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THE USE OF BIM METHODOLOGY IN THE MANAGEMENT OF THE OAES LIFE CYCLE THROUGH DIGITAL TWINS

A UTILIZAÇÃO DA METODOLOGIA BIM NA GESTÃO DO CICLO DE VIDA DE OAES ATRAVÉS DE GÊMEOS DIGITAIS

EL USO DE LA METODOLOGÍA BIM EN LA GESTIÓN DEL CICLO DE VIDA DE LOS OAES A TRAVÉS DE GEMELOS DIGITALES

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ABSTRACT
The growing adoption of Building Information Modeling (BIM) in Brazil, driven by Decree No. 11,888 of January 22, 2024, has reached various sectors of the construction industry, such as bridges and viaducts. While the design and structural analysis phases of bridges and viaducts are widely discussed in technical and academic forums, their operation and maintenance stages remain largely underexplored, primarily due to the slow pace of technological advancement in the sector. This gap has led to serious consequences, such as structural failures and service disruptions. This study aims to investigate how Digital Twins (DT), derived from BIM-based models, can serve as strategic tools for the operation and maintenance of bridges and viaducts. Based on Brazilian standards, such as ABNT NBR 9452:2023, and the information management principles defined in ABNT NBR ISO 19650, a methodological Tablework is proposed to integrate sensor data into digital environments, enabling real-time asset monitoring. The research is supported by a statistical survey on the inoperability of bridges and viaducts in Brazil, as well as an analysis of inefficiencies in current management models and the use of enabling technologies, such as Autodesk Tandem. The results highlight the urgent need for digitalization in infrastructure asset management and propose Digital Twins as a viable solution to enhance the performance, safety, and longevity of these structures.

Keywords: Building Information Modeling (BIM). Bridges. Digital Twins (DT).

RESUMO
A crescente adoção do Building Information Modeling (BIM) no Brasil, impulsionada pelo Decreto nº 11.888, de 22 de janeiro de 2024, tem alcançado diversos segmentos da indústria da construção, incluindo as Obras de Arte Especiais (OAE). Embora as etapas de projeto e análise estrutural de pontes e viadutos sejam amplamente discutidas em fóruns técnicos e acadêmicos, suas fases de operação e manutenção ainda permanecem pouco exploradas, em grande parte devido ao ritmo lento de avanço tecnológico no setor. Essa lacuna tem

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contribuído para consequências graves, como colapsos estruturais e interrupções de serviço. Este estudo tem como objetivo investigar como os Gêmeos Digitais (GD) derivados de modelos baseados em BIM, podem atuar como ferramentas estratégicas para a operação e manutenção de OAEs. Com base em normas brasileiras, como a ABNT NBR 9452:2023, e nos princípios de gestão da informação definidos pela ABNT NBR ISO 19650, propõe-se uma estrutura metodológica que integra dados provenientes de sensores a ambientes digitais, permitindo o monitoramento em tempo real dos ativos. A pesquisa é sustentada por um levantamento estatístico da inoperabilidade de OAEs no Brasil, além da análise de ineficiências nos modelos atuais de gestão e do uso de tecnologias habilitadoras, como o Autodesk Tandem. Os resultados evidenciam a necessidade urgente de digitalização na gestão de ativos de infraestrutura e propõem os Gêmeos Digitais como solução viável para aprimorar o desempenho, a segurança e a longevidade dessas estruturas.

Palavras-chave: Building Information Modeling (BIM). Obras de Arte Especiais (OAE). Gêmeo Digital (GD).

RESUMEN

La creciente adopción del Modelado de Información de Construcción (BIM) en Brasil, impulsada por el Decreto N.º 11.888 del 22 de enero de 2024, ha alcanzado diversos segmentos de la industria de la construcción, incluyendo las Obras de Arte Especiales (OAE). Si bien las etapas de diseño y análisis estructural de puentes y viaductos son ampliamente discutidas en foros técnicos y académicos, sus fases de operación y mantenimiento permanecen poco exploradas, en gran medida debido al lento ritmo de avance tecnológico en el sector. Esta brecha ha contribuido a graves consecuencias, como colapsos estructurales e interrupciones del servicio. Este estudio tiene como objetivo investigar cómo los Gemelos Digitales (DG) derivados de modelos basados en BIM pueden actuar como herramientas estratégicas para la operación y el mantenimiento de las OAE. Con base en estándares brasileños como ABNT NBR 9452:2023 y los principios de gestión de la información definidos por ABNT NBR ISO 19650, este estudio propone un marco metodológico que integra datos de sensores con entornos digitales, lo que permite el monitoreo de activos en tiempo real. La investigación se sustenta en un estudio estadístico sobre la inoperabilidad de las OAE en Brasil, así como en un análisis de las ineficiencias de los modelos de gestión actuales y el uso de tecnologías facilitadoras, como Autodesk Tandem. Los resultados resaltan la urgente necesidad de digitalización en la gestión de activos de infraestructura y proponen los Gemelos Digitales como una solución viable para mejorar el rendimiento, la seguridad y la longevidad de estas estructuras.

