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Digital Trio: Integration of BIM–EIR–IoT for Facilities Management of Mega Construction Projects

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Abstract: Facility Management (FM) has increasingly focused on integrating Building Information Modeling (BIM) with the Internet of Things (IoT), known as digital twins, in large-scale development projects. Effective BIM integration in FM requires improved cooperation among participants across various project stages. This digital revolution aims to enhance planning, construction, and asset management efficiency, benefiting all parties. However, BIM utilization in FM is limited by incomplete owner understanding, insufficient data accessibility, and stakeholders' unfamiliarity with BIM procedures and standards. Despite recognizing BIM's significance, the FM industry faces significant implementation challenges. Facility managers often lack a comprehensive understanding of BIM's benefits in streamlining operations and enhancing cost efficiency, as well as the necessary skills for its use. Addressing these barriers requires developing an Employer's Information Requirements (EIR) document at a project's outset, providing a strategic plan and vision for all involved parties. BIM and IoT are pivotal technologies for transitioning to efficient building operations and crucial for reducing time, costs, and operational challenges throughout any project. This research aims to establish a digital trio workflow, integrating BIM, EIR, and IoT to maximize stakeholder benefits. It explores how preparing the EIR through stakeholder communication can improve design processes, sustainability, efficiency, cost, and time, especially for megaprojects.

Keywords: facility management (FM); building information modeling (BIM); Internet of Things (IoT); digital twin (DT); digital trio; employer's information requirements (EIR)

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1. Introduction

The integration of BIM–IoT data has introduced new added value into the market; the physical object is now considered a product that carries information throughout its life cycle. This transformation is expected to significantly aid the construction industry, which has just begun a shift from being product-oriented to service-oriented, similar to more industrialized sectors. However, to fully benefit from this transformation, the integration of data into BIM models must be managed in the most effective manner. Studies on BIM and IoT are often based on proprietary files and closed ecosystems, in which information is not openly shared among stakeholders. Therefore, subsequent research within the BIM–IoT integration domain should focus on open data and open communication standards [1].

Despite advancements, many buildings still suffer from suboptimal management due to outdated procedures and insufficient data utilization. Digitization in FM has been propelled by new technologies, including the Internet of Things (IoT), big data, cloud computing, and cyber–physical systems, which have revolutionized traditional industry practices by enhancing efficiency, accuracy, and precision. The connection between the physical and virtual worlds enables the creation of self-adapting and self-managing communication networks [1].

This study introduces a comprehensive and innovative methodology for assessing building conditions and making informed decisions, yielding significant findings and contributions substantiated by quantitative data. A new approach utilizing Building Information Modeling (BIM) as a visualization platform for predictive maintenance is proposed, which simplifies the evaluation of building comfort and accelerates the often-lengthy fault-detection process.

As BIM gains substantial momentum in the Architecture, Engineering, and Construction (AEC) sector and as many governments push for full BIM adoption, the integration of BIM and Facilities Management (FM) systems has become inevitable. BIM functions as a centralized repository for the data collected throughout a project's life cycle. Research suggests that facility managers can exploit BIM capabilities to enhance the management of extensive data volumes. However, the integration of BIM and FM systems faces significant technical and nontechnical challenges. An exhaustive literature review conducted for this study identifies gaps in research related to BIM for FM and the practical challenges associated with BIM implementation during the facility management phase. Demonstrating the value of BIM for FM through case studies and empirical evidence is crucial for addressing these practical challenges. Strengthening relationships among various stakeholders within the AEC industry and fostering collaboration among facility managers, designers, and constructors are imperative [2–6].

There is considerable debate regarding data acquisition, data exchange formats, and data management in FM systems. To ensure that a building information model effectively meets the needs of facility management, it is essential for the FM to proactively define information requirements at the beginning of the project life cycle, rather than waiting until the project concludes to gather data [1,7].

The integration of BIM and the Internet of Things (IoT) has been identified as a critical requirement for managing smart buildings [7]. This integration can be achieved by developing a platform that combines BIM, Enhanced Information Request (EIR), and IoT into a user-friendly interface, enabling the monitoring and control of all assets and operation of any structure without requiring specialized engineers. This combination aims to evolve from the concept of a digital twin to that of a "digital trio" by incorporating (EIR) into the workflow. This research includes a case study on a platform created to manage and control a city by implementing sensors for various activities and displaying the data on a digital twin platform.

