Analysis of Digital Solutions Integration into the Design Process in Construction and Engineering: from BIM to Artificial Intelligence

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ABSTRACT : *This article explores the impact of digital technologies on design and construction processes in the engineering and construction industries. It examines key tools such as BIM, artificial intelligence (AI), augmented and virtual reality (AR/VR), the Internet of Things (IoT), Big Data, and Scan-to-BIM, as well as their applications at various stages of an object's lifecycle. The study investigates the potential and challenges associated with integrating digital solutions, including improved efficiency, cost reduction, process sustainability, and the need for training qualified specialists. Particular attention is given to the prospects of technological advancements and their role in transforming the industry.*

KEYWORDS -*digital technologies, BIM, artificial intelligence, AR/VR, IoT, digital twins, Scan-to-BIM, design, construction.*

I. INTRODUCTION

Modern construction and engineering are developing rapidly under the impulse of advancing digital technologies. Holistic application of information systems, automation, and artificial intelligence (AI) brings new possibilities to redefine design, construction, and management practices. Optimized use of information, automation of repetitive processes, and adoption of new methodologies appreciably enhance the quality of the final output, while reducing costs, mitigating risks, and compressing project durations concurrently.

Some of the most important underlying technologies for this revolution include Building Information Modeling (BIM), AI technologies, augmented and virtual reality (AR/VR), and the Internet of Things (IoT). These technologies enable a new level of collaboration among project participants, enable more precise planning, and deliver solutions not deemed attainable even a few years ago. Their synergy creates unique opportunities to revolutionize traditional approaches in design and construction. The purpose of this study is to analyze the integration of digital technologies into the design process within the construction and engineering industries.

II. MAIN PART. OVERVIEW OF DIGITAL TECHNOLOGIES FOR DESIGN AND CONSTRUCTION

Contemporary design and construction are being transformed in a revolutionary manner by the need to improve process efficiency, reduce costs, and meet increasing market demands. These changes span the entire lifecycle of assets, from early design through to operational stages and final decommissioning.

One of the main technologies behind the digitalization of the construction industry is BIM [1]. It is a process of creating and managing an information model of an object, which integrates data linked to all aspects of its life cycle. Based on 3D models, BIM allows designers, architects, and engineers not only to visualize projects but also to integrate temporal, financial, operational, and environmental parameters. The implementation of BIM substantially reduces the chance of errors all

through the layout section, guarantees transparency in processes, and optimizes production schedules.

A distinguished technology in virtual transformation is Scan-to-BIM, a system that creates digital fashions of current structures based on laser scanning records. This technology is extensively used in constructing reconstruction, restoration, and modernization tasks. The key advantage of this approach lies in its high-precision models, which account for all details of existing constructions. An example of such technologies application can be seen in the projects carried out by Epicon, a company specializing in digital solutions for construction and design. Their expertise includes creating precise Scan-to-BIM models for projects such as oil and gas industry facilities, including the reconstruction of a bitumen warehouse, as well as industrial cooling systems, such as circulation cooling systems in industrial plants [2].

Equally important in the digitalization of the construction industry is AI, which offers extensive capabilities for data analysis, forecasting, and process automation. Machine learning (ML) algorithms are employed to assess risks, analyze construction drawings, and identify potential issues at early stages. The AI technology also plays a significant role in resource optimization, enabling cost reduction in material procurement and workforce allocation. Furthermore, AI automates routine tasks such as generating drawings and calculations, saving time and increasing the accuracy of project execution. Through computer vision, AI facilitates automated quality control on construction sites, reducing the likelihood of defects and ensuring higher standards of delivery.

The incorporation of AR/VR are upgrading design, training, and project presentations by opening up new possibilities for immersive experiences [3]. With VR, clients and architects can see a building in the future virtually «step into» a building, viewing it in its entirety before the construction process begins. This facilitates the discovery of inconsistencies and the imposition of necessary changes while the design is being created. The AR technology, on the other hand, overlays digital models over existing building sites, and real-time tracking and control of construction progress can be carried out.

The IoT is one of the major elements within smart construction sites and building operations. IoT-enabled devices, fitted with sensors, allow for real-time monitoring of equipment conditions, material inventories, and site safety. During construction, IoT technologies allow for predictive maintenance of equipment, reducing the chance of downtime and ensuring seamless progress on-site.

Big Data has become a very important tool in construction and engineering. The collection and processing of large datasets allow high accuracy in making predictions in areas such as project completion dates and cost estimation of materials. Analysis of historical data aids in construction time optimization, which decreases delays and generally raises the effectiveness of the projects. Furthermore, Big Data assists in supply chain management, guaranteeing that materials are duly delivered to the construction sites on time.

Digital Twins are one of the most prominent technologies of construction and engineering. Such a digital replica of an asset is, in turn, updated in real-time with data streaming in from sensors and other devices. This tool enables the simulation of a building's operational performance and also the prediction of potential issues and optimization of maintenance processes. Their application can be particularly valuable for complex infrastructure projects, where high precision and immediate access to current system information are important [4].

According to the 2023 report [5], the adoption of various digital technologies in the global construction industry remains at an early stage. While some tools, such as drones and smart sensors, demonstrate significant implementation within individual projects, technologies like AI and digital twins are still limited to selective applications (fig. 1).