Palabras clave: Modelado de Información de Construcción (BIM). Obras de Arte Especiales (OAE). Gemelo Digital (GD).

1 INTRODUCTION

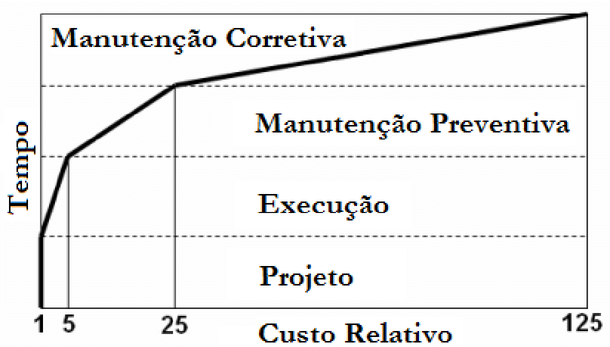
Uncertainty regarding the number of bridges and viaducts in the country is the first factor that contributes to the poor management of road infrastructure assets in Brazil (DNIT, 2017). It is estimated that there are about 137 thousand Special Works of Art (OAE), of which 5,827 federal bridges are under the responsibility of the National Department of Transport Infrastructure (DNIT) for inspection and maintenance purposes. According to the report, as of May 2023, 727 federal bridges have been classified as critical or in poor condition, which represents approximately 12.5% of the total federal bridges in the country.

In 2023, only 49 maintenance plans were prepared for OAEs, out of a total of 1,724 under the responsibility of the Regional Superintendencies. The system used by DNIT to store inspection data is the Special Works of Art Management System (SGO). Each registered OAE undergoes periodic evaluations of its physical condition, being assigned a score from 1 (worst condition) to 5 (best condition). This classification aims to assist in the prioritization of maintenance actions. Grades 1 and 2 correspond, respectively, to "critical works" and "works with problems" (DNIT, 2004).

The need for prioritization stems from the absence of policies and strategies aimed at the preservation of OAEs. Sitter (1984) highlights the importance of preventive actions in the design/construction phases, since costs increase significantly in the repair and renovation phases, as illustrated in Figure 1.

Figure 1

Cost Evolution Act, Sitter's Act (Sitter, 1984)



One of the main factors driving the growing interest in concrete durability is the alarming frequency of corrosion damage to reinforcement. Mehta and Monteiro (2008) point out that no material can be considered intrinsically durable, since microstructures inevitably evolve over time due to interactions with the environment. The end of the useful life of a structure is reached when its properties, under certain conditions of use, degrade to such an extent that its continuous operation becomes unfeasible, both from an economic and structural safety point of view.

This paper investigates how the combination of BIM and Digital Twins (DG), in compliance with ABNT NBR 9452:2023 (ABNT, 2023) and ISO 19650 series standards (International Organization for Standardization, 2018), can significantly improve the lifecycle management of OAE in Brazil. A statistical analysis of structural pathologies is presented, gaps in current practices are identified and solutions for intelligent infrastructure management are discussed.

2 ASSET PRESERVATION

Asset preservation refers to the set of actions required to ensure that a structure remains safe, functional, and conforms to its original design throughout its entire life cycle. These actions begin with the systematic collection of data on the physical conditions of the structure, usually obtained through standardized inspections (Vitório, 2006).

In Brazil, ABNT NBR 9452:2023 (ABNT, 2023) defines the technical requirements and procedures for the inspection of Special Works of Art, covering bridges, viaducts and walkways in concrete, steel or mixed structures. This standard establishes a classification system and determines different types of inspection based on the frequency, purpose and conditions that trigger them. Cadastral inspections are carried out after construction, integration into the road system or after significant modifications. Routine inspections take place annually, with the aim of assessing the overall condition of the structure. Special inspections are carried out every five years, or up to eight years, for a more detailed evaluation. Finally, extraordinary inspections are performed after events such as natural disasters or accidents.

