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INNOVATIVE APPROACHES AND PRACTICES OF INFORMATION TECHNOLOGY FOR THE TECHNICAL CONDITION ASSESSMENT OF BUILDING STRUCTURES

***Li Shuting*[1], *N. V. Chernoivan*[2]**

[1] *Graduate student, Faculty of Architecture and Civil Engineering, Brest State Technical University, Brest, Belarus, e-mail: 1393756742@qq.com*
[2] *Candidate of Technical Sciences, Associate Professor, Deputy Dean for Academic and Scientific Work of the Faculty of Architecture and Civil Engineering, Brest State Technical University, Brest, Belarus, e-mail: chernoivan@inbox.ru*

Abstract

The accelerated digitalization of the construction industry emphasizes the need for developing accurate and efficient methods for assessing the technical condition of buildings and structures. Despite the growing adoption of Building Information Modeling (BIM) and Digital Twin (DT) technologies, their potential for diagnostic purposes and forecasting the residual service life of structures remains underutilized. This paper presents the results of a systematic literature review aimed at identifying and analyzing specific approaches at the intersection of BIM, DT, the Internet of Things (IoT), and Artificial Intelligence (AI) methods, specifically focused on condition assessment. The SLR procedure, covering 100 relevant publications, enabled structuring the research field along three aspects: types of monitoring data and sensors used, methods for integrating diagnostic data with digital models, and analysis algorithms for damage detection and degradation forecasting. The results indicate a transition from passive digital models to active diagnostic systems operating in near real-time. However, a key barrier remains the fragmentation of solutions: data on physical condition often exist in isolation from the semantic context of the BIM model, while analysis algorithms are not adapted to handle spatially distributed and multi-parametric information streams. Based on the conducted analysis, the article proposes a conceptual framework for building comprehensive diagnostic DT systems. This framework includes the semantic enrichment of models with condition attributes, unified protocols for streaming sensor data, and hybrid analytical algorithms combining physical degradation models with machine learning. This research contributes to the systematization of knowledge in the field of IT-enabled structural health monitoring and outlines directions for further applied development.

Keywords: building information modeling (BIM), digital twin, structural health monitoring (SHM), internet of things (IoT), artificial intelligence (AI), systematic review.

ИННОВАЦИОННЫЕ ПОДХОДЫ И ПРАКТИКИ ИНФОРМАЦИОННЫХ ТЕХНОЛОГИЙ В ОЦЕНКЕ ТЕХНИЧЕСКОГО СОСТОЯНИЯ СТРОИТЕЛЬНЫХ КОНСТРУКЦИЙ

Ли Шутинг, Н. В. Черноиван

Реферат

Ускорение цифровизации строительной отрасли актуализирует задачу разработки точных и эффективных методов оценки технического состояния зданий и сооружений. Несмотря на растущее внедрение технологий информационного моделирования (BIM) и цифровых двойников (Digital Twin, DT), их потенциал для целей диагностики и прогнозирования остаточного ресурса конструкций раскрыт не полностью. В данной статье представлены результаты систематического обзора литературы, выполненного с целью выявления и анализа специфических подходов на стыке BIM, DT, интернета вещей (IoT) и методов искусственного интеллекта (ИИ), ориентированных именно на оценку технического состояния. Процедура SLR, охватившая 100 релевантных публикаций, позволила структурировать исследовательское поле по трем аспектам: типы используемых данных и сенсоров для мониторинга, методы интеграции данных диагностики с цифровыми моделями, алгоритмы анализа для выявления повреждений и прогнозирования износа. Результаты указывают на переход от пассивных цифровых моделей к активным диагностическим системам, функционирующим в режиме, близком к реальному времени. Однако ключевым барьером остается фрагментарность решений: данные о физическом состоянии зачастую существуют изолированно от смыслового контекста BIM-модели, а алгоритмы анализа не адаптированы к работе с пространственно-распределенными и многопараметрическими потоками информации. На основе проведенного анализа в статье предлагается концептуальная рамка для построения комплексных диагностических DT-систем, включающая семантическое обогащение моделей атрибутами состояния, унифицированные протоколы потоковой передачи данных с датчиков и гибридные аналитические алгоритмы, сочетающие физические модели деградации с машинным обучением. Данное исследование вносит вклад в систематизацию знаний в области ИТ-обеспечения мониторинга состояния конструкций и задает направления для дальнейших прикладных разработок.

Ключевые слова: информационное моделирование зданий (BIM), цифровой двойник, мониторинг технического состояния конструкций (SHM), интернет вещей (IoT), искусственный интеллект (ИИ), систематический обзор.

