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Digital twins as enablers of structure inspection and maintenance

Uso de gêmeos digitais como facilitadores da inspeção e manutenção de estruturas

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Abstract: The emergence of new technologies based on the exchange of data and information via the internet has prompted a revolution in the industry as a whole. First applied in manufacturing, the movement known as the Fourth Industrial Revolution soon spread and changed the dynamics of many other fields. Digital twins (DTs), one of the technologies that emerged in this scenario, are used to replicate physical environments in virtual models. Such models must be supplied with up-to-date information throughout a product's lifecycle to ensure accurate representation of the real asset. DTs have great potential to impact the construction industry, supporting facilities management, simulation tasks, and centralized management and recording of interventions. However, despite the attention the theme has attracted among researchers and companies, implementation of the concept in practical situations is still largely underexplored. Thus, this study aims to critically analyze the concept of DTs and their potential in the construction industry, particularly in inspection and maintenance tasks for existing structures. The study comprises a literature review undertaken to identify the multiple types of DT models, examine barriers and opportunities associated with their use, and discuss their potential as enablers of inspection and maintenance strategies. Furthermore, research opportunities related to the use of DTs for structural inspection and maintenance are suggested.

Keywords: Digital twin; Construction; BIM; Inspection; Maintenance of structures.

Resumo: O surgimento de novas tecnologias baseadas na troca de dados e informações, viabilizado pelo uso da internet, fez nascer uma nova revolução na indústria como um todo. Iniciado a partir da manufatura, o movimento que hoje é conhecido como a Quarta Revolução Industrial vem se espalhando e alterando a dinâmica de muitos outros campos. Dentre as tecnologias emergente desse cenário estão os Gêmeos Digitais (DG), que buscam replicar os ambientes físicos em modelos virtuais. Estes modelos devem ser alimentados com informações atualizadas ao longo de todo o ciclo de vida do produto, de modo que formem uma representação realista do ativo real. Os DG mostram-se com grande potencial de impactar também a indústria da construção, dando suporte à gestão de instalações, à realização de simulações e à gestão e registro centralizados de intervenções. Porém, em que pese a atenção que o tema vem atraindo por parte de pesquisadores e empresas, a implementação deste conceito em situações práticas ainda é pouco explorada. Nesse contexto, o presente trabalho busca analisar criticamente o

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conceito de DG e seu potencial de utilização na indústria da construção, sobretudo no que tange às tarefas de inspeção e manutenção de estruturas existentes. O estudo compreendeu uma revisão de literatura visando identificar os tipos de DG, as barreiras e oportunidades associadas ao seu uso e discutir seu potencial de suporte às estratégias de inspeção e manutenção. Ainda, são sugeridas oportunidades de estudos relacionados com o uso dos DG para inspeção e manutenção de estruturas.

Palavras-chave: Gêmeos digitais; Construção; BIM; Inspeção; Manutenção de estruturas.

1 Introduction

Technological development has gained considerable momentum in recent decades, stimulated by the growing demands and needs of the industry for fast, customizable, flexible, and efficient solutions, both from an environmental and an economic standpoint (Lasi et al., 2014). Such advances set forth a revolution in the industrial sector—the so-called Fourth Industrial Revolution. It is in this context that emerged the concept of digital twins, which consist in the application of technological innovations to recreate real physical environments in the virtual realm.

The construction industry, despite its well-known resistance to technological changes, has been gradually analyzing and consolidating the use of different methods in an attempt to heap the benefits of the current revolution, including the adoption of digital twin technologies. Digital twin models have broad applicability throughout the lifecycle of a construction project, from project design to building operation, maintenance, and recovery phases (Opoku et al., 2021).

In Brazil, given its recent construction history compared with Old World countries, building maintenance culture is still in its infancy, and the country is increasingly faced with the need for interventions that ensure the durability and safety of assets and their users. Corrective maintenance, performed only after the occurrence of damage, is still predominant among Brazilian managers (Ferreira & Souza, 2021). Given this mindset, it is a great challenge to carry out the continuous inspections and actions required for preventive maintenance. In addition to operational barriers, problems related to storage of documentation and records are common throughout a building's lifecycle, further hampering continuous monitoring efforts.