These inspections form the basis for asset data management and should be integrated into a structured information management process, ideally supported by BIM methodologies as recommended by ISO 19650. This ensures that inspection data is not only collected, but also organized and accessible throughout the asset's lifecycle, from design and construction to maintenance and eventually rehabilitation.

By centralizing and updating this information in a Common Data Environment, it becomes possible to improve decision-making, prioritize interventions, and reduce maintenance costs. BIM also allows real-time visualization of inspection results and assists in planning corrective measures with greater accuracy and agility.

CLASSIFICATION OF SPECIAL WORKS OF ART

The classification of OAE is a fundamental step in asset management, serving as a basis for prioritizing maintenance, risk assessment and planning interventions. According to the ABNT NBR 9452:2023 standard (ABNT, 2023), this classification must consider three main dimensions: structural, functional, and durability performance. Each of these dimensions is evaluated on a scale of 0 to 5, with a score of 5 indicating excellent condition and a score of 0 representing total collapse or complete loss of functionality.

The assessment must be carried out by qualified inspectors, and the final classification must be validated by the engineer responsible for managing the asset. Table 1 presents a summarized version of the criteria defined by the standard.

Table 1

Classification of OAEs according to ABNT 9452/23 (ABNT, 2023)

Note	Structural	Functional	Durability
5	No problem; Irrelevai defects.	Safe and fully functional	No relevant anomalies.
4	Little damage, no safe risk.	Minimal discomfort. Safe	Minimal deterioration.
3	Monitorable risk, withou instability.	User discomfort. It require attention.	Moderate deterioration.
2	Compromised safet repair needed.	Compromised use, safe risk.	Severe deterioration.
1	Critical condition, risk collapse.	Restrictive use, parti closure.	Marked localized deterioration.
	Structural failure, collapsed.	Non-functional. Interdiction necessary.	Critical deterioration. Emergency intervention

The classification must take into account the individual components of the bridge, such as the superstructure, mesostructure, infrastructure, complementary elements and the runway system. Each component can be evaluated separately in relation to each of the three dimensions, allowing for a more detailed and accurate prioritization of the interventions required.

When integrated with BIM-based models, the results of these classifications can be stored, visualized, and updated in real-time, creating a dynamic digital asset management environment. This approach increases transparency, reduces the subjectivity of analyses, and facilitates automated reporting for public agencies and utilities.

3 CHALLENGES FOR THE MAINTENANCE OF OAEs

The maintenance of OAEs is marked by critical challenges arising from the different phases of the asset's life cycle. The main factor that contributes to the emergence of structural pathologies in Brazilian civil works is poor execution (Souza, 1991). Complementary studies carried out by Gnipper and Mikaldo Jr. (2007) reinforce this finding by quantifying the main causes of endogenous failures in civil structures: design errors correspond to 36%–49%, execution failures to 19%–30%, component failures to 11%–25%, and inappropriate use to 9%–11%.

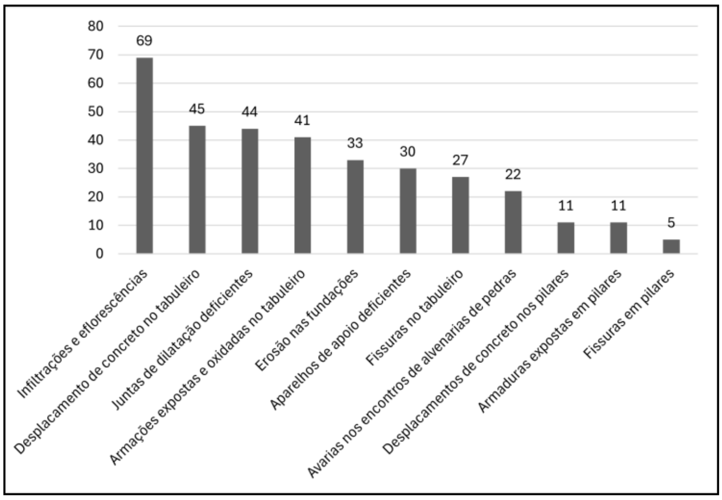
Failures in OAEs are compounded by complex designs, harsh environments, and high operational demands. In the absence of preventative maintenance and reliable data, deterioration often goes unnoticed until it reaches a critical state.

