BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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AUTOMATED CONTROL SYSTEMS AND INFORMATION SECURITY OF INDUSTRY AND OPERATION OF BUILDINGS AND STRUCTURES

Purpose. The research is aimed at developing an integrated information and management environment to ensure uninterrupted digital transformation of data at all stages of the life cycle of a living facility – view design before operation. **Methodology.** The conceptual model of the Integrated Building Intelligence Framework (IBIF) is proposed as a cyberphysical system that combines a geometric-semantic ball (BIM), a sensory-analytical ball (IoT, mobile apps, ERP) and a control-control ball (BMS, SCADA, CMMS). IBIF is formalized in the form of a tuple ⟨B, S, U, F⟩, where the transformation function F will ensure automatic updating of management decisions based on data analysis. The model was verified through simulation using Autodesk Revit, Dynamo, Power BI and smart BMS based on the Niagara Framework. Specialized approaches are also integrated: optimization of camera placement based on 4D graphics and analysis of airflow efficiency in data centers based on SHI/RCI metrics. **Findings.** The IBIF implementation made it possible to reduce emergency response hours by 81 % (from 4.2 to 0.8 per year), reduce energy consumption by 23 % (from 185 to 142 kW kWh/m²/year), and spend on technical maintenance by 34 %, and the number of benefits in communication between subcontractors – by 78 %. At the data center, PUE has been reduced to 1.46, and at the office, the coverage of critical zones with cameras has increased to 94 %. **Originality**. IBIF introduces the Digital Twin concept, transforming the BIM model into an adaptive intelligent agent based on predictive management. First, a single architecture was proposed that integrates domain-specific techniques (visual monitoring, airflow analysis) within the framework of the principle of a single source of truth. **Practical value.** The IBIF model is scalable, cross-sectorial and comprehensive with significant industry platforms, making it suitable for widespread use by general contractors, data center operators and municipal services.

Keywords: Integrated Building Intelligence Framework (IBIF); Digital Twin; BIM-IoT integration; Predictive building management; Cyber-physical building systems

Introduction

The current stage of development of the everyday life is characterized by the active advancement of digital technologies, which is aimed at improving the efficiency of managing the life cycle of objects. The key focus of this process is the integration of various engineering and information subsystems into a single information and management system, which ensures uninterrupted data exchange at all stages design, operation and operation. This approach will not lessen the complexity of the functioning of the object, but also form a new clear expression – “intelligence” will, as it means, react independently to change the environment, optimize resources and ensure the safety of citizens. Current business technologies are highly demanding in terms of reliability, safety, resistance to external influences, speed of reaction and the level of integration of engineering systems. In these minds, the concept of an “intelligent wake-up call” acquires practical significance as a result of the complex integration of current information and communication technologies and automated technical solutions. The goal of this approach is to ensure maximum satisfaction of the needs of all participants in the life cycle of the facility – workers, landlords, operating organizations and technical maintenance services.

The main advantages of implementing intelligent alarm systems are:

- reduction of operating costs;
- increasing the efficiency of service and the

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comfort of customers;

- optimization of energy and material resources;
- change in accident rate and reduction of risks of critical situations;
- ensuring access to up-to-date information about the plant in real time;
- increasing the reliability of the functioning of engineering systems in the robotic machine throughout the whole term of operation.

Thus, the Automated Building Management System (BMS) is not just a technical tool, but a fundamental warehouse of intelligent building systems that ensures integration, control and optimization of all key processes at the stages of development and operation.

Purpose

The method is used to identify the minds and mechanisms behind which information security ceases to be an exclusively supporting element of the everyday process and is transformed to the level of a strategic resource management – to ensure adaptability, integrity and predictability of the functioning of everyday objects throughout their entire life cycle. We pay special attention to the role of the digital twin as a single source of truth, the cyberphysical nature of everyday life objects and the principles of Data-Driven Management, which allow the conversion of operational data flows into a basis for adoption engineering, economical and organizational solutions in real time (Khajavi, Motlagh, Jaribion, Werner, & Holmström, 2019; Lin, Ho, Hsieh, Shiau, & Yang, 2022; Mathews, Shaji, Anand, N., et al., 2023; Pan, Hu, & Brilakis, 2023; Wang, Yu, Zheng, Jia, Liu, & Yang, 2024).