Introduction

The dynamics of the modern construction industry are characterized not only by the pursuit of optimizing construction processes but also by increasing demands for safety, operational reliability, and lifecycle management of existing buildings and structures. In this context, Structural Health Monitoring (SHM) is evolving beyond periodic instrumental surveys into a task of continuous, data-driven analysis [1]. The «Construction 4.0» paradigm, integrating IoT, AI, and big data, creates the technological foundation for this transformation, as discussed in detail in review works on this topic [2, 3]. However, as researchers note, the technological arsenal itself does not guarantee results; its targeted orientation towards solving specific engineering problems, such as damage identification and residual life prediction, is critically important.

BIM has established itself as the standard for the digital representation of the physical and functional characteristics of an asset. However, the traditional BIM model, while being a rich source of static information on geometry, materials, and components, is not inherently designed to work with dynamic data concerning the actual behavior and condition of structures under load and over time [4]. This is precisely the limitation that the Digital Twin (DT) concept aims to overcome, proposing the creation of a connected, synchronized, and continuously updated digital copy of a physical asset [5]. Thus, the DT presents itself as an ideal platform for SHM, potentially capable of enabling a shift from reactive to predictive maintenance, which is particularly relevant in light of global trends in sustainable development and lean asset management [1].

Despite the obvious synergistic potential, research at the intersection of BIM, DT, and SHM remains fragmented. A significant volume of work is devoted to the general principles of DT in construction, their architecture, or specific implementation cases [6, 7]. At the same time, questions regarding *what specific data* on structural condition is most informative, *how* it should be semantically linked to BIM model elements, and *by which algorithms* diagnostically significant conclusions can be extracted from this data remain insufficiently studied. A clear gap exists in the systematization of technological pipelines that transform the abstract DT concept into a working tool for a diagnostics engineer. This problem is partially addressed in works dedicated to interoperability and standardization, but the focus in them is often shifted towards general data rather than highly specialized condition parameters [8, 9].

The aim of this article is to structure and critically analyze existing research and practical approaches to using information technologies (BIM, DT, IoT, AI) for the tasks of assessing the technical condition of building structures. To achieve this aim, a systematic literature review (SLR) was conducted to answer the following questions: 1) What are the dominant data types and sources in modern IT systems for SHM? 2) Which architectural and technological solutions are used to integrate monitoring data streams with digital models? 3) Which analytical methods are applied to interpret data and assess condition? The results of this analysis will reveal prevailing trends, identify bottlenecks, and define promising directions for creating holistic, interoperable, and effective diagnostic systems.

Research Methodology

To achieve the stated aim, the Systematic Literature Review (SLR) method was applied, following established protocols that have proven effective in technical sciences [10]. The process was divided into clear stages: planning, search, selection, analysis, and synthesis. This approach minimizes subjectivity and ensures the reproducibility of results.

Planning. The three points outlined above were formulated as Research Questions (RQs). They are aimed at identifying technological components and their interrelationships in the SHM context, shifting the focus from general rhetoric about digitalization to specific technical implementations.

Search. The search for relevant publications was conducted in the Scopus, Web of Science, and IEEE Xplore databases, which have high citation indices in technical and computer sciences. The search period was limited to the last decade (2014–2024) to cover the period of active development of DT and IoT. However, to understand the evolution of some basic concepts, earlier fundamental works were also consulted. A combination of key terms, grouped into thematic clusters, was used:

1) *objective*: «structural health monitoring» OR «condition assessment» OR «damage detection» OR «structural integrity»;

2) *technology*: «digital twin*» OR «BIM» OR «Building Information Modeling»;*

3) *tools: («IoT» OR «sensor*» OR «artificial intelligence» OR «machine learning».

This search strategy allowed covering the interdisciplinary nature of the topic.

Selection. The initial search yielded 412 results. After automatic and manual removal of duplicates, 378 publications remained. At the preliminary screening stage based on titles and abstracts, works not meeting the inclusion criteria were excluded: articles had to be peer-reviewed, written in English, and directly describe the application of BIM/DT/IoT/AI for monitoring, diagnosing, or predicting the condition of building structures (buildings, bridges, tunnels). Works focused solely on energy efficiency [5, 11], comfort management, or general project management issues without an emphasis on structural condition were excluded. After this stage, 152 publications remained in the pool.