In a study conducted by Vitório (2013), 100 bridges located in the states of the Northeast region of Brazil were analyzed, with the identification of the main pathological occurrences (Figure 2). The study pointed out that the lack of maintenance of these assets contributed significantly to the structural damage observed in the bridges evaluated.

The predominant classification was potentially problematic structures (38%), followed by structures in poor condition (35%), structures without significant manifestations (24%) and structures in critical condition, with potential risk of structural collapse (3%).

Figure 2

Incidence of the main structural damage in the 100 bridges surveyed (Vitório, 2013)



In this context, the need for new strategies to face the challenges identified becomes evident. The integration of BIM into infrastructure projects represents a transformative opportunity. By ensuring centralized and structured data throughout the entire asset lifecycle, BIM contributes to the mitigation of design inconsistencies, improves executive documentation, and allows the monitoring of component conditions for future maintenance planning.

When BIM is combined with technologies such as Digital Twins and real-time sensor monitoring, it becomes possible to transition from corrective maintenance models to predictive approaches. This change not only increases operational reliability, but also reduces lifecycle costs and user risks associated with infrastructure failures.

4 BUILDING INFORMATION MODELING (BIM)

The concept of BIM has evolved considerably since its origin. Although the term "BIM" was not yet established at the time, Charles M. Eastman introduced the fundamental idea of the computational model of building components (Eastman, 1975). Over time, this concept has matured and consolidated itself as an integrated methodology that covers the digital representation, coordination, and management of constructive information throughout the entire life cycle.

According to Sacks et al. (2018), BIM can be defined as a set of processes and technologies for the creation, management, and use of structured information about a built asset. The system includes the representation of intelligent objects, with graphical and parametric data, integrates behavioral data that allows components to react to predefined rules and constraints, ensures data consistency so that changes to an element are reflected in all views and documents, and uses a common data environment to maintain version control, foster collaboration and ensure the integrity of information.

In accordance with ISO 19650 standards (International Organization for Standardization, 2018), BIM is not limited to geometric modeling, but to the management of structured information at all stages, from design and construction to operation and decommissioning. These international standards reinforce the importance of data interoperability and collaboration, especially in public infrastructure projects.

BIM models can be categorized according to the concept of "BIM dimensions", which correspond to the addition of project-specific information to the 3D model. BIM dimensions include 3D (geometric modeling), 4D (construction timing and sequencing), 5D (cost management), 6D (sustainability and energy performance), and 7D (operation and maintenance).

Among them, the 7D dimension is especially relevant for infrastructure management, as it incorporates data related to inspections, warranties, maintenance schedules, and asset performance indicators. Despite its strategic value, the 7D dimension remains underutilized, especially in Brazil, due to the limited digital maturity of facility managers and public agencies (Bąkowski, 2017).

4.1 BIM IN INFRASTRUCTURE

The application of BIM in infrastructure projects has gained global relevance, especially for its ability to increase efficiency, reduce costs, and improve decision-making throughout the life cycle of assets. However, one of the main obstacles to its widespread adoption, especially in public sector projects, is the difficulty in accurately measuring the return on investment (Dodge Data & Analytics, 2017).

The Mitchell Interchange project in the United States demonstrated the benefits of BIM in reducing costs and improving coordination (USFHA, 2013). Table 2 presents a summary of the estimated impacts on costs arising from the use of BIM, while Figure 3 displays a digital visualization of the project.

Table 2

Impact of the estimated cost from the use of 3D modeling (USFHA, 2013)

Project Issue Notifications	Estimated reduction (%)	Total Cost (M USD)	Average cost per review ($)
General Structures	30,50%	6,8	45,674
Sanitation / Drainage	25,50%	5,7	85,631
Highways / Drainage	11,10%	2,4	27,120
Bridges	8,00%	1,8	15,557
Acoustic Barriers	8,00%	1,7	12,909
Retaining Walls	7,70%	1,7	21,818
Earthworks	4,50%	1,5	59,220
Electric	2,60%	0,6	15,557
Traffic	2,10%	0,5	18,174
Signage	0,10%	2,32	738
TOTAL	100%	22,32	-

Figure 3

3D model, The Mitchell Interchange (USFHA, 2013)

The results highlight the transformative role of BIM in complex infrastructures, especially in the face of budget and schedule constraints. In the case of OAE, BIM integrates geometry, structure, chronology, and costs into a unified digital model.

