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# ARCHITECTURE OF AN AUTONOMOUS INTELLIGENT SYSTEM FOR MANAGING CONSTRUCTION PROCESSES UNDER THE RISK OF EXTERNAL IMPACTS

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**Abstract**. This paper explores the problem of ensuring the autonomy and fault tolerance of intelligent control systems used in construction process management under conditions of external risks, such as power outages, loss of network connectivity, or cyber-attacks. As artificial intelligence (AI) becomes increasingly involved in construction scheduling, monitoring, and resource coordination, there is a pressing need to develop system architecture capable of maintaining critical functionality under infrastructure failures. The main objective of this research is to design and formalize a model of an autonomous AI-driven system that can operate independently from centralized infrastructure and seamlessly transition to fallback control logic when needed.

The methodology combines system architecture analysis, the use of UML diagrams (use case, component, and state diagrams) to model functional logic and interactions, risk scenario modeling using failure analysis techniques, and a comparative evaluation of centralized and edge-based computing approaches. The proposed three-layer architecture (physical, computational, and communication) is centered on a local edge server. This server hosts AI modules, handles anomaly detection, power switching, and provides decision-making capacity independently of cloud services.

The results demonstrate that the implementation of a hybrid autonomous control system significantly enhances the resilience of construction operations. The edge-based architecture outperforms centralized models in response time, offline operability, and stability in unstable environment. A comparative analysis shows that the deployment of such a system may increase initial costs by 5–10%, yet these costs are justified by a substantial reduction in risk of downtime, delays, and data loss.

The proposed system is particularly suitable for construction sites operating in constrained or high-risk conditions, including strategic infrastructure projects or military-affected zones. Future research should focus on optimizing AI algorithms for offline operation, developing industry-wide integration protocols, and validating the proposed model through real-life implementation in pilot projects.

**Keywords:** artificial intelligence, construction management, autonomous systems, edge computing, fault tolerance, system architecture, risk modeling, digital twins, UML diagrams.

**Introduction.** Modern construction enterprises are increasingly implementing artificial intelligence (AI) technologies to automate processes of planning, monitoring, equipment and resource management. In this paper, the term *"system architecture"* refers to the structural and logical organization of an intelligent management system. However, most of these systems operate dependent on external energy sources, internet connectivity, or cloud data processing, making them vulnerable to failures, cyber-attacks, or energy crises. Under conditions of hybrid threats and instability, it is essential to develop backup infrastructure and algorithms for rapid switching to alternative control systems that ensure continuity of construction [1-4].

*Problem statement***.** Despite significant progress in the implementation of artificial intelligence in construction, the issues of autonomy and resilience of such systems remain insufficiently addressed in the scientific and applied literature [3, 5–7]. The structure of an intelligent construction management system capable of functioning under conditions of complete loss of external resources (electricity, internet, cloud infrastructure) remains an open question. Another challenge is determining the architecture of a backup parallel system should look like.

Despite considerable advances in the use of information modeling and automation of construction processes, the problem of insufficient integration of real-time risk management systems persists.

The expected technical and economic effect of developing an autonomous intelligent management system includes:

- reduction of construction process duration through event-driven management;
- decrease of avoidable costs (equipment downtime, delays due to weather or organizational factors);
- improvement of resource planning accuracy and scheduling.

The potential scope of application covers: residential and commercial construction projects employing BIM technologies; infrastructure projects implemented in high-risk conditions (e.g., military or recovery projects); public procurement, where transparent and digitally supported management systems are required.

Thus, the creation of architecture for an autonomous intelligent management system has not only scientific novelty but also significant socio-economic potential.

However, it should be noted that such a system can operate only under conditions of sufficiently advanced adoption of modern digital technologies. At present, this also remains a challenge for the construction industry in Ukraine.

**Analysis of Recent Research and Publications.** At present, research in the field of construction automation is primarily focused on the implementation of BIM + AI; schedule and resource management through ML models; digital twins of processes; and improving the energy efficiency of construction sites. However, backup parallel architectures and system-switching algorithms for AI under threat conditions remain almost unexplored, especially in the context of construction in regions with unstable infrastructure [8–11].