Digital twins hold vast untapped potential to change this reality. Virtual models synchronized with the physical world can be used to monitor systems, support facilities management, perform simulations, and manage and record interventions in a centralized manner (Opoku et al., 2021). In view of these possibilities, this study aimed to investigate the application of the digital twin concept to the maintenance of existing buildings, especially from a structural point of view, and critically analyze its potential in the reality of the construction sector. For this, a literature review was carried out to understand the concepts and uses of digital twin models addressed by the academic community and identify advantages and knowledge gaps for implementation of digital twins in the studied context. Finally, recommendations were proposed to advance research on the topic and promote the maturation of digital twin applications in the Brazilian construction industry.

2 Research method

This study was developed based on a systematic review of the literature using the snowballing technique described by Wohlin (2014). The review commenced with the definition of a research question, which was the point of departure for selection of search terms. The guiding question was “How can building information modeling (BIM) and digital twins assist in the inspection and maintenance of existing structures?”

The database used was ScienceDirect, chosen for its wide scope and relevance. The search strategy included the English terms “BIM,” “digital twin” (the search engine retrieves articles containing plural and singular forms of terms), and “structural inspection” or “structural maintenance.” Search terms were connected by the Boolean operators AND and OR to obtain the final search string, as follows: BIM AND digital twin AND (structural maintenance OR structural inspection).

The search retrieved 228 titles, which were filtered to select only those related to the field of engineering. Only publications classified in the database as review and research articles and book chapters were included in the search. A total of 155 articles remained after application of these filters. Then, articles were screened for eligibility by reading the title, abstract, and keywords. At this stage, studies not related to civil engineering or building structures were excluded, as well as those that did not contain information on the use of digital twins for structural maintenance, monitoring, or inspection. In addition to the articles selected from this initial search, related titles were also identified by snowball sampling (Wohlin, 2014).

The final list of articles included 41 titles, which were used to support the next stages of the study. A flowchart of the search and selection strategy is illustrated in Figure 1. The selected articles were first read in full to gain a broader understanding of their contents, starting with general applications of the digital twin concept and moving to specific uses in the studied context.

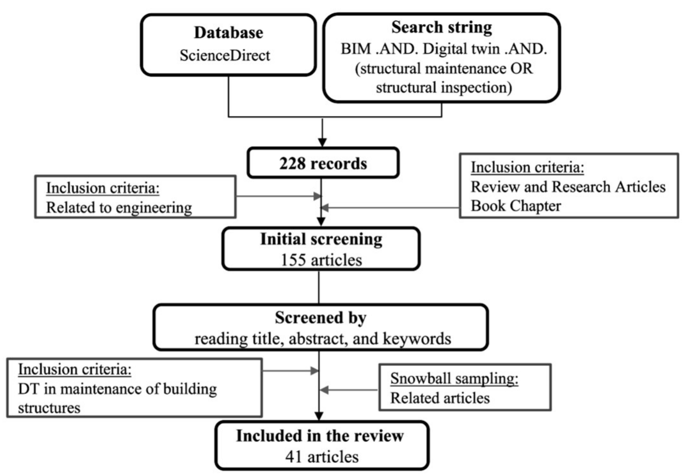

Figure 1. Flowchart of the literature review process.

3 Digital twins and their uses in the construction industry

3.1 The concept of digital twins

The now widely known concept of digital twins was first introduced by Michel Grieves in an academic presentation to the industry in 2002. Although he did not use the term “digital twins” at the time, the conceptual model presented by him contemplated all the basic characteristics of the technology: a physical environment, a virtual environment, and information exchange between them (Grieves & Vickers, 2016). The premise is that a virtual world could mirror the real world in the most varied aspects by being fed with up-to-date information throughout a product's lifecycle. The original model and its nomenclature evolved with time, leading to their consolidation in the industry under the term “digital twins” in 2011, which gained great visibility in aerospace research (Grieves & Vickers, 2016).

Grieves & Vickers (2016) stated that a digital twin model must not only describe an existing physical product but also remain connected to it during all phases, compiling operation, maintenance, test, and sensor data. A digital twin should make it possible to forecast failures, predict behaviors, and perform simulations. The model needs to be ultrarealistic and represent the mirrored object with high fidelity (Glaessgen & Stargel, 2012).