In Brazil, Decree No. 10,306/202024 (Brazil, 2020) establishes the mandatory adoption of BIM in federal public works, in line with international standards such as ISO 19650. In addition to the design and construction stages, BIM supports interoperability, for example via *the Industry Foundation Classes* (IFC) format, allowing *As Built* records to be linked to maintenance systems for real-time updates, cost forecasting, and rehabilitation planning. Thus, BIM becomes a strategic asset for infrastructure governance, promoting transparency, efficiency, and data-driven decisions.

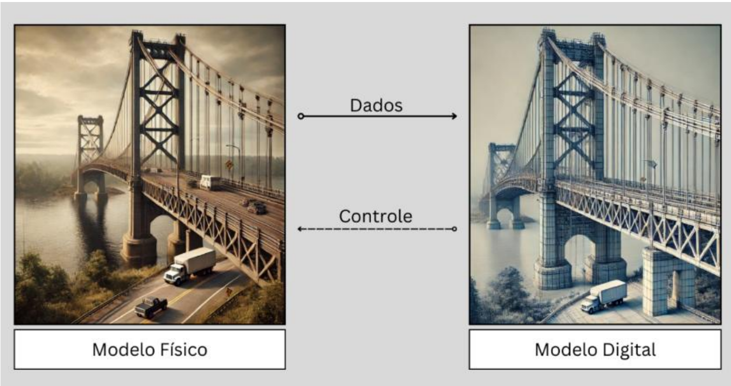
4.2 DIGITAL TWINS

Digital Twins are increasingly recognized as transformative tools in infrastructure management. According to Parrot and Warshaw (2017), a DG can be defined as a virtual replica of a physical asset or system, built from cumulative and real-time data, capable of simulating and predicting its performance. These digital models enable proactive asset management through continuous monitoring and analysis.

According to Grieves (2019), a DG establishes the connection between the physical asset, its digital model, and the data flows between them (Figure 4). The ultimate goal is to support real-time decision-making regarding the operation, maintenance and optimization of asset performance.

Figure 4

Concept of the 3 elements of a DG (Delgado et al., 2021)



In the context of infrastructure, the integration of BIM with Digital Twins creates a robust foundation for digital asset management. BIM provides the structured data, geometric and non-geometric, necessary for the construction of the digital correspondent. However, the original BIM model, as designed, does not reflect the actual condition of the work performed. For the creation of a true GD, the model must be updated during the commissioning process to represent the *As Built reality*.

This process, while essential, can be time-consuming and costly, especially in large or complex structures such as bridges and overpasses. To overcome these difficulties, recent advances in reality capture technologies, such as drones and laser scanners, have proven to be highly effective. These tools generate dense point cloud models that serve as an accurate geometric reference for updating post-construction BIM models.

Once integrated with a DG platform, such as Autodesk Tandem or similar environments, these models allow infrastructure managers to monitor structural behavior through sensor integration, simulate degradation patterns, plan predictive maintenance based on performance trends, and centralize documentation and field data in a single platform.

In addition, the synergy between DGs and BIM is fully aligned with the principles of the ISO 19650 series, which promotes structured information flows and data interoperability at all stages of the asset's life cycle.

As infrastructure assets in Brazil age and demand more efficient management, the adoption of Digital Twins, supported by BIM methodologies, represents a strategic shift from the reactive model to predictive and preventive maintenance models. This not only increases safety and performance, but also contributes to significant cost savings and increased asset longevity.

4.3 MONITORING OF OAE STRUCTURES BY SENSORS

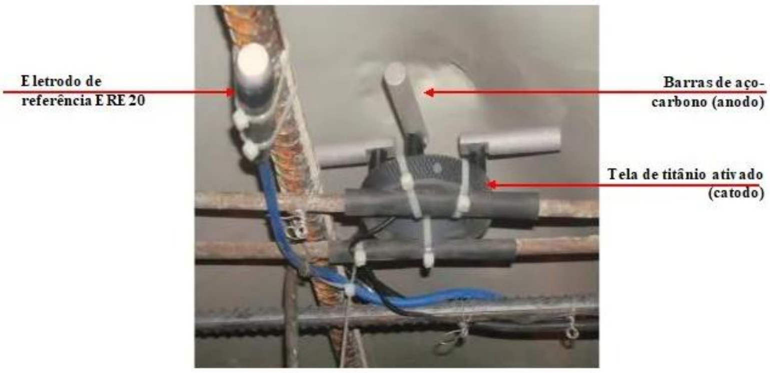
Bridge and viaduct monitoring is an essential component of structural asset management, enabling the early detection of anomalies and the prevention of catastrophic failures. This process, known as Structural *Health Monitoring* (SHM), consists of techniques that evaluate the behavior of the structure without compromising its integrity, based mainly on non-destructive testing and data acquisition by sensors (Baleagas et al., 2010)