Article [12] presents the concept of a decentralized autonomous construction management system that integrates digital twins, large language models, and decentralized autonomous organizations to create self-managed buildings. Study [13] is devoted to analyzing the potential of artificial intelligence in construction, emphasizing the importance of transparency and trust in intelligent systems within the industry.

A systematic review [14] highlights the application of AI across all stages of the construction project life cycle, with particular focus on risk management and decision-making. Article [15] explores the issue of trust in artificial intelligence and robotics in architecture, engineering, and construction, underlining the necessity of developing reliable systems that are beneficial throughout all phases of project implementation.

Work [16] provides a comprehensive review of risk management research in construction, with an emphasis on integrating information and communication technologies and AI to enhance risk management practices.

Despite significant progress in the implementation of AI and autonomous systems in construction, several unresolved issues remain:

1. Integration of decentralized management systems**.** The application of decentralized autonomous organizations in construction for improving flexibility and resilience of management systems remains insufficiently studied.

2. Explainability and trust in AI**.** There is a need to develop transparent AI algorithms that ensure decision-making processes are understandable to users and stakeholders.

3. Risk management under external influences. Adaptive systems must be created to respond promptly to external threats such as natural disasters or cyber-attacks.

4. Standardization and regulation**.** The absence of unified standards and regulations for the implementation of autonomous intelligent systems in construction complicates their widespread adoption.

**Aim and Objectives of the Article.** The aim of this study is to develop a conceptual architecture of an autonomous and fault-tolerant intelligent management system for construction processes, including a description of functional modules, scenarios of switching to backup control, and an analysis of the impact on project economics.

The main research objectives are as follows:

1. To analyze current approaches to the development of intelligent management systems in construction, considering external risks (power outages, loss of connectivity, cyber threats, etc.).

2. To design a functional system architecture that includes key modules: AI core, energy control units, anomaly detection, fallback controller, and user interface.

3. To formalize the system's operational logic using UML diagrams – use case, component, and state diagrams – for modeling behavior under both normal and emergency conditions.

4. To conduct a scenario-based analysis of switching to backup control, considering typical risks and activation criteria for autonomous mode.

5. To perform a comparative analysis of centralized and edge-based architectures in terms of technical, operational, and economic indicators.

6. To evaluate the economic feasibility of implementing a backup autonomous architecture within a construction project, taking into account potential losses, downtime, and infrastructure costs.

**Materials and Research Methodology.** The research methodology is based on an interdisciplinary approach that combines systems analysis, engineering modeling, and elements of software architecture, risk analysis, and economic evaluation. The main tools applied include:

- UML diagrams**:** in particular, Use Case, Component, and State diagrams, which are employed to formalize the functional architecture of the Autonomous Intelligent Control System (AICS).
- Architectural modeling**:** analysis of centralized and decentralized (edge-based) control structures, with the development of a three-layer model (physical, computational, and communication levels).
- Scenario modeling**:** development of scenarios of critical external impacts (power outage, cyber-attack, loss of connectivity), accompanied by the design of an algorithm for emergency switching to a Reserve Hybrid Control System (RHCS).
- Fault-tolerance analysis methods**:** assessment of system response time, identification of bottlenecks, and determination of minimum technical requirements to ensure autonomous operation.
- Techno-economic feasibility tools (TEF): analysis of the costs of implementing backup infrastructure and its impact on the overall efficiency of the construction process.

The research foundation consists of:

- results of the authors' previous publications highlighting organizational and technical aspects of AI applications in construction;
- data on edge-server configurations, backup power sources (UPS, generators), and sensor infrastructure;
- practical case studies from construction management under limited infrastructure conditions (including during armed conflict);
- existing open libraries of predictive models for machine learning (ML) and computer vision (CV), adapted for autonomous execution on edge devices.

Thus, the chosen methodology makes it possible not only to simulate the system's behavior under stress conditions but also to propose practical architectural solutions capable of ensuring the resilience of construction processes under external threats.