In the field of manufacturing, Tao & Zhang (2017) proposed a conceptual model of digital twins comprising four components: (i) the physical environment, which contemplates entities that objectively exist in the real world, including people; (ii) the virtual environment, which consists of multidimensional models supplied with geometric and behavioral information on the physical environment; (iii) data on physical and virtual environments, which are analyzed together; and (iv) services, which encompasses commands and controls created from available information and simulations. According to Park et al. (2020), the process of using a digital twin includes three stages: (i) development of the virtual model to represent the real object, (ii) synchronization of information between physical and virtual environments, and (iii) operation, which includes simulations, predictions, and other features and services provided by the model.

As with many other concepts that have emerged with the advent of novel technologies, many disagreements and doubts still permeate the definition of digital twins. A major topic of discussion is the level of information integration between physical and digital environments. According to Kritzinger et al. (2018), every representation of a real object in a virtual space is being referred to as a digital twin; however, care must be paid to the forms of information exchange. The authors proposed a classification system that divides digital twins into three subcategories: digital models, which are nothing more than virtual representations of physical objects without automated information exchange; digital shadows, wherein information from the physical environment is automatically updated in the virtual model; and digital twins, characterized by bidirectional and automated flow of information between environments, in such a manner that the virtual space also automatically interferes with the physical object (Figure 2).

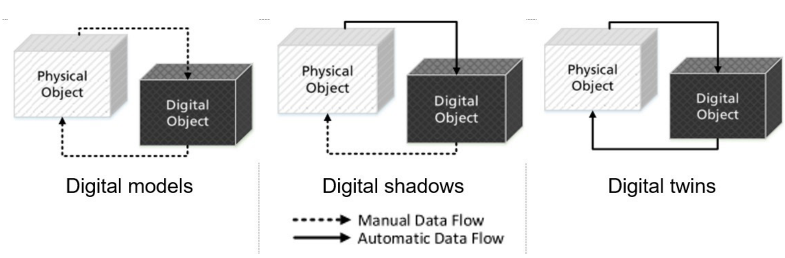

Figure 2. Classification of digital twins (Kritzinger et al., 2018).

The consensus is that there is a need for convergence between the two spaces; that is, for a model to be considered a digital twin, there must be information exchange between the real object and its representation. Ideally, such an exchange should occur automatically, bidirectionally, and in real time.

3.2 Digital twins and the civil engineering industry

With the diffusion of BIM and a growing awareness of its potentialities, it became possible to visualize different applications for BIM-based tools. The possibility of virtually reproducing a physical environment in use or under construction has attracted the attention of the construction sector, mainly in the last three years (Errandonea et al., 2020; Opoku et al., 2021; Ozturk, 2021), as evidenced by studies focused on BIM (Opoku et al., 2021).

However, in the construction sector, as well as in the industry as a whole, the conceptualization of digital twins is still evolving and may represent a source of uncertainties. With this in mind, Jiang et al. (2021) adapted the digital twin classification developed by Tao & Zhang (2017) for the construction sector (Figure 3). The authors concluded that there is a need for a *virtual representation* that faithfully expresses a *physical reality* with *transfer of information* from the physical part to the virtual part. It is possible for the virtual part to provide feedback and control the physical part, but this function is not essential. Finally, the digital twin must provide certain *services to users*, such as support in decision-making, simulation, monitoring, and control of the physical environment. Physical, virtual, and service data are stored in a central *database*.