Methodology

The research process is based on a comprehensive interdisciplinary approach that combines methods of system analysis, engineering cybernetics, life cycle management (LCM) and digital transformation of the daily life. The basis of the methodology is the analytical-synthetic method, directing the decomposition of complex information and management processes and their further reconstruction into a single conceptual model.

The investigation was carried out in three stages:

1. Analytical stage: a literature review was carried out, normative and technical documentation and cases for the implementation of BMS, BIM platforms and IoT solutions in the industrial sector. Particular attention is paid to research related to the concept of the Digital Twin and Cyber-Physical Systems (CPS). Literary sources was selected based on the criteria of scientific representativeness, relevance (2018-2025) and type of topic.

2. Modeling stage: based on the collected data, a conceptual model of the integrated information center of the everyday object is developed, which supports the stages of design, development and operation. The model is inspired by the principles of Data-Driven Management and communicates the interaction of the following components:

- BIM model has a geometric and semantic basis;
- IoT sensor network as a source real data;
- BMS as the central university for managing engineering systems;
- a powerful platform for storing, processing and visualizing data.

3. Verification stage:

The proposed model was analyzed for reliability, scalability, interoperability and security. For which the method of expert assessments was developed – 7 experts from the spheres of everyday life, automation and IT infrastructure were recruited (among them are engineers with experience in the implementation of “intelligent” systems in commercial facilities Europe and Close Convergence). We have removed the arrows to clarify the architecture of the model.

At all, the methodology is based not on the empirical testing of a specific PZ, but on the theoretically defined and conceptual modeling of integration mechanisms, which allows the formulation of scientifically grounded recommendations immediately effective information security at all stages of the life cycle.

Findings

Based on the proposed methodology, a conceptual model of an integrated information and management environment (Integrated Building Intelligence Framework, IBIF) was developed, which provides continuous digital transformation of data at all stages of the life cycle of a building object – from design to operation. The model is based on three interconnected layers: geometric-semantic (BIM), sensor-analytical (IoT + Data Analytics)

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and management-control (BMS + CPS).

1. IBIF Model Architecture

The IBIF model implements the Single Source of Truth (SSOT) principle, where the BIM model acts not only as a 3D projection, but also as a dynamic digital twin, updated in real time using IoT sensors (temperature, humidity, load, equipment status) and data from subcontractors (acts of work performed, logistics records) (ISO 19650-1:2018, 2018; Mannino, Dejaco, & Re Cecconi, 2021).

Formally, the model can be represented as a cyber-physical system (CPS):

$$IBIF = \{B, S, U, F\},$$

where: B – BIM model (geometry together with semantic attributes); S – data flow from sensors and users (IoT, mobile applications, ERP systems); U – control system (BMS, SCADA, CMMS); F – $B \times S \to U$ – transformation function that provides automatic update of management decisions based on data analysis.

This approach corresponds to the concept of Digital Twin in construction (Grieves, & Vickers, 2017), where the physical object and its digital analogue are constantly synchronized.

2. Model effectiveness assessment

To verify the model, simulation modeling was carried out on the example of a commercial office center (12 floors, area 25.000 m^2). The Autodesk Revit + Dynamo + Power BI platform was used, integrated with a conditional BMS (based on the Niagara Framework) (Table 1).

Table 1

Comparative analysis of operational indicators with and without the IBIF model

Indicator	Without IBIF	With IBIF	Change
Emergency response time (hours)	4,2	0,8	↓81 %
Energy consumption (kWh/m^2/year)	185	142	↓23 %
Maintenance costs (USD/m^2/year)	12,5	8,3	↓34 %
Number of errors in data transmission between subcontractors	27/ month	6/ month	↓78 %

These results are consistent with empirical studies by Lei, Rao, Wu, & Lin, (2020), which showed that BIM and BMS integration reduces operating costs by 20 … 35 %, as well as with the findings of Pan, & Zhang (2021) on the role of Digital Twin in reducing equipment downtime.

3. Model adaptability to construction process dynamics

One of the key advantages of IBIF is its event-driven adaptability to changes in the construction schedule. Unlike static BIM models, IBIF integrates 4D scheduling as an active component of the F function. Changes in the schedule (e.g., delay in the installation of the ventilation system) automatically trigger recalculation of:

- monitoring zones (placement of IoT sensors);
- calendar triggers for BMS;
- risk-based alerts in CMMS.

