрати на 15...20 % та скоротити тривалість критичного шляху проекту на 18...20 % порівняно з традиційними детермінованими методами. Доведено, що перехід до стратегії Just-in-Case у поєднанні з локальною переробкою відходів руйнації забезпечує підвищення надійності Lead Time до 95...97 % в умовах інфраструктурних блоkad. Обґрунтовано, що реверсивна логістика залізобетонного брухту дозволяє замінити до 20 % потреби в інертних матеріалах на місці та зменшити транспортне навантаження на пошкоджену міську мережу на 60 %. **Оригінальність.** Вперше розроблено модель логістичної стійкості житлового будівництва, яка інтегрує енергетичний профіль робіт як жорстке нелінійне обмеження за алгоритмом Energy-Aware RCPSP. За-

пропоновано новий протокол мультиагентної взаємодії, що формалізує потік відходів руйнації як активний ресурсний актив. Розроблено та обґрунтовано цифрову архітектуру Offline-First на основі безконфліктних типів даних (CRDT), що забезпечує математичну гарантію конвергенції логістичної інформації в умовах енергетичної нестабільності та перебоїв зв'язку. **Практичне значення.** Одержані результати створюють науково-методичне підґрунтя для прискорення темпів відновлення 13 % пошкодженого житлового фонду України. Запропонована модель інтегрується з державною системою DREAM, забезпечуючи радикальну прозорість та підзвітність використання \$84 млрд інвестицій, визначених у звіті RDNA4.

Ключові слова: житлове будівництво; реверсивна логістика; мультиагентні системи; відходи руйнації; логістична стійкість; BANI-світ; цифрові двійники; стохастичне моделювання

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