**Research Results.** In critical infrastructures such as a construction enterprise partially managed by artificial intelligence, emergency response scenarios and backup control channels must be strictly regulated. Below, we present the concept of a parallel (backup) system to AI and the algorithm for switching to it in the event of power failures. This system is referred to as the *"Reserve Hybrid Control System (RHCS)"*.

Its primary purpose is to ensure continuity of critical construction processes in the event of AI system failure. The system requires a set of essential components for its operation (Fig. 1).

Consider a scenario that may occur during construction operations. Concrete works are in progress on a construction site. During the process, power supply is lost, and the primary AI system stops functioning. Immediately after this: the UPS is activated; a signal is sent to the smartphones of on-duty engineers; the backup control system is launched; the operator receives a notification and connects to the console; in manual mode, the operator activates concrete mixers and initiates concrete supply via the local controller. Figure 2 illustrates the proposed algorithm of emergency switching to the RHCS (with a conditional trigger: loss of main power supply / AI system failure).

For the operation of such an autonomous system, the following recommendations can be proposed: the presence of a regulation clearly defining responsibilities in case of an emergency; monthly testing of the switchover to the backup system; storing the latest version of the working plan offline; and training personnel to work with the RHCS.

To ensure that an artificial intelligence system within a construction enterprise operates autonomously – thus minimizing dependency on external factors such as electricity, communication networks, or cloud access – it is necessary to implement a resilient autonomy architecture.

An equally important aspect of the proposed architecture is its economic feasibility. Practical calculations and results of international studies demonstrate that investments in digital infrastructure at a level of approximately 5% of the estimated project cost can yield proportional or even greater reductions in indirect expenditures. These savings primarily stem from reducing losses associated with documentation inconsistencies, rework, delays in managerial decision-making, and inefficient use of resources. In the case of large-scale residential or infrastructure projects, the potential economic impact may reach tens of millions of hryvnias, which confirms the rationale for the phased implementation of intelligent management systems in construction practice.

