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STUDY OF THE FEASIBILITY OF IMPLEMENTING NEW TECHNOLOGIES IN THE INFRASTRUCTURE SECTOR

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Abstract. Despite the conservative stance on adopting technological innovations in civil engineering, the advancement of Construction 4.0 has been evident, characterized by the introduction of tools such as Building Information Modeling (BIM), Internet of Things (IoT), Artificial Intelligence (AI), drones, digital twins, and even the metaverse. These technologies are transforming the design, execution, and operation of infrastructure projects, promoting greater efficiency, precision, sustainability, and safety. This study aims to identify the main barriers and benefits to the implementation of new technologies and propose an analysis of the maturity level of emerging technologies in the context of civil engineering, focusing on their feasibility of application. To this end, a systematic literature review method was employed, allowing for a critical and informed analysis of the main technical and academic contributions, and a method based on the Technology Readiness Level (TRL) was developed. The results indicate a trend toward improvements in construction processes, particularly with regard to data integration, automation, and decision-making support. However, significant barriers to the widespread adoption of these innovations remain, especially among small and medium-sized enterprises. These challenges highlight the need for investments in public policies, professional training, and standardization of practices, aiming at consolidation.

Keywords: Construction 4.0, Infrastructure, Technological Revolution, Technology Readiness Level.

1 Introduction

In the last decade, the construction industry has begun to adopt digital technologies such as Building Information Modeling (BIM) and smart sensors, inspired by Industry 4.0 and enabled by advances in computing power. Currently, advances in Artificial Intelligence (AI) are driving the Construction 4.0 era, redefining the paradigms of design, execution, and maintenance. In this new construction sector, digital technologies do not function individually but are integrated throughout the project lifecycle. According to Tang et al. [1], these digital solutions drive improvements in efficiency, project control, and sustainability principles. However, their widespread adoption faces challenges such as high initial costs, skill gaps, and interoperability issues between platforms, which affect small and medium-sized companies more strongly and hinder their implementation [2].

In this context, the World Economic Forum [3] highlighted that while other sectors, such as information technology, are leading the way in AI adoption, the construction sector is lagging behind. Therefore, it is important to understand the feasibility of these promising technologies, which depend on several factors, especially in complex and high-investment infrastructure projects, where the benefits and practical results can be more easily disseminated to the market.

Furthermore, the construction industry has long been known for its low productivity and slow pace of innovation, despite the potential of emerging technologies. In contrast, there is a scarcity of studies that empirically link technological implementation to productivity gains, as pointed out by Zuluaga, Saad, and Omotayo [4]. The main barriers to progress include a lack of standardization, insufficient investment in research and development, cultural resistance to change, and fragmentation of the sector [5].

In this sense, the main barriers and benefits to the implementation of Construction 4.0 and propose an analysis of the maturity level of emerging technologies in the context of civil engineering, focusing on their feasibility of application.

2 Literature review

It is noteworthy that the topic of digital construction has gained increasing attention from academics. According to Franco et al. [2], 69.2% of related publications appeared in the year leading up to 2021. This process of digital transformation in the construction industry, known as Construction 4.0, integrates technologies such as BIM, Internet of Things (IoT), AI, digital twins, augmented reality (AR), drones, among other digital technologies, into construction processes. And, according to Keogh & Smallwood [6] and Chileshe [7], the main objectives are to increase project productivity, improve occupational safety, and promote environmental sustainability—note that this is linked to the Triple Bottom Line sustainability principle [8].

The practical benefits are diverse and may vary depending on the type of project and the technology adopted, but in the infrastructure domain, the main applications include:

• BIM for the integration of other digital technologies and all phases of the life cycle – from planning to operation; [9];

• IoT and Digital Twins for continuous, real-time monitoring of critical assets such as bridges and highways, creating dynamic models that support management decision-making processes [10, 11];

• Big Data and Blockchain for predictive decision-making and transparent contract tracking [12];

• Augmented and Virtual Reality (AR/VR) for immersive training simulations [13];

• Robotics and 3D Printing to facilitate construction in remote or hazardous areas, reducing project timelines, human risk, and overall waste in construction [14], [15].