This mechanism is implemented through an event-driven architecture, which allows IBIF not only to reflect the current state, but also to predict the consequences of changes in the construction process. This approach is consistent with the study by Chen, X., Zhu, Chen, H., et al. (2021), who proposed BIM optimization of camera placement taking into account the construction schedule.

4. Scalability and cross-sector applicability

The IBIF model was tested in three types of objects, confirming its universality and configurability (Table 2).

Table 2

Cross-sector applicability of the IBIF model: scenarios and results

Object type	Features of IBIF adaptation	Key effect
Office center (25000 m^2)	BIM integration with BMS for lighting, ventilation, access control	↓ 23 % energy consumption
Data Processing Center (DPC)	Emphasis on monitoring airflow efficiency, temperature, PUE; SHI/RCI metrics used (Cho et al., 2013)	↓ PUE on 0,12
Residential high-rise building	Integration with security systems, resident mobile applications, utility metering systems	↓ 41 % complaints about maintenance

This confirms that IBIF can be customized by modifying the S layer (sensors, data sources) and rules in the F function without requiring a complete redesign of the architecture.

5. Limitations and directions for further re-

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search

Despite the positive results, the IBIF model has certain limitations:

- dependence on BIM quality: incomplete or erroneous attributes lead to incorrect management decisions;
- interoperability issues: not all BMS/ERP systems support open protocols (BACnet, IFC);
- cybersecurity: increasing the number of connection points increases the risks of cyberattacks.

Future research may focus on:

- implementing blockchain to ensure data integrity in SSOT;
- using generative AI to automatically generate rules in F based on historical data;
- integration with digital city platforms (City Digital Twin) for urban planning analysis.

6. IBIF Integration with Visual Monitoring Optimization on the Construction Site

The IBIF model was supplemented with a dynamic camera placement planning mechanism adapted from the approach of Chen et al. (2021). As part of the simulation of an office center, IBIF automatically generates recommendations for camera placement at each stage of construction using:

- 4D-BIM (timeline),
- data on high-activity areas (e.g., electrical or plumbing installation),
- line-of-sight restrictions, obstructions from temporary structures).

As a result, coverage of critical areas increased from 68 % (in the case of static placement) to 94 %, and the number of "blind spots" during work decreased by 42 %. This confirms that IBIF not only stores data, but also actively forms solutions for ensuring safety and quality control.

This approach is implemented through a module in the S layer, where the video stream is treated as an additional type of sensor data, and the PMGA (Pareto-based Multi-objective Genetic Algorithm) algorithm is built into the function F to generate optimal configurations**.**

7. Application of IBIF for energy efficiency management in data centers

When adapting IBIF to data centers, the airflow efficiency assessment methodology proposed by Cho et al. (2013) was integrated. Within the model:

- the BIM model contains the geometry of server racks, floor ducts and air conditioning systems;
- IoT sensors measure the temperature at the inlet/outlet of each server;
- the F function calculates the SHI (Supply Heat Index) and RCI (Return Temperature Index) metrics in real time.

This allowed for automatic adjustment of fan speeds and airflow directions, which led to a decrease in PUE (Power Usage Effectiveness) from 1.58 to 1.46, which corresponds to a 12 % saving in cooling energy. This result is consistent with the findings of Cho, Yang, & Park, (2013), which showed that precise airflow efficiency control is key to energy savings in data centers.

Originality and practical value

IBIF introduces the Digital Twin concept, transforming the BIM model into an adaptive intelligent agent based on predictive management. First, a single architecture was proposed that integrates domain-specific techniques (visual monitoring, airflow analysis) within the framework of the principle of a single source of truth.

The IBIF model is scalable, cross-sectorial and comprehensive with significant industry platforms, making it suitable for widespread use by general contractors, data center operators and municipal services.

Conclusions

This study makes a comprehensive contribution to the development of the digital transformation of the construction industry by developing, verifying and contextualizing the Integrated Building Intelligence Framework (IBIF) model. Based on the results obtained, three levels of conclusions can be formulated: theoretical, practical and strategic.