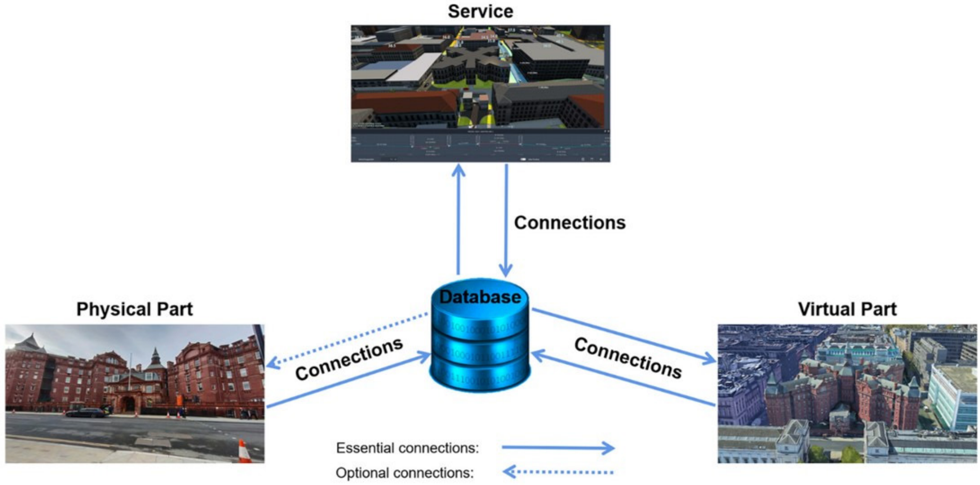

Figure 3. Digital twin structure for the civil engineering industry (Jiang et al., 2021).

Jiang et al. (2021) also noted that there is some confusion between the concepts of BIM and cyber-physical systems (CPS) with that of digital twins. The authors clarified the major differences between them: both BIMs and digital twins require a virtual model; however, BIMs do not necessarily include a real physical part linked to the virtual model and, therefore, do not require or allow for connection or synchronization between virtual and physical parts. Furthermore, a digital twin model must be constantly updated, whereas a BIM model is not primarily intended to be an accurate, up-to-date replica of an asset's conditions throughout its lifecycle (Davila Delgado & Oyedele, 2021). As for CPS and digital twins, both models necessitate physical objects and data exchange between them and a digital part (Davila Delgado & Oyedele, 2021; Jiang et al., 2021). However, in CPS, these data need not be linked to a centralized virtual model that is a faithful representation of the physical environment, as is the case of a digital twin.

A multitude of methods, such as sensors, RFID tags, laser scanning systems, GPS data, digital images, and mobile devices, can be used to acquire data for feeding and updating a digital twin model. The processing, analysis, and storage of data generated by these sources is a great challenge, both from a technological point of view, given the large volume of information produced, and from an operational point of view, given the need to address usability in a holistic and integrated manner (Opoku et al., 2021). For this reason, technologies such as big data, cloud computing, and artificial intelligence are crucial for the feasibility of digital twins (Jiang et al., 2021).

As with other fields, the technologies used in civil engineering vary with project phase (design, execution, operation, maintenance, and recovery). Likewise, the degree of applicability and services provided by digital twins will be different depending on the phase of the enterprise. In the design phase, when physical parts have not yet been built, digital twins can be useful for modeling the surroundings, the land, and neighboring buildings, both for the construction of new structures and for the recovery or expansion of existing ones (Jiang et al., 2021). This information can support the design and development of a new project, allowing for simulations, conflict assessment, and scenario analysis. In the construction phase, sites equipped with intelligent systems connected to a digital twin can assist in the management and real-time monitoring of operations. Jiang et al. (2021) argued that, in this step, BIM and CPS can be combined to generate a digital twin of parts already executed, in addition to being useful for the monitoring of employees, machinery, and materials. It should be noted that, because a digital twin must be connected to a real physical environment, parts that have not been built are not contemplated in the virtual model. In the operation and maintenance stage, the physical part has been completely executed; therefore, a digital twin holds greater applicability, and the model can replicate and monitor physically existing systems. A digital twin of an existing structure can contribute to the management and monitoring of the asset, facilitate analysis and diagnosis, contribute to decision-making, and support disaster prevention and retrofit actions (Jiang et al., 2021). Each use will require a specific model, with different levels of fidelity and complexity.

4 Digital twins in building maintenance

According to Errandonea et al. (2020), application of digital twins in the maintenance phase is the main focus of research in the area. In the construction sector, maintenance of buildings and structures is of fundamental importance to preserve and extend their useful life, as well as to ensure user safety and adequate system performance. However, this task is still largely neglected by Brazilian managers (Ferreira & Souza, 2021).

As argued by Eastman et al. (2011), BIM contributes to facilities management and building maintenance through the generation of information during design and construction phases for use in later phases. However, because the models are not connected to the real physical environment, they do not have the ability to continuously update themselves according to the state of assets throughout operation (Tavares, 2020). This gap can be filled by digital twins (Opoku et al., 2021), as digital twins are “living” models that change, improve, and evolve throughout the lifecycle of the structure (Errandonea et al., 2020).