Collectively, these innovations have a proven positive impact on reducing errors, increasing on-site productivity, and improving worker safety [16]. In addition, the integration of BIM with life cycle analysis enables more accurate long-term planning, directly contributing to energy efficiency and the sustainability, longevity, and overall performance of infrastructure assets [7], [17]. Similarly, the literature consistently expresses optimistic expectations regarding the potential of Construction 4.0 to address global challenges such as climate change, urbanization, and socioeconomic disparities [18]. Despite these benefits, significant barriers to widespread adoption remain. The high cost of technology acquisition, the need for specialized technical training, the lack of standardized regulations, and cultural resistance to innovation remain critical challenges. These obstacles are particularly pronounced in developing countries and among small and medium-sized enterprises (SMEs) [10], [16].

3 Methodology

The methodology proposed for this study is the application of the Technology Readiness Level (TRL) framework, adapted to the context of civil engineering and infrastructure projects. This approach seeks to systematically assess the maturity of development and practical readiness of key emerging technologies for the construction infrastructure sector. The goal is to provide a structured and objective identification of which technologies have the greatest maturity and, therefore, the greatest potential for immediate implementation.

The TRL framework, originally developed by NASA (National Aeronautics and Space Administration), is a globally recognized methodology for classifying technologies based on their stage of development, ranging from initial concept to proven application in an operational environment [19]. For this research, the standard TRL scale—from TRL 1 (basic principles observed) to TRL 9 (system proven in an operational environment)—was specifically adapted to address the technical, operational, regulatory, and market-specific challenges of the

construction industry. Figure 1 shows the standard TRL scale.

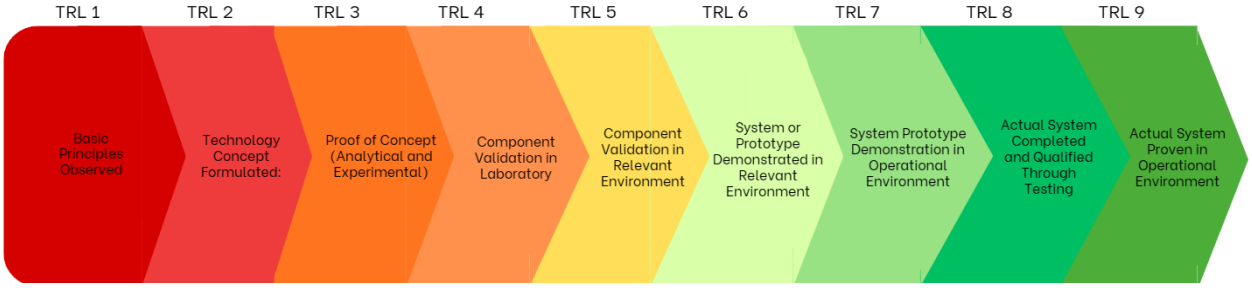


Figure 1. Technology Readiness Level (TRL) scale (1-9)

In this research, the assessment will focus on six main groups of technology selected through the literature review presented, which focused on the general context of infrastructure works. It is worth noting that the selection of these technologies may vary according to the specific nature of the type of project and construction. The figure below presents an effective initial methodology for analyzing the feasibility of applying these technologies in civil engineering.