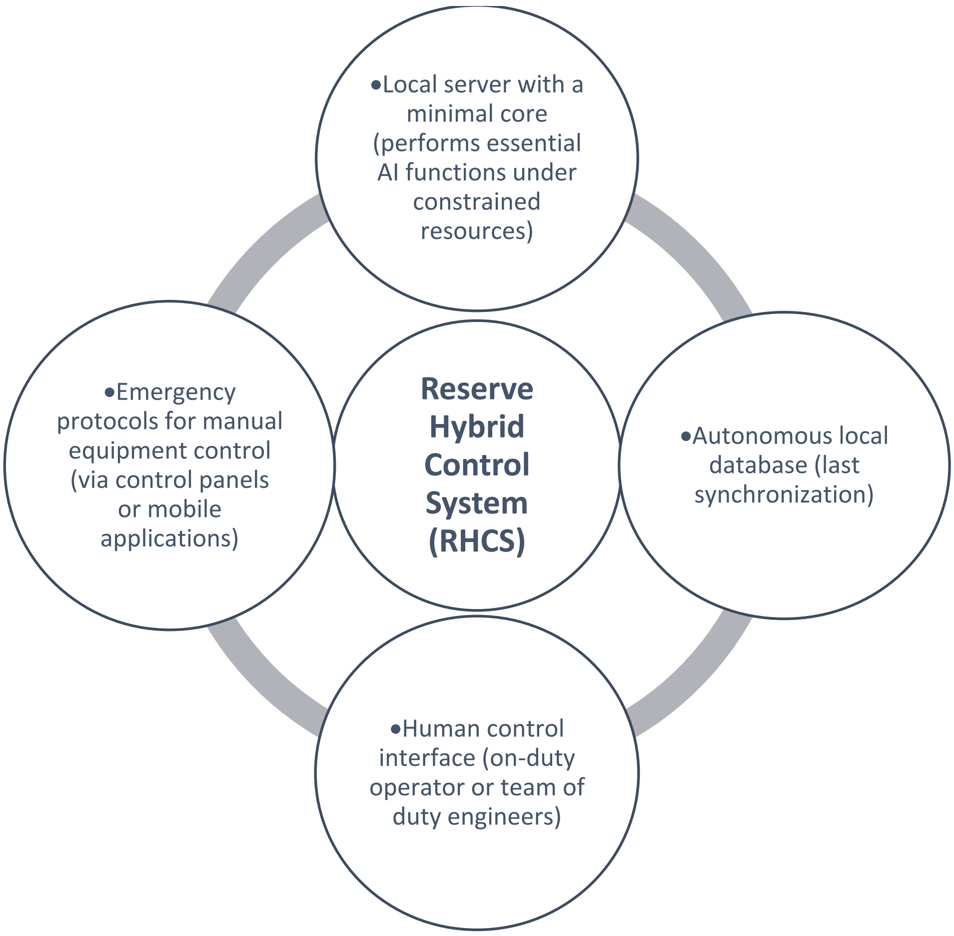


Fig. 1. Components of the Reserve Hybrid Control System (RHCS)

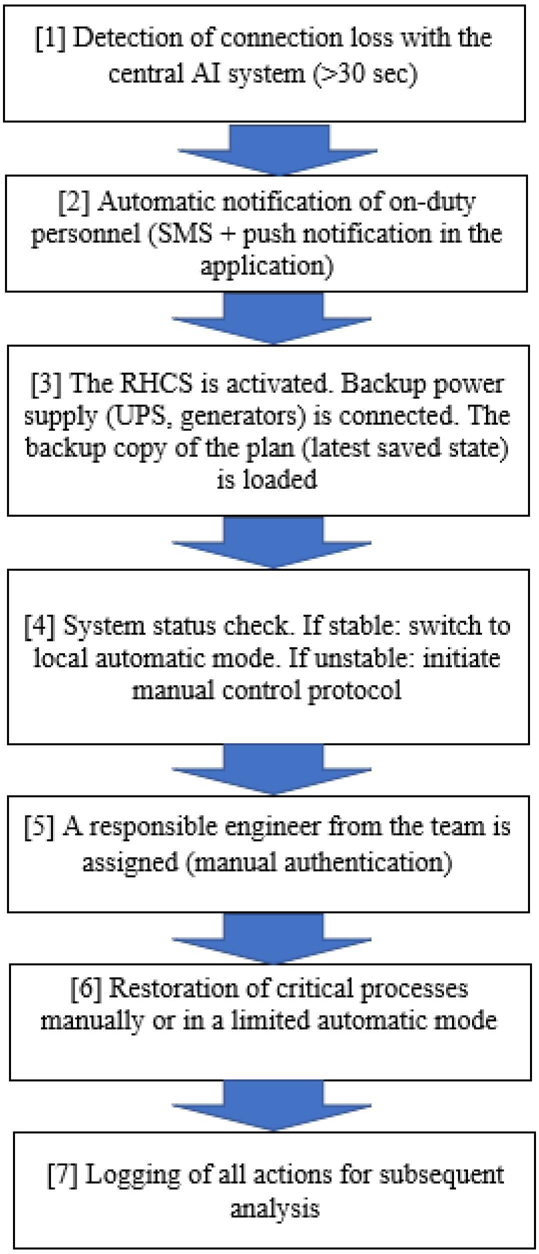


Fig. 2. Algorithm of emergency transition to RHCS (trigger condition: loss of main power supply / AI system failure)

At the same time, it is important to emphasize that a fallback scenario based on a complete reversion to manual management relying solely on construction specialists cannot be considered an effective alternative. This limitation is explained by the high complexity of modern projects, the multichannel nature of information flows, and the dynamic character of external factors (climatic, economic, regulatory). Under such conditions, manual control does not provide the required speed of reaction, transparency of decision-making, or adequate risk forecasting. Therefore, the backup approach should not mean abandoning digitalization, but rather the development of hybrid models that combine partial expert involvement for AI decision verification with automated processes, thereby integrating technological efficiency with human expertise.

Considering the presented response algorithm, it is reasonable to highlight the key technical solutions that form the foundation of the autonomy architecture of the intelligent system. A summary of these solutions is provided in Table 1.