The Brazilian standard ABNT NBR 5674 (ABNT, 2012), which refers to the requirements for building maintenance management, describes three types of maintenance: routine, with cyclical and standardized actions that occur at defined time intervals; corrective, which aims to recover lost performance, allow for continued system use, and avoid serious risks and losses; and preventive, with actions scheduled in advance based on requests and/or periodic assessments of system conditions. There are also other forms of classification, in which routine interventions are called preventive (time-based) and preventive interventions are named predictive (condition-based). Here, we adopted the classification proposed by NBR 5674:2012 to standardize the terms according to the current norm used in Brazil.

Errandonea et al. (2020) reported that preventive maintenance has the greatest potential for optimization with digital twins. This management strategy may be benefited by updated data on the conditions of the physical environment obtained using sensors. Current information, combined with historical data, allows simulating and predicting the behavior of assets to plan the necessary maintenance actions. The authors stated that digital twins used for preventive maintenance may be classified as digital shadows, given that the flow of information would occur automatically from the physical environment to the virtual model with the use of sensors.

Routine maintenance can benefit from digital twins because they record all interventions performed and can assist in the planning of periodic maintenance (Errandonea et al., 2020). Corrective maintenance, in turn, can be assisted by digital twins through automatic detection of anomalies and support for the choice of more appropriate solutions (Jiang et al., 2021).

A digital twin model aimed at supporting the inspection and maintenance of structures must meet some specific requirements about data to ensure efficient maintenance management (Ferreira & Souza, 2021). As observed by Davila Delgado & Oyedele (2021), several authors consider that digital twins constitute a set of different models, which together faithfully represent the physical asset. In view of this and the propositions of Tao et al. (2018), the virtual dimension of a digital twin applied to structure inspection should include (i) a model containing geometric information of the structure, coupled with models that (ii) simulate the physical properties of the structure, such as crack analysis, stresses, and deformations, (iii) behavioral characteristics, such as human interference and exogenous factors, and (iv) constraints, which contribute to compliance with requirements determined by official standards and users (Figure 4). In this case, similar to the need for coordination between the different dimensions of a BIM project, “[...] a correct interaction among the various models is essential in order to reflect the changing conditions of the physical asset accurately [...]” (Davila Delgado & Oyedele, 2021, p. 11).

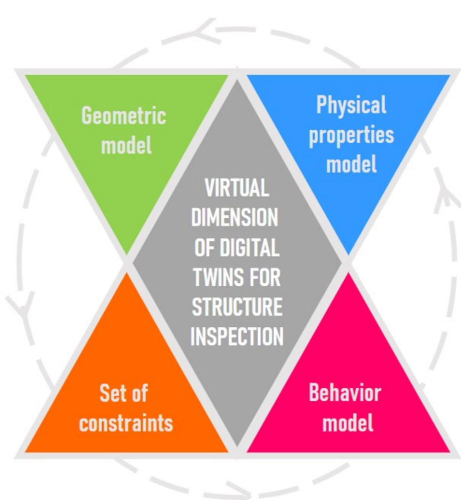

Figure 4. Virtual dimension of a digital twin for structure inspection (based on Tao et al., 2018).

Other relevant aspects are the manner by which data are obtained from the physical environment and which technologies are involved in data collection. In the engineering, architecture, and construction sectors, a large part of case studies involving digital twins for asset monitoring are focused on the assessment of structural integrity (Davila Delgado & Oyedele, 2021). Several technologies can be used to monitor and analyze existing structures for composition of a database to create and feed data into the digital twin.

Laser scanning, for example, is used to geometrically survey existing structures. The point cloud originated by scanning allows automatic or semi-automatic creation of virtual geometric models and identification of deviations in structural elements (Lu & Brilakis, 2019; Moyano et al., 2021). One can also obtain a point cloud by means of photogrammetry, with the use of unmanned aerial vehicles (Angjeliu et al., 2020; Zhao et al., 2021). Isailović et al. (2020), Zhao et al. (2021), and Morgenthal et al. (2019) used images and point clouds originated by surveys to identify structural damage, such as cracks and corrosion displacements. Mesquita et al. (2018) used sensors to collect data on temperature, relative humidity, crack opening, and relative displacement to assess the risk of structural collapse of a 16th-century church. Lin et al. (2021) used data from accelerometers and displacement transducers to evaluate the behavior of cables of a cable-stayed bridge using finite element models.