Analysis and Synthesis. The full texts of these 152 articles were examined for compliance. Ultimately, 100 publications that most fully and substantively answered the research questions were included in the final selection for in-depth qualitative analysis. Data from the selected articles were extracted into a structured table by categories: structure type, sensors and data used, method of integration with BIM/DT, applied analytical algorithms, key findings. Information synthesis was carried out through thematic analysis and comparison of the identified approaches, which allowed not just listing technologies but identifying patterns in their application and mutual influence.

Results and Analysis

The literature analysis allowed for the identification of three interconnected technological layers in condition assessment systems based on DT: the *data* layer, the *integration* layer, and the *analytics* layer. Each layer has its own development logic and set of problems, but their effectiveness is determined precisely by the coherence of interaction.

1. Data Layer. Sources and Types of Condition Information. The dominant data source is a network of heterogeneous IoT sensors, installed either permanently or used mobile. Several categories can be distinguished, each covered in a number of studies.

- **Geometric Data.** Laser scanning (LiDAR) and photogrammetry provide high-precision point clouds for detecting deformations, deflections, and cracks [12]. Their primary value lies in creating an up-to-date geometric «shell» for the DT, which is the first step towards detecting macro-damage.
- **Dynamic and Vibration Data.** Accelerometers, gyroscopes, and strain gauges record the structural response to static and dynamic loads (wind, traffic, operational impacts). Analysis of frequency characteristics and mode shapes is a classical method for identifying changes in stiffness and the emergence of damage, as confirmed by both fundamental and applied works [13, 14].
- **Physico-Chemical Data.** Corrosion, humidity, temperature sensors, and acoustic emission sensors (for crack detection) provide information on material degradation processes and the environment [15]. This data often has a local character but is critically important for assessing progressive damage. A critical problem at this layer, noted by many authors, is the uncertainty in selecting the optimal sensor type, quantity, and placement for specific structure types, as well as ensuring the long-term autonomy and calibration of measurement systems. A dilemma exists between sensor network density and the economic feasibility of its deployment.

2. Integration Layer. Linking Data with the Digital Model. The integration problem extends beyond simply «attaching» a sensor reading to coordinates in the model. It concerns the semantic enrichment of BIM/DT, i. e., endowing digital objects with the ability to «understand» incoming condition data. Two main approaches have been identified, which often compete and sometimes complement each other.

- **Extension of Data Standards.** Attempts to extend the open IFC (Industry Foundation Classes) format with classes and attributes for storing monitoring data, maintenance history, and condition assessments [8]. This is a «heavy» but potentially the most interoperable path, as it relies on an already existing ecosystem. However, the standardization process is extremely slow and often lags behind the pace of technological development.
- **Use of Ontologies and Linking Models.** Creating separate semantic models (e. g., based on the Brick Schema developed for buildings) that act as an intermediate layer linking raw sensor data to BIM model concepts [7, 16]. This allows for flexible description of complex relationships (e. g., that a group of vibration sensors belongs to a specific beam, which in turn is part of the load-bearing frame) but creates the problem of ontology multiplicity. The main challenge here remains the lack of a unified, widely accepted standard for describing the «condition» of a structural element in a digital representation, which hinders data exchange between different software platforms and creates barriers to scaling solutions [9]. Moreover, as shown by the research of Seghezzi et al. [8], even when technical solutions exist, the key obstacle can be the absence of clear organizational information management processes.

3. Analytics Layer. From Data to Diagnostic Insights. This is where the role of AI and physical modeling is fully realized. The analysis showed an evolution from simple to complex hybrid methods, with each stage having its niche application.

- **Threshold Methods and Physical Models.** The basic level, where an alarm is triggered when a predefined limit (e. g., strain) is exceeded. Detailed finite element analysis (FEA) models, embedded in the DT, allow for simulating structural behavior and comparing it with reality, performing so-called virtual load testing [16]. These methods are well interpretable but require precise knowledge of material properties and boundary conditions.

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- **Machine Learning (ML) and Deep Learning (DL).** These methods dominate contemporary research, as clearly seen in the dynamics of publications. Unsupervised learning techniques, such as clustering or principal component analysis (PCA), are used to detect anomalies in data streams without prior knowledge of damage, which is convenient for monitoring complex objects with non-obvious degradation modes [10]. Supervised learning methods, e. g., convolutional neural networks (CNN), are applied for automatic classification of damage types in images or vibration spectra, demonstrating impressive accuracy in controlled conditions [6, 18]. Recurrent neural networks (RNN) are effective for analyzing time series and forecasting future trends (e. g., deformation development or accumulation of fatigue damage).
- **Hybrid (Physics-Informed) Models.** The most promising direction, where physical laws (equations of solid mechanics) are embedded into neural network architectures or used to generate synthetic data for their training [14]. This helps overcome the «data hunger» characteristic of purely data-driven approaches in SHM and improves the explainability of results, which is a critical requirement for engineering practice. Such approaches essentially create a digital twin that not only reflects but also «understands» the physics of the process.