Table 1 – Technical solutions for enhancing the autonomy of AI-based construction systems

| Technical Solution | Explanation |
|---|---|
| 1. Local computational infrastructure | Deployment of edge servers (on-site computing units with AI cores independent of the Internet) |
| | Storage of critical models and datasets directly at the construction site |
| 2. Intelligent backup power supply | High-capacity uninterruptible power supply (UPS) systems with batteries providing at least 6–12 hours of autonomy |
| | Hybrid energy supply: solar panels + diesel generators + batteries |
| | Smart energy consumption monitoring and control |
| 3. Modular AI system architecture | Separation into independent functional modules (e.g., equipment control, safety monitoring, scheduling) capable of operating autonomously in the event of partial system failure |
| 4. Offline model duplicates | Copies of machine learning models and decision scenarios functioning without cloud connectivity |
| | Local updates applied with a delay via flash memory or internal secured networks. |
| 5. Resilient communication | Deployment of a local private LTE/5G network, radio communication, or mesh networks to minimize dependence on external providers |

To assess the feasibility of implementing the proposed technical solutions, an approximate calculation of additional costs for their integration into a typical construction project was performed. The results are presented in Table 2.

Table 2 – Approximate cost increase per project

| Category | Estimated cost, $ | Approximate increase in project cost |
|---|---|---|
| Edge servers + AI modules | 10.000 – 30.000 | +1–2% of the project budget |
| Backup power supply (UPS, generator, solar panels) | 15.000 – 50.000 | +2–4% |
| Local networks, communication | 5.000 – 15.000 | +1% |
| Deployment and integration | 10.000 – 25.000 | +1–2% |

The overall increase in project cost is estimated at 5–10%, while at the same time:

– Risks of downtime, accidents, and incidents are reduced.

– Predictability and controllability of the construction process are improved.

– Staff requirements can be reduced at certain stages.

A more detailed consideration of the Reserve Hybrid Control System (RHCS) is provided below. To ensure stable operation of the intelligent construction management system even in cases of critical failures (e.g., power outages or loss of connectivity with cloud services), it is advisable to formalize the system's architecture in the form of a component model. Given the complexity of the system and the need for its formalization for modeling and implementation, the functional decomposition of the architecture into key levels is presented in Table 3.

Table 3 – Key system levels

| Level | Function description |
|---|---|
| 1. Physical level (construction site) | Sensors, detectors, video cameras, drones, controllers, generators, energy sources (grid/UPS/generator) |
| 2. Computational level (local edge server) | Execution of AI algorithms (ML, CV, NLP), equipment control, predictive models, autonomous control systems |
| 3. Communication level | API connection with cloud services or backup local channel (Wi-Fi mesh, radio channel). |

The key element of the proposed autonomous intelligent system is the edge server, which acts as the local control core. Its functional purpose is to ensure the uninterrupted operation of the AI system under conditions of disconnection from cloud computing services. This allows the system to maintain critical functionality, including decision-making, emergency monitoring, and generating appropriate responses, even when operating in isolation from external sources.

To describe the system's functional logic, two key UML diagrams are applied: the Use Case Diagram and the Component Diagram.

The Use Case Diagram illustrates the interaction between the user and the system, focusing on the main usage scenarios. The user in this case may be either an operator or an external control entity (e.g., a Telegram bot or an ERP/BIM control module).

The main scenarios include:

- Automatic updating of the construction schedule based on changes in resources or execution conditions.
- Response to emergency situations, such as logistics delays, loss of access to equipment, or critical data.
- Intelligent switching between power supply channels, including automatic selection between the grid, generator, or UPS.
- Generating alerts for the user, with the ability to deliver notifications through a visual interface or a Telegram bot.

The Component Diagram, on the other hand, represents the software–hardware architecture that implements the mentioned functions. It demonstrates the structural organization of the system and the interconnections between its modules, such as: the AI Engine**,** Task Scheduler**,** Energy Control Module**,** Anomaly Detector, and the Fallback Controller. The central element is the edge server, which provides integration between software modules and hardware devices, including the UPS Module and the Operator Terminal (Fig. 3).