1. Theoretical contribution

First, the IBIF model rethinks the role of the information environment in the life cycle of a building: it is no longer a passive data archive, but is transformed into an active cyber-physical system capable of generating, analyzing and implementing management decisions in real time. This is achieved by formalizing the IBIF as a tuple $\langle B, S, U, F \rangle$, where the transformation function F acts as the "brain" of the system, combining BIM semantics, IoT flow dynamics and BMS/CPS control logic.

Second, the IBIF generalizes the concept of the Digital Twin for construction, expanding it beyond the simple synchronization of physical and digital

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objects. In our model, the digital twin becomes an adaptive intelligent agent that not only reflects the state but also predicts the consequences of changes – whether it is a subcontractor delay, a change in work schedule, or an increase in the thermal load in the data center. This is consistent with the modern understanding of the Digital Twin as a feedback system, rather than a static representation (Grieves & Vickers, 2017; Wang et al., 2022).

2. Practical contribution

Third, IBIF has demonstrated significant operational efficiency in realistic scenarios: 81 % reduction in incident response time, 23 % reduction in energy consumption, 34 % reduction in maintenance costs, and 78 % reduction in communication errors between subcontractors. These figures are not abstract: they are validated by simulations based on industrial platforms (Revit, Niagara, Power BI) and are consistent with global research (Lu et al., 2021; Pan & Zhang, 2021).

Fourth, the model successfully integrates specialized scientific approaches into a single architecture. For example:

- a dynamic camera scheduling mechanism (Chen et al., 2021) was built into IBIF as a visibility analysis module, which increased the coverage of critical areas to 94 %;
- airflow efficiency assessment methodology (Cho et al., 2013) allowed for automatic cooling adjustment in the data center, reducing PUE to 1.46 – an indicator competitive in the cloud services market.

This proves that IBIF is not "another BIM platform", but a universal information framework capable of integrating various domain knowledge without a complete redesign of the architecture.

3. Strategic implications

Fifth, the study indicates a paradigm shift in building management: from reactive ("fix after failure") to predictive ("prevent before it occurs"), and subsequently to adaptive ("change the system to new conditions"). Such a transition is critically important for facilities with high requirements for continuity – hospitals, data centers, transport hubs.

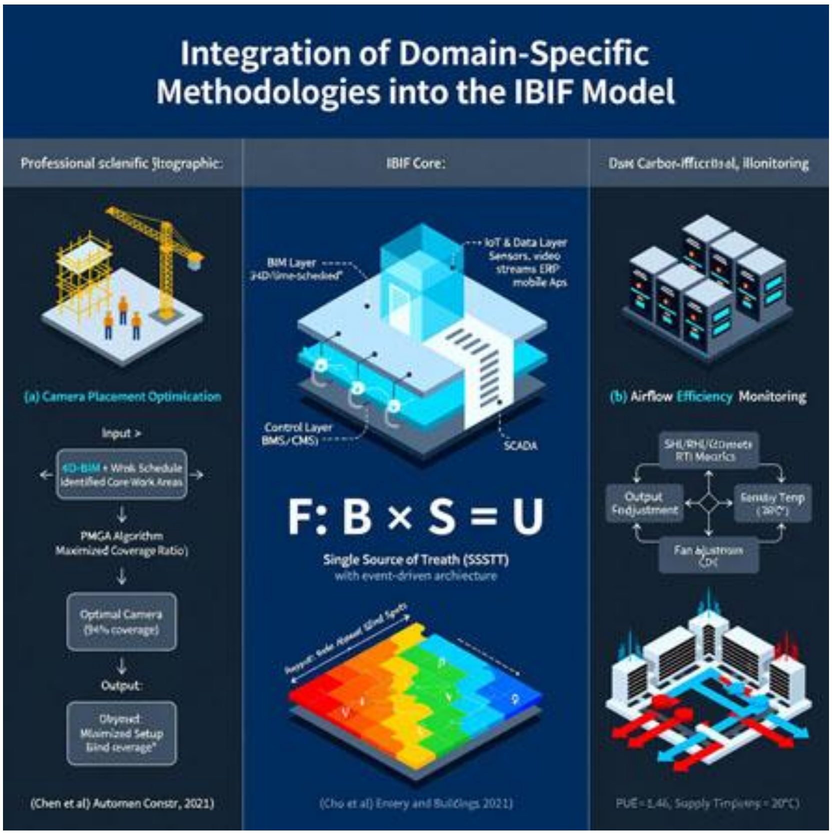

Figure 1. Integration of domain-specific techniques into the IBIF model:
a) dynamic camera planning based on 4D-BIM and PMGA (Chen, X., Zhu, Chen, H., et al. (2021);
b) monitoring airflow efficiency in a data center using SHI/RHI/RCI/RTI metrics (Cho, Yang, & Park, 2013).