One of the challenges of digital twins is the integration of data from the physical environment (Jiang et al., 2021). It is necessary that information collected from multiple sources converge into a cohesive, centralized, connected database to feed virtual models. This centralized environment is called connected data environment (CDE), a term analogous to the common data environment used in BIM. It must (i) allow information originating in one technology to be used by others (interoperability), (ii) contain information on the context of the asset (environment), and (iii) update information on the asset (Tavares, 2020). According to Opoku et al. (2021), a few case studies used more than one technology to feed the same database with the purpose of providing a wider variety of applications.

For machinery maintenance, Ali et al. (2020) used cloud-connected technologies to monitor the physical environment, interconnect data, and interpret information to assist in the choice of maintenance strategies. Cloud computing is therefore another technology that allows applying digital twins for maintenance and structural inspection.

Davila Delgado & Oyedele (2021) reported that it has not yet been determined, for the construction sector, the different levels of fidelity that digital twin components must have to meet the requirements for practical applications. As occurs in BIM with level of development specification, it is necessary to define the level of detail of elements that make up the virtual replica (Davila Delgado & Oyedele, 2021). In the context of digital twins, this degree of detail is called the fidelity level. However, there is still no consensus or consolidated guidelines as to which data are essential for digital twins to be applied to specific uses, such as inspection of structural elements.

Another question arises as to the periodicity of data synchronization between physical and virtual environments, given that it is not always necessary or feasible to synchronize data in real time (Davila Delgado & Oyedele, 2021). Park et al. (2020) described two possible synchronization types: footprint synchronization, in which historical data are recorded and synchronized periodically throughout the product lifecycle, and snapshot synchronization, in which synchronization occurs only at specific times, according to the need for data collection. Davila Delgado & Oyedele

(2021) argued that, in the construction sector, snapshot synchronization is suitable for detecting anomalies in buildings.

It can be said, therefore, that for routine and preventive maintenance, digital twins can be synchronized by the footprint method, with periodic updates of predefined data. This method generates a historical record of interventions and structural conditions and allows for simulations and predictive analyses. For corrective maintenance, snapshot synchronization is recommended, with data collection occurring whenever repair interventions are required.

Regarding the cost-benefit of digital twins, Opoku et al. (2021) reported that financial investment depends on the degree of sophistication of the technology and the effort and time involved in its development. It is necessary to evaluate the benefits of the tool in face of the required investments to determine the feasibility of its implementation.

In the aerospace industry, for instance, digital twins have gained prominence owing to the need to expand analysis and monitoring of structural behavior and material degradation of vehicles subjected to extreme situations in order to ensure safety during missions. No other method would be sufficient to guarantee the success of spacecrafts in idealized missions (Glaessgen & Stargel, 2012).

Errandonea et al. (2020) reported that monitoring and prediction of damage, as well as optimization of maintenance plans, are essential for critical assets. For non-critical assets, corrective maintenance can be simpler and more cost-effective. Therefore, the choice of adopting digital twins, as well as their degree of fidelity and synchronization, for inspection and maintenance of structures must be based on analysis of their criticality and cost-benefit. Opoku et al. (2021) observed that the literature on the construction sector is mostly focused on large infrastructure projects, explained by their importance and criticality. Several applications have been proposed for the inspection of historic buildings, whose cultural value justifies the investment in novel monitoring and preservation techniques.

5 Discussion

Although there have been efforts toward conceptualizing, understanding, and transferring the use of digital twins to the construction sector, most of the studies remain at the theoretical level. The predominant discussion still refers to the creation of digital twins but should evolve to the following phases, namely synchronization and use. It is necessary, therefore, to consolidate research on the theoretical field and advance it to the practical level (Ozturk, 2021) for assessment of the applicability of the technology in real situations and identification of barriers to be overcome for effective application.

In general, digital twins have the potential to impact the maintenance strategy of the Brazilian construction industry, which is mostly based on corrective maintenance. The technology provides better prediction of damage and behavior, supporting preventive maintenance strategies.

According to Ozturk (2021), there are still some difficulties in the implementation of digital twins, such as inefficiency in data integration and management, interoperability problems, operational problems, and difficulty in managing and using the knowledge gained throughout the product lifecycle. The author observed that these challenges are similar to those faced with BIM; therefore, the experience of the industry with BIM can facilitate the adoption of digital twins.