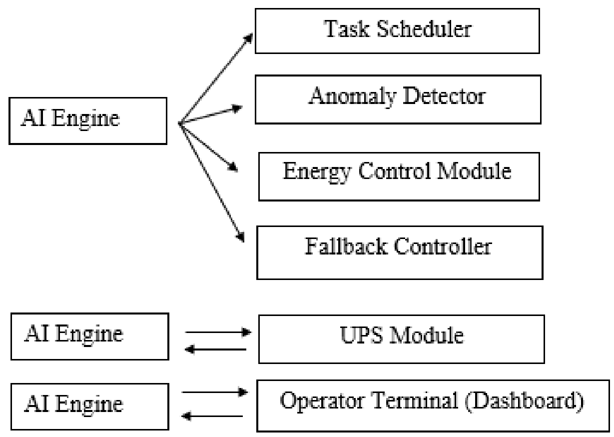


Fig. 3. Architecture of the hardware–software complex and interactions between its main modules

The combination of these diagrams allows aligning the behavioral logic of the system with its architectural structure, which is essential for further development, testing, and implementation of such systems within the context of digital transformation of construction processes.

Thus, the described UML diagrams make it possible to systematically present the operational logic of the autonomous system, align software and hardware components, and create a foundation for further implementation. It should be noted that UML diagrams are an important stage of system design and may also serve as part of the digital passport of a facility or its digital twin.

The State Diagram in this case represents the dynamic behavior of the autonomous system in response to external events (e.g., power outage, risk detection, loss of communication channel, etc.) and internal conditions (resource-related or operational). This makes it possible to formalize the transitions between operating modes, which is critically important for designing a reliable, fault-tolerant architecture (Figure 4).

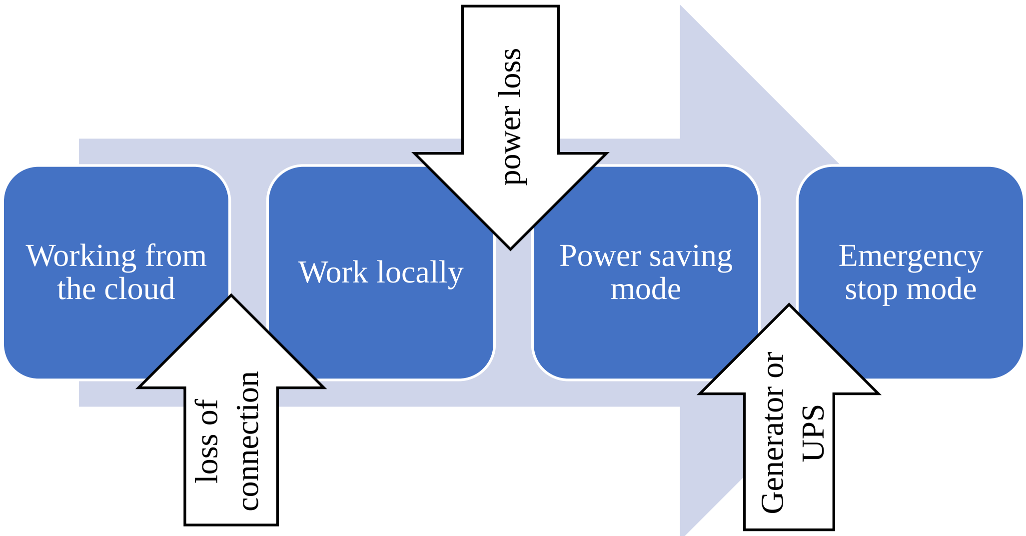


Fig. 4. Mode Switching Model

Based on the state model (Fig. 4), the system operates in several defined modes: normal (standard), autonomous (fallback), and critical (emergency). Switching between these modes is implemented according to event-driven logic and is triggered depending on external or internal factors. Table 4 presents typical scenarios of such transitions.