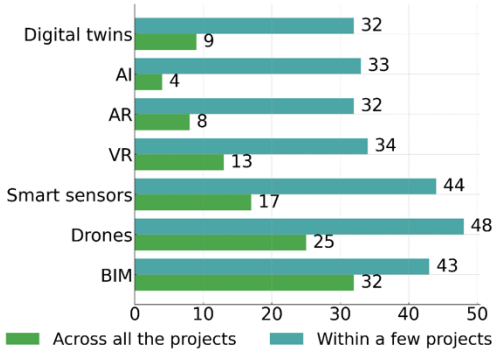

Fig. 1. Rate of adoption of different technologies in worldwide construction industry in 2023, %

Technologies such as BIM, AI, AR/VR,

IoT, Big Data, and Scan-to-BIM are revolutionizing design and construction procedures. These technologies can improve process accuracy and efficiency and even facilitate sustainability, which is a key driver for reducing global environmental and economic problems. However, successful implementation of these technologies entails more than technical investment.

III. POTENTIAL AND CHALLENGES OF DIGITAL TRANSFORMATION IN THE CONSTRUCTION INDUSTRY

The construction industry is undergoing significant transformations driven by the active adoption of digital technologies [6]. These are remapping design, build, and asset management strategies. However, whereas advancement can be seen, a lot of areas of digital transformation are brought back by technical, organizational, and workforce-related barriers when implementing.

To fully enjoy the potential of digitalization, it is essential to balance its advantages with the industry's challenges. These can include the need to adapt traditional methods, develop unified standards, and overcome the high costs associated with implementing innovative solutions. At the same time, there is a clear trend toward increased investment in technical and digital solutions for design and construction, creating favorable conditions for accelerating the development of a technologically advanced construction sector (fig. 2).

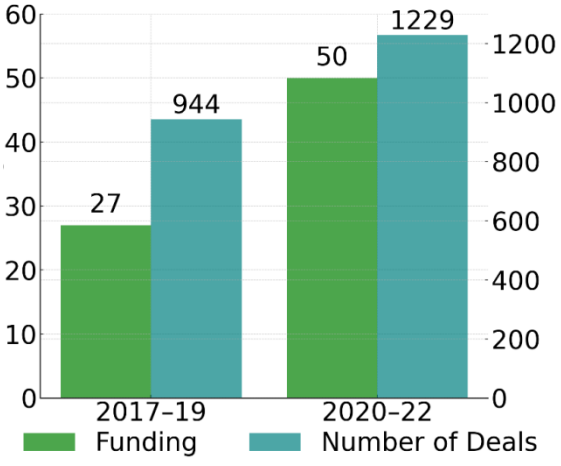

Figure 2. Global deals and investment in architecture, engineering, and construction tech, billion dollars [7]

Another element of digitalization is that it brings about an increase in both effectiveness and clarity in several processes. Their integration helps to minimize errors and inconsistencies, which mostly appear with traditional methods of design and construction. Further, through the use of digital twins and generative design technologies, improvements are seen in project outcomes because a wide range of variables, like costs, distribution of resources, and environmental conditions, is brought under consideration during optimization.

Moreover, the whole process of digital transformation supports the creation of structures that are sustainable and ecologically sound. For example, energy modeling and integration of GIS data encourage architectural designs for buildings in compliance with up-to-date standards of energy efficiency and environmental safety. These practices are increasingly becoming relevant in the era of a global movement toward sustainable development. Another paramount aspect of digital transformation is its impact on the safety of construction activities. The use of drones, IoT-monitored systems, and robotic technologies helps in reducing the likelihood of workplace injuries while ensuring compliance with safety standards during construction activities.

Despite these well-apparent advantages, digitalization is faced with various challenges, a vast majority of which are structural in nature. The greatest limitation is the cost of technology adoption. Technology acquisitions, such as machines, hardware and software, and training personnel, are extremely expensive, and digital transformation is most challenging for small and medium-sized enterprises.

The construction industry is based on deeply ingrained practices and methods, and therefore the use of new technology is a point of contention for employees, wherein they resist or do not wish to use new machinery. This is also fueled by the general lack of digital literacy in its workforce, necessitating huge investment in training and education initiatives to close the gap. Researches highlight that such challenges are observed in the implementation of various AI technologies in the construction industry, which, despite their clear advantages, also have inherent limitations (table 1).

Table 1. Advantages and limitations of AI subfields in construction [8, 9]

Category	Advantages in construction	Limitations in construction
ML	Relevant predictive and prescriptive insights, increased efficiency, cost savings, improved safety, efficient utilization of resources, reduced mistakes and omissions.	Incomplete data, learning from streaming data, dealing with high-dimensional data, scalability of models and distributed computing.
Computer vision	Faster inspection and monitoring, better accuracy, reliability and transparency, cost effective, increased productivity and safety.	Total scene understanding, action recognition of equipment and/or workers, improvement of tracking accuracy and effective visualization of tracking results.
Automated planning and scheduling	Cost savings due to improved processes e.g. logistics, increased productivity, reduced planning effort, simplified monitoring and control, optimal plan and schedules.	Mostly expensive to implement, could be complex, knowledge representations for needed models, monitoring issues, integration issues, synthesis techniques, etc.

Another crucial challenge is the lack of shared standards and regulations defining means of the application of digital technologies in construction. Different countries, even regions of a single country, have their own needs, and therefore it is not simple to implement global projects. In addition, use of heterogeneous solutions for software most frequently leads to problems of compatibility, which are damaging to the efficiency of collaboration of project participants.

IV. CONCLUSION

The technological advances of BIM, AI, AR/VR, IoT, Big Data, and Scan-to-BIM are the fulcrum points upon which these two disciplines revolutionize. These drive accuracy, effectiveness, and sustainability in the process and aid in coping with ever-more dynamic marketplace demands and world-class challenges. Implementation of these technologies makes design and management practices more optimal and opens new innovation frontiers. However, the full value of digitalization can be achieved only through a structured process including the development of standards, training courses, and infrastructure facilitation. This will enable the construction sector to cope with current challenges and become a pioneer in using cutting-edge technologies.

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