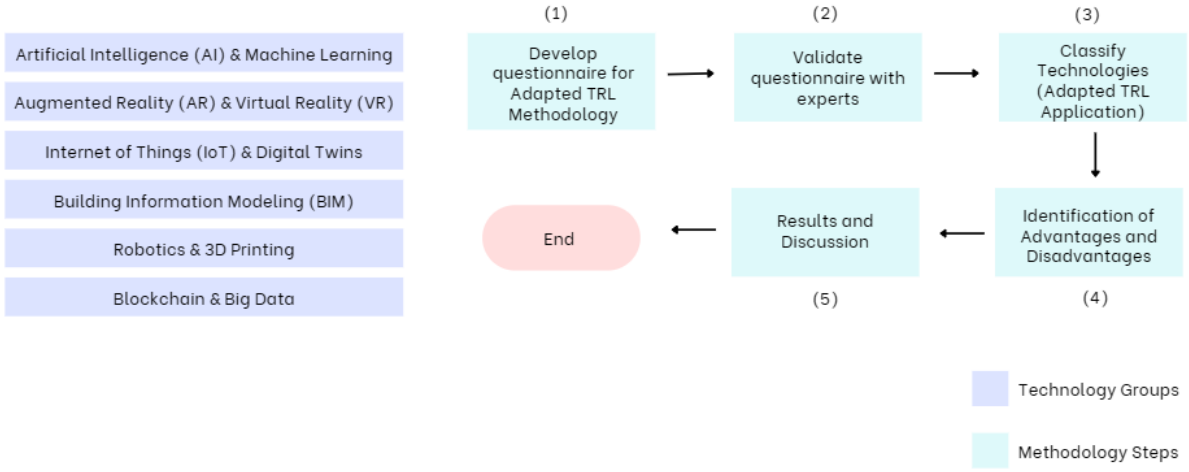


Figure 2. Technologies for analysis and methodological process

The study is based on a methodology structured in five main stages: (1) development of the adapted TRL methodology questionnaire; (2) validation of the questionnaire with experts; (3) classification of technologies through the application of the adapted TRL; (4) identification of the main advantages and disadvantages of the technologies evaluated; and (5) analysis and discussion of the results obtained. This methodological structure aims to integrate technical, operational, and regulatory aspects, providing a critical and comparative assessment of the technological readiness level of the innovations studied.

The data collection instrument used consists of a structured questionnaire complemented by an analysis based on an extensive review of the scientific literature, as well as technical reports, case studies, and institutional publications. The questionnaire, based on an adaptation of the TRL method, contains objective, closed-ended questions aimed at investigating the technical, operational, regulatory, and market aspects of the selected technologies. Examples of questions include: “Have the characteristics of the technology been validated through modeling and simulation?”; “Are analytical studies available to support the predicted performance of the technological elements?”; and “Have the areas of risk and mitigation strategies been identified in general terms?” Possible answers are “Yes,” “No,” or “Not applicable,” enabling a systematic and objective analysis of the results. After preparation, the questionnaire will be submitted for validation by experts or professionals responsible for the projects analyzed, in order to ensure the reliability and adequacy of the evaluation criteria. The research sample will consist of a set of technologies previously selected based on their relevance to the civil infrastructure sector

and their potential for innovation and practical applicability to the project in question.

Data processing will be carried out through quantitative analysis of the aggregated responses, allowing the technological readiness level (TRL) of each technology evaluated to be determined. Based on this classification, it will be possible to identify the technologies with the highest degree of maturity, which will then be subjected to a qualitative analysis to map their main advantages and disadvantages in the context of civil engineering. Finally, the results obtained will serve as the basis for a comparative analysis of the technological maturity among the innovations studied, highlighting those most prepared for implementation in infrastructure projects. The purpose of this final stage is to offer a critical and evidence-based assessment capable of providing strategic support for decision-making, supporting technological planning, and promoting sustainable and innovation-oriented adoption in the civil construction sector.

4 Results and discussions

The literature review shows that the Technology Readiness Level (TRL) already has great potential to be used in assessing the maturity and feasibility of technological innovations in the civil construction sector if adapted correctly. In this context, Ma, Guowei et al. (2022) [20] applied the TRL to 3D concrete printing, classifying it between levels 6 and 7, indicating validation in a relevant environment, but with standardization challenges. Abdul-Samad et al. (2024) [21] evaluated Industry 4.0 technologies, such as robotics and sensors, and observed intermediate levels (TRL 4–6), dependent on greater investment and training. Wijaya (2025) [22] proposed an adaptation of TRL to the organizational context, incorporating financial and structural factors, while a review published in 2021 [23] reinforced its use as a metric for innovation and sustainability.