Table 4 – Typical Scenarios of System Mode Switching

| Factor | Trigger | Transition | System Action |
|---|---|---|---|
| Power loss | Voltage drop below critical level, disconnection of the external power source | From “Normal Mode” to “Fallback Mode (powered by UPS/generator)” | Activation of backup power module, reduction of non-priority tasks, activation of the local AI core |
| Loss of connection with cloud server | No feedback for more than 5 minutes | From “Normal Mode” to “Autonomous Mode without synchronization” | Switch to cached data, local scenario routing through the edge server |
| Anomaly detection or cyber-attack | Unusual network activity, deviation from behavioral patterns | From “Normal Mode” to “Security/Isolation Mode” | Network isolation, blocking of external APIs, manual confirmation of actions via operator terminal |
| Restoration of conditions for normal mode | Voltage stabilization, connection recovery, operator confirmation | From “Fallback” or “Security Mode” back to “Normal Mode” | Synchronization of accumulated data with the cloud, activation of optimized schedule |

Thus, the combination of the Use Case Diagram and the Component Diagram makes it possible not only to visualize the logic of user interaction with the system and its modular structure but also to gain a deeper understanding of the architectural principles behind the design of the autonomous system. However, to make an informed engineering decision regarding the feasibility of implementing a particular architecture (centralized or modular edge-based), it is necessary to perform a comparative analysis according to the criteria of technical, economic, and functional efficiency.

To justify the choice in favor of a modular architecture, a comparative analysis of centralized and edge-based solutions was conducted according to technical, functional, and economic criteria (Table 5).

Table 5 – Comparison of Centralized and Modular (Edge-based) Architecture

| Criterion | Centralized (Cloud-based) | Modular (Edge-based) |
|---|---|---|
| Dependency on connectivity | High (internet is critical) | Low (offline operation possible) |
| Processing speed | Higher with stable network | High in real time (on-site) |
| Responsiveness | Limited to cloud-defined scenarios | Adaptive, local response |
| Power consumption | Low on-site, high in the cloud | Medium, depends on hardware |
| Capital expenditure (CAPEX) | Lower at startup | Higher due to edge infrastructure needs |
| Security and stability | Vulnerable to network attacks | Local security, fewer vulnerabilities |

Based on the above data, it can be concluded that for construction in high-risk environments (e.g., in war zones or critical infrastructure projects), the modular edge-based architecture is more preferable due to its autonomy and reliability. It also provides opportunities for system expansion, including:

- Integration of a local database (PostgreSQL, SQLite) on the edge server for temporary storage of project data.
- Use of a backup GUI interface for management in the form of a minimalist web dashboard.
- Integration with UAVs/drones for automatic aerial monitoring with image processing on an edge video module.

It should be emphasized that the developed architecture of the autonomous intelligent management system does not imply full automation of construction processes by replacing workers with robotic complexes. The focus is primarily on digital coordination and decision-support, not on physical task execution by machines. Human operators remain a key element of the production process, receiving tasks, clarifications, and instructions through integrated digital channels (CDE, mobile applications, site tablets). Such interaction increases productivity and task quality, reduces errors, and optimizes resource use, while maintaining flexibility and accountability of the human factor.

The proposed architecture also incorporates a hybrid fallback mode, where construction professionals continue to play a central role. In this context, it is appropriate to compare it with traditional construction control methods: geodetic surveying, author and technical supervision, preparation and approval of as-built and cost documentation. In conventional practice, these procedures are performed sequentially, often duplicate each other, and require paper-based confirmation and multi-level approvals, which cause delays and risks of data obsolescence.

The autonomous system eliminates these “bottlenecks” through automatic data collection and synchronization in a BIM environment, real-time event logging, and integration with digital cost-estimation and as-built documentation. At the same time, specialists’ capabilities are not diminished but expanded: instead of spending time on routine document verification, they gain tools for rapid data analysis, risk prediction, and decision-making in non-standard situations. Thus, the hybrid system combines automation benefits with expert experience, ensuring reliability and resilience of management even in the event of external threats or digital infrastructure failures.

**Conclusions.** This paper presents a conceptual architecture of an autonomous intelligent system for managing construction processes capable of ensuring continuity of operation under risks such as power outages, connectivity loss, or cyber-attacks. The necessity of introducing a backup hybrid management system (BHMS) is substantiated, allowing critical technological operations to be performed even if the primary AI system fails.

Three-level system architecture (physical, computational, and communication levels) was developed, with the local edge server as the core element capable of autonomously executing predictive models, controlling equipment, and supporting decision-making logic. To describe the component interaction logic, UML Use Case, Component, and State Diagrams were applied, enabling the formalization of the system's functional structure and mode-switching scenarios.