The effectiveness of SHM increases significantly when integrated with DGs. Real-time data obtained by field sensors can be fed directly into the digital environment, enabling continuous performance monitoring, predictive diagnostics, and automated alerts. This synergy enhances decision-making and prioritizes interventions based on actual structural conditions.

Among the most commonly used sensors in OAE applications, sensors that monitor strain, vibration, temperature and humidity, galvanic corrosion (Figure 5) and fiber optical sensors stand out, all of which support proactive maintenance.

Figure 5

Galvanic Sensor (Araújo et al., 2013)



The SHM methodology involves more than just installing sensors. It encompasses a structured system of data acquisition and transmission, analytical processing (including statistical models and artificial intelligence), decision support, and integration of feedback into maintenance planning (Grieves, 2019). Figure 6 illustrates the basic architecture of an SHM system, in which sensors, processing units and management *software* are interconnected to support real-time analysis and visualization.

In the context of BIM and Digital Twins, the integration of SHM data with 3D models enables asset management based on real conditions. Teams can view sensor data, simulate deterioration processes, and plan actions directly in the digital model. The system enables early detection of anomalies, reduces the number of unplanned interventions, supports the prioritization of resources based on asset conditions, and offers long-term documentation for planning and auditing.

As part of a national infrastructure strategy, the incorporation of SHM into BIM-based Digital Twins represents a paradigm shift from reactive to predictive maintenance, as recommended by contemporary standards and digital transformation roadmaps for public works. A life-cycle diagram of the design of a DG is suggested in Figure 7.

Figure 6

Principles and organization of an SHM system (Baleagas et al., 2010)

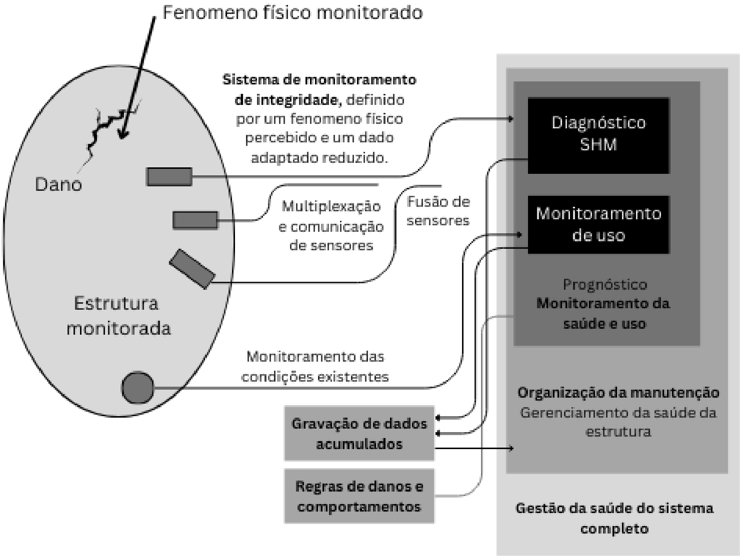
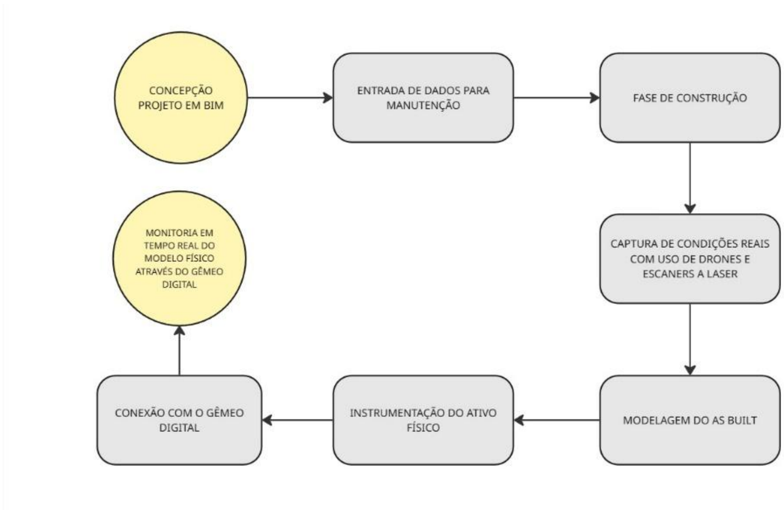