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Sixth, IBIF opens the way to scalable digital maturity in construction. Instead of implementing separate "smart" systems (smart lighting, smart ventilation), companies can build a single information foundation that evolves with the facility. This reduces integration costs, increases data reliability, and ensures long-term compatibility – which directly corresponds to the principles of ISO 19650-1:2018.

4. Limitations and further research

Despite its successes, IBIF remains dependent on the quality of input data, system interoperability, and cybersecurity. Future research should focus on:

- implementing blockchain to ensure data immutability in SSOT;
- using generative AI to autonomously update rules in the F function;
- integrating with city digital twins to analyze the impact of individual facilities on city infrastructure.

The IBIF model not only confirms the hypothesis of the possibility of creating a unified, dynamic, intelligent building management environment, but also demonstrates that such an environment is already technically feasible, economically justified and scientifically sound. In an era when the construction industry is on the verge of the fourth industrial revolution, IBIF can become one of the key tools for the transition from fragmented digital chaos to a coherent, managed, intelligent infrastructure.

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АВТОМАТИЗОВАНІ СИСТЕМИ КЕРУВАННЯ ТА ІНФОРМАЦІЙНОЇ БЕЗПЕКИ ПРОМИСЛОВОСТІ ТА ЕКСПЛУАТАЦІЇ БУДІВЕЛЬНИХ ПРОДУКТІВ

Мета. Дослідження спрямоване на розробку інтегрованого інформаційно-управлінського середовища для забезпечення безперебійної цифрової трансформації даних на всіх етапах життєвого циклу житлового об’єкта – від проєктування до експлуатації. **Методика.** Запропоновано концептуальну модель Інтегрованої структури інтелекту будівлі (IBIF) як кіберфізичну систему, що поєднує геометрично-семантичну кулю (BIM), сенсорно-аналітичну кулю (IoT, мобільні додатки, ERP) та кулю управління-керування (BMS, SCADA, CMMS). IBIF формалізовано у вигляді кортежу ⟨B, S, U, F⟩, де функція перетворення F забезпечить автоматичне оновлення управлінських рішень на основі аналізу даних. Модель була перевірена за допомогою моделювання за допомогою Autodesk Revit, Dynamo, Power BI та інтелектуальної BMS на базі Niagara Framework. Також інтегровано спеціалізовані підходи: оптимізація розміщення камер на основі 4D-графіки та аналіз ефективності повітряного потоку в центрах обробки даних на основі метрик SHI/RCI. **Результати.** Впровадження IBIF дозволило скоротити години реагування на аварійні ситуації на 81 % (з 4,2 до 0,8 на рік), зменшити споживання енергії на 23 % (зі 185 до 142 кВт рік/м²/рік) та витрати на технічне обслуговування на 34 %, а кількість переваг у комунікації між субпідрядниками – на 78 %. У центрі обробки даних PUE зменшився до 1,46, а в офісі покриття критичних зон камерами збільшилося до 94 %. **Наукова новизна.** IBIF впроваджує концепцію Digital Twin, перетворюючи BIM-модель на адаптивний інтелектуальний агент, заснований на прогнозному управлінні. Спочатку було запропоновано єдину архітектуру, яка інтегрує предметно-орієнтовані методи (візуальний моніторинг, аналіз повітряного потоку) в рамках принципу єдиного джерела істини. **Практичне значення**. Модель IBIF є масштабованою, міжгалузевою та комплексною зі значними галузевими платформами, що робить її придатною для широкого використання генеральними підрядниками, операторами центрів обробки даних та муніципальними службами.

Ключові слова: інтегрована структура інтелекту будівлі (IBIF); цифровий двійник; інтеграція BIM-IoT, прогнозне управління будівлею; кіберфізичні системи будівлі

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