Case Study. A Retrospective View of Shanghai Tower from an SHM Perspective. Although the Shanghai Tower project [19] is often cited as a benchmark for BIM application, its potential for continuous condition monitoring was only partially realized. The integration of BIM with Building Management Systems (BMS) was primarily focused on energy and climate. However, viewing this model as a foundation for a future DT reveals key points for SHM implementation. For example, elements of the complex facade and the high-rise structures, subject to significant wind and seismic loads, are ideal candidates for equipping with a network of fiber optic strain sensors and accelerometers. Data streams from these sensors, integrated into the BIM platform via a semantic layer, could enable real-time tracking of stress levels, identification of fatigue phenomena, and prediction of the need for targeted intervention, minimizing risks and maintenance costs for the unique structure. This example illustrates the evolution from BIM as an archival model to DT as an active diagnostic system. Interestingly, a similar approach, but for bridge structures, is demonstrated in the work of Tita et al. [20], indicating the universality of the identified principles for different types of infrastructure.

Figure 1 – Schematic diagram of the BIM model structure of Shanghai Tower

Conclusion and Future Research Directions

The conducted systematic review confirms that the convergence of BIM, Digital Twin, IoT, and Artificial Intelligence is shaping a new paradigm in the field of technical condition assessment for building structures. IT is ceasing to be merely a visualization tool and is becoming the core of predictive analytics systems. A key conclusion is the recognition that the value of DT for SHM is determined not by the complexity of 3D graphics, but by the depth of semantic connections between model elements and data streams, as well as by the intelligence of the algorithms interpreting this data. The application of these technologies, as shown in various studies, covers a wide spectrum of tasks – from virtual design and safety management [18] to structural health monitoring [14] and even modeling the spread of hazardous substances in buildings [6].

The analysis revealed several persistent problems hindering widespread industrial adoption. These problems are systemic in nature and require interdisciplinary efforts.

1. **Semantic Gap.** The lack of unified ontologies for describing structural condition and its linkage to monitoring data. Existing works, such as [8], offer partial solutions, but there is no industry-wide consensus.
2. **The «Last Mile» Data Problem.** The difficulty of automatic, reliable, and cost-effective collection of high-frequency data from distributed sensor networks over decades of operation. Issues of power supply, data transmission, and physical durability of sensors in aggressive environments remain relevant [15].
3. **The «Black Box» of Analytics.** Insufficient explainability of decisions proposed by complex machine learning models, which is critically

important for making engineering decisions in the realm of safety. An engineer must understand the basis on which the system recommends an inspection or structural strengthening.

4. **Ecosystem Fragmentation.** Incompatibility between proprietary platforms for BIM, IoT, and analytics, leading to the creation of «siloed» solutions, as rightly mentioned in the context of the construction industry as a whole [9].

As directions for future research, based on the synthesis of the reviewed works, it is proposed to focus efforts on the following areas:

- **development and validation of open, industry-focused ontologies**, focusing specifically on condition attributes, damage, and diagnostic metrics, rather than general building descriptions. This work should be carried out by consortia involving all stakeholders;
- **investigation of hybrid analytical architectures** that combine physical fidelity (e. g., reduced-order FEA models) with the adaptability of machine learning methods for working with incomplete and noisy data, characteristic of real-world operation [14];
- **conducting long-term pilot projects** on real assets, aimed not at demonstrating individual technologies, but at quantitatively assessing the effectiveness of comprehensive DT-based SHM systems in terms of enhancing safety, reducing maintenance costs, and extending the service life of structures. Such projects should be accompanied by careful collection and analysis of economic indicators;
- **exploring economic models and regulatory aspects** of implementing such systems, including issues of liability for decisions made based on AI recommendations, risk insurance, and updating building codes considering the new possibilities of digital monitoring. Without solving these issues, even the most advanced technologies will remain within the framework of laboratory experiments.

Thus, the path from the concept of a Digital Twin to an everyday tool for a diagnostics engineer lies through solving not so much technical as systemic and methodological challenges. This requires close and equal cooperation among specialists in structural mechanics, computer sciences, data theory, and industry management. Only such a comprehensive approach will allow realizing the transformative potential embedded in Construction 4.0 technologies for creating a sustainable and safe living environment.

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