For digital twin implementation, it is necessary to understand the influence of the context on innovation adoption, as underscored by Silva et al. (2022). Taking into account the classification made by Kritzinger et al. (2018) and the definition given by Jiang et al. (2021), it can be predicted that digital twins will likely be implemented in construction first as digital models, gradually evolving to digital shadows, without automatic control of the physical environment by the virtual one, at least in the short term. This last factor would be necessary for the strategy to be considered a digital twin. Jiang et al. (2021) argued, however, that automatic control of the physical environment represents an advanced level of digital twin application and that, for the reality of the construction sector, the possibility of monitoring, conducting analyses, optimizing management, and assisting in decision-making in operation and maintenance phases represents an important gain.

It is necessary to evaluate the financial feasibility of using digital twins in different scenarios in order to define the critical situations that best justify their adoption. The tendency is that digital twins be first incorporated in complex structures with great importance and criticality, for which the standard requirements are insufficient, prototype tests are expensive, and there is special interest in ensuring structural stability, as occurred in the aerospace sector (Glaessgen & Stargel, 2012). Examples of such systems include infrastructure works, such as bridges, viaducts, tunnels, dams, and skyscrapers, and historic buildings of great cultural value.

Digital twin implementation will create another paradigm shift in the construction sector, which may promote the need for new technologies and specialization of professionals (Davila Delgado & Oyedele, 2021). A previous study highlighted the lack of qualified professionals as the main barrier to the adoption of technologies related to the Fourth Industrial Revolution (Firmino et al., 2020).

On the basis of the information obtained in the present study, it is understood that, to ensure the advancement of research on the subject and the maturation of digital twins in the construction sector, some gaps need to be filled. Therefore, we propose some questions to be answered for the development of an action plan to increase the maturity of digital twin use for structure inspection and maintenance. These questions are listed in Table 1 and are associated with the different dimensions of maturity.

Table 1. Future research opportunities.

Maturity dimension	Research opportunities
Strategy	What are the benefits of adopting digital twin technologies?
Technology	What type of data should be collected and what level of fidelity do model components require for digital twins to be used in structure inspection and maintenance?
Processes	What periodicity of data synchronization is necessary for structure inspection and maintenance?
Human resources	Who is responsible for the steps involved in creating, synchronizing, and using digital twins?
Strategy	What are the critical structures that should be considered a priority in digital twin models?
Technology	What technologies enable the collection, processing, integration, and management of data and how will they be used?
Strategy	What are the costs involved in creating and operating digital twins?
Strategy	In which contexts are digital twins justified, given the observed benefits and costs?

6 Conclusions

This study explored the conceptualizations and categories of digital twins and their potential to support different strategies for structure inspection and maintenance. The obstacles to be overcome for implementation of digital twins, as well as opportunities arising from their use, were also analyzed.

The literature review indicated great potential for application of digital twins in structure monitoring. Virtual models conceived in the design phase or even generated from existing physical assets, combined with intelligent monitoring throughout the operation phase, can originate a digital twin capable of assisting managers in inspection and decision-making in the maintenance stage.

Literature information revealed that digital twins can be developed from different models and serve functions that, in combination, are able to faithfully represent the physical environment. This article brought to light the components that are necessary to create the virtual dimension of digital twins for structure inspection and maintenance, examined the barriers that may hinder the development of the tool, and examined the contexts in which digital twin applications are more advantageous.

The need for maturation and practical application of digital twin concepts is underscored. It is necessary to consider the costs and benefits of the technology and enable data integration to create a connected data environment that supports users. Furthermore, it was possible to identify opportunities for future studies related to the use of digital twins in structure inspection and maintenance, which could contribute to the maturation of the technology in the field of civil engineering. The different dimensions of maturity to be covered are technology, processes, human resources, and strategy.

It should be noted that we reviewed research papers published in a single database, identified through a search for English terms. Therefore, the results of this study are limited to a select number of publications and should be validated by further studies.

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Authors contribution

Julia Menegon and Eduardo Luís Isatto were responsible for conceptualization and development of the theoretical–methodological approach. Theoretical review and data analysis were conducted by Julia Menegon and coordinated by Eduardo Luís Isatto. All authors participated in the writing and revision of the final version of the manuscript.