Research by by Iranshahi et al. (2025) [24] analyzed the use of TRL in the evaluation of Digital Twins in different engineering sectors, including construction and urban infrastructure, classifying the average TRL at 4.8, which represents the transition between laboratory validation and application in real environments. The main challenge identified was integration with the digital thread, i.e., the connection between virtual models and physical systems. This cross-sectoral approach reinforces the potential of TRL as a comparative tool for technological maturity, useful for civil engineering and for analyzing the feasibility of digital innovations applied to infrastructure. Filipovic et al. (2024) [25] expanded the traditional concept of TRL, giving rise to the xRL (extended Readiness Levels) model, which incorporates financial, regulatory, and behavioral dimensions. This approach demonstrates that technological maturity alone is not sufficient to ensure the successful adoption of an innovation.

In the context of applying the adapted TRL to the use of Building Information Modeling (BIM) in the construction of a prestressed concrete bridge, for example, the analysis suggests intermediate to advanced readiness levels (between TRL 6 and 8), especially in the modeling and project compatibility stages, which are already consolidated in civil engineering practice. On the other hand, phases such as execution and operation still face significant challenges, especially regarding integration with digital systems, interoperability between platforms, and technical training. In this scenario, the adapted TRL can help identify barriers and potentialities related to the adoption of BIM, also considering organizational, regulatory, and economic factors that influence its implementation in infrastructure works.

Together, these studies demonstrate that technological maturity alone is not sufficient to ensure the successful adoption of innovations. The application of the Technology Readiness Level (TRL) in the sector follows this same logic: in addition to indicating the stage of development, it is necessary to consider aspects of practical feasibility, regulatory compliance, and sustainability. Thus, the TRL acts as a multidimensional innovation management tool, capable of integrating technical, economic, and regulatory factors in the assessment of technological readiness. This approach allows mapping the degree of maturity of technologies, reducing uncertainties, and supporting safer strategic decisions, promoting a gradual, sustainable, and effective technological transition in the civil infrastructure sector.

5 Conclusions

This study highlights the crucial role of emerging digital technologies in advancing the infrastructure sector toward Construction 4.0. The application of the adapted TRL methodology reveals disparities in the technological maturity levels of the solutions analyzed, establishing itself as a determining criterion for assessing their potential for effective implementation in different project contexts. Relevant barriers such as high implementation costs, technical training gaps, and regulatory challenges remain critical obstacles, especially for small and medium-sized enterprises, which face greater difficulty in incorporating innovations. However, systematic assessment based on TRL provides valuable evidence for strategic decision-making, allowing stakeholders to prioritize technologies with proven maturity and greater potential for impact. These insights reinforce the need for specific public policies and training programs aimed at digital transformation in the infrastructure sector, with a focus on reducing barriers to technology adoption. Thus, TRL proves to be not only a technical indicator of readiness, but also a tool to support the management and strategic planning of innovation. Finally, it is recommended that future research adopt longitudinal approaches to monitor the evolution of technological maturity and evaluate the effectiveness of strategies for integrating and disseminating new technologies. In addition, it is suggested that methods complementary to the TRL be explored, capable of considering financial, regulatory, and environmental dimensions (advantages and disadvantages), in order to provide a more comprehensive assessment aligned with the complexity of innovation processes in the infrastructure sector. Such efforts are essential to accelerate the digital transition, optimize the benefits of Construction 4.0, and consolidate a more efficient, sustainable, and technologically prepared infrastructure model for future challenges.

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Authorship statement. The authors confirm that they are solely responsible for the authorship of this work and that all material included in this article is the property (and authorship) of the authors or has been permitted by the owners to be included here.

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