This research investigated two databases, namely, the Web of Science and Scopus, focusing on digital twins in the AEC-FM industry. Publications from 2020 to 2024 were examined to ensure that the study was updated with the latest research.

2. Literature Review

In today's globalized world, organizations require a unique and dynamic performance measurement system. Furthermore, organizations need a multidimensional perspective on performance control because of the increasing competitiveness of the business environment [8–13]. The urgent need to implement mega industrial projects in developing countries, such as Egypt, intensifies the challenges and difficulties faced by project management units [14].

The implementation of Building Information Modeling (BIM) in project management has been shown to significantly enhance construction planning, reduce rework, and minimize time waste. BIM facilitates the efficient exchange of project information, thereby resolving issues stemming from poor communication among stakeholders. Numerous studies have investigated the benefits of BIM in construction project management. In Slovakia, for example, BIM has been found to reduce costs, eliminate documentation errors, improve the quality of project documentation, enhance cost control, and improve communication among project stakeholders. Additionally, BIM reduces the time required for preparing documents and drawings and aids in decision-making processes. As a relatively new technology for designing, constructing, maintaining, and managing projects, BIM enhances the efficiency of project cost analysis. Another study highlighted BIM's advantages in project management, including improved performance and productivity, reduced waste, and shortened project delivery times. Technical reports from project stakeholders also underscore the benefits of BIM, such as simultaneous access to project data, facilitation of collaboration through a virtual digital medium, interdisciplinary interactions, reduced risk of conflicts, improved communication, and automated quantification for enhanced accuracy and multidimensional integration. Furthermore, there have been efforts to combine BIM with other applications to optimize construction projects. For instance, a study in Egypt explored the integration of Building Energy Modeling (BEM) with BIM to advance environmental policies, identifying several barriers to implementing this approach [15].

Data sources based on BIM, IoT, and EIR represent relatively new fields. BIM and IoT data can be viewed as mutually reinforcing components, each compensating for the deficiencies of the other. Researchers have examined several facets of Building Information Modeling (BIM) and the Internet of Things (IoT) and their use in a unified manner, encompassing areas such as sustainability, hazards, and safety [15,16].

Therefore, this research examines studies and research that have been published on the integration of BIM and IoT data. The content is organized as a bibliographic inquiry in which an examination of the present utilization of these technologies is conducted. The objectives of this study are to conduct a comprehensive bibliographic study of research endeavors focused on the integration of BIM and IoT to enhance FM procedures. The objective was to identify constraints in the research and present a plan for future research on enhancing FM through the utilization of novel technology [17,18].

BIM is advantageous in building management because of its proven capability to streamline inspection and evaluation processes, potentially leading to more automated practices. By utilizing maintenance data, it is possible to effectively reduce the effort required for inspections and prioritize inspection tasks [19,20]. Despite the substantial potential of Building Information Modeling (BIM) and BIM Execution Plans (BEPs), the absence of standardized procedures for the creation and implementation of BEPs poses a considerable challenge. This study aims to explore the complexities inherent in BIM Execution Planning to address a critical gap in current industry standards. The rationale for this study stems from the recognition that the construction industry operates within a highly regulated environment, governed by an intricate web of regulations, standards, guidelines, and codes of conduct. The industry's complexity is underscored by the diversity of these regulatory and enabling frameworks; hence, a systematic and standardized approach is essential to ensure the effective deployment of BIM [1]

Table 1 presents journal articles on BIM, IoT, and their integration for FM and core functions in the WoS (W) and Scopus (S) databases (until February 2021). It shows that many products were found in each database and matching each FM core function with the three tools' categories. Although the contemporary use of BIM and IoT is relatively recent, some FM core functions, like "Sustainability", "O&M", "Communication", and "Technology", have a significant number of publications. On the contrary, perhaps because of the novelty of the two tools' simultaneous use, some functions have a minimal number of publications. It is noteworthy that "Sustainability" is the most studied core function even when considering BIM or IoT separately. The numbers of publications related to several of the FM core functions are relatively homogeneous if only BIM products are queried [1].

Recently, FM has experienced changes owing to the implementation of innovative technologies, which offer the potential to address the shortcomings of ineffective communication. To ensure the smooth transition of data from one phase to another, it is necessary to utilize technologies that facilitate information management. BIM, or construction information modeling, is a valuable tool for storing and representing historical data in a database. It is particularly beneficial throughout construction and operational stages due to its advanced data storage capabilities and ability to vividly portray building information [21].

Table 1. Journal articles on BIM