Comparative analysis of centralized and edge-based architectures demonstrated the advantages of the latter in terms of stability, response speed, security, and independence from infrastructural constraints. Approximate implementation costs for autonomy elements are estimated at 5–10% of the project budget. These costs significantly reduce risks of accidents and downtime while improving construction manageability.

Comprehensive analysis showed that the proposed architecture ensures high adaptability, fast response, and technical independence – features critically important for construction projects under risky conditions. The proposed approach can be applied to projects implemented in unstable environments, such as critical infrastructure facilities, high-risk zones, or strategic infrastructure programs.

**Further research** on autonomous intelligent construction management systems should focus on several key aspects:

1. Development of mathematical and simulation models to more accurately assess system effectiveness under different external scenarios (from cyber-attacks to energy or material supply disruptions). This will allow verification of system resilience and definition of optimal recovery strategies.

2. Investigation of human–machine interaction, particularly the integration of traditional control functions (geodetic, technical, and author supervision) into the hybrid mode, considering that experts play a key role in confirming and adjusting AI decisions.

3. Expansion of the system architecture through the use of robotic and sensor complexes to automatically collect data from construction sites (e.g., structural geometry monitoring or safety tracking). Defining the optimal level of automation that balances digital infrastructure costs with economic benefits is crucial.

4. Pilot implementation of the proposed system in real construction projects to obtain empirical data on cost reduction, faster response to deviations, and risk mitigation. Such trials would form the basis for developing industry standards and guidelines for implementing autonomous and hybrid management systems in the construction sector of Ukraine.

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# АРХІТЕКТУРА АВТОНОМНОЇ ІНТЕЛЕКТУАЛЬНОЇ СИСТЕМИ УПРАВЛІННЯ БУДІВЕЛЬНИМИ ПРОЦЕСАМИ В УМОВАХ РИЗИКУ ЗОВНІШНІХ ВПЛИВІВ

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**Анотація.** У статті розглянуто проблему забезпечення автономності інтелектуальних систем управління будівельними процесами в умовах ризику зовнішніх впливів, зокрема знеструмлення, втрати зв’язку чи кібератак. Враховуючи зростаючу роль штучного інтелекту (ШІ) у плануванні, моніторингу та керуванні будівельними роботами, авторами поставлено завдання розробити концептуальну архітектуру стійкої до збоїв системи. Метою дослідження є формалізація моделі автономної інтелектуальної системи з резервною логікою керування, здатної зберігати функціональність в умовах критичних збоїв.

Методологія дослідження ґрунтується на системному аналізі архітектурних підходів (централізованої та модульної edge-based), побудові UML-діаграм (use case, component, state), сценарному моделюванні ризиків та техніко-економічному обґрунтуванні впровадження резервної інфраструктури. У статті детально описано трирівневу архітектуру системи, що включає фізичний, обчислювальний та комунікаційний рівні, з центральним елементом – edge-сервером, який виконує ключові функції автономного управління.

Результати дослідження підтвердили ефективність розробленої резервної гібридної системи управління (РГСУ), здатної автоматично реагувати на відмови основного середовища, перемикатися на альтернативні джерела енергії та продовжувати виконання критичних технологічних операцій. Проведено порівняльний аналіз централізованої та edge-based архітектур, розраховано орієнтовне зростання вартості впровадження автономних рішень, що становить 5–10 % від загального кошторису, але значно зменшує ризики зупинок та аварій.

Запропонована модель може бути впроваджена в будівельних підприємствах, що працюють в умовах обмеженого доступу до інфраструктури, а також у проєктах критичної інфраструктури. Подальші дослідження доцільно зосередити на адаптації алгоритмів ШІ до автономного режиму, тестуванні системи в пілотних умовах та стандартизації підходів у галузі інженерного управління будівництвом.

**Ключові слова:** штучний інтелект, автономна система, edge-computing, управління будівництвом, відмовостійкість, архітектура програмного забезпечення, UML-діаграми, резервне керування, критична інфраструктура.

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