Figure 7

Flowchart of the process of setting up a GD (Own Elaboration)



4.4 O AUTODESK TANDEM

Among the latest advancements in GD technologies for the Architecture, Engineering, and Construction (AEC) industry, Autodesk Tandem stands out as a comprehensive platform designed to connect BIM-based design models to facility operating environments.

Autodesk Tandem makes it possible to create a connected GD by leveraging data from the design and construction phases, enriching the model with operational metadata and real-time information from sensors. The tool is aligned with the 7D dimension of BIM, focusing on asset performance, maintenance, and lifecycle optimization.

The system integrates design data sourced from Autodesk Revit or IFC-based models, operational systems including sensor networks and Internet of Things (IoT) infrastructure, maintenance schedules and asset inventories, as well as visualization tools such as dashboards, heat maps, and real-time indicators. Among its main functionalities are the visualization of operational data through graphs, KPIs and heat maps to display temperature variations, stresses and vibration anomalies in structural elements. Interoperability with open standards is another strength, as Tandem supports the IFC format and integrates with Autodesk tools, ensuring data continuity and compliance with ISO 16739 (International Organization for Standardization, 2024) and ISO 19650 standards, it also offers sensor integration via IoT, allowing real-time data collection from physical assets to support status monitoring, maintenance alerts and performance forecasting. In addition, Tandem has asset inventory management, in which BIM elements are transformed into digital assets with attributes such as serial numbers, warranties, and inspection dates.

The process flow begins with the design and construction of the asset using BIM, followed by *as-built* modeling, usually through laser scanning or drone photogrammetry, and instrumentation of the physical structure. Once the GD is configured, the Tandem becomes a dynamic environment for continuous operation and maintenance, as illustrated in the GD lifecycle diagram (Figure 7). For bridge and viaduct projects, this enables infrastructure managers to monitor the integrity of critical components in real time, allowing for timely detection of problems. Interventions can be planned based on predefined sensor thresholds and observed deterioration trends. Users can instantly access digital documentation, either on-site or remotely, ensuring greater operational efficiency. In addition, the platform ensures historical traceability of all asset-related events, supporting informed decision-making and regulatory compliance.

In the Brazilian context, especially with the federal push for the adoption of BIM established by Decree No. 11,888/2024, solutions such as Autodesk Tandem are powerful allies to reduce the gap between project delivery and long-term infrastructure management.

5 CONCLUSIONS

The increasing complexity and aging of infrastructure assets in Brazil, especially bridges and viaducts, highlight the urgent need for smarter, more integrated, and proactive maintenance strategies. This study demonstrates that the combined use of BIM and Digital Twins provides a robust foundation for improving the operation, monitoring and management of OAE. By applying BIM principles and aligning with the ISO 19650 standard for structured information management, it becomes possible to centralize design, construction, and inspection data throughout the entire asset lifecycle. Integration with real-time sensor data, through the Digital Twin paradigm, enables the transition from traditionally reactive maintenance to a more predictive and condition-based approach, in compliance with international best practices.

The alarming number of OAE in critical condition in Brazil, evidenced by data from federal inspections, reinforces the limitations of current asset management models, which are often fragmented, lagging behind and lacking interoperability. This work proposes a clear alternative, presenting tools such as Autodesk Tandem, which allows real-time visualization of structural integrity, supports the automated inventory of digital assets, facilitates communication between physical systems and digital environments, and enables data-driven planning for interventions and inspections.

The methodology discussed in this article is also directly aligned with the objectives of Decree No. 11,888/2024 and Decree No. 10,306/2020, which establishes the mandatory use of BIM in public works. Thus, the proposed *Tablework* offers not only technical benefits but also political relevance, contributing to a broader digital transformation in infrastructure governance.

Finally, this study highlights the need for technical training in public agencies and concessionaires to support the effective implementation of BIM and DG solutions. Future research should explore cost-benefit analyses of digital twin deployments in infrastructure, as well as the development of national protocols for the digitalization of assets, especially for road and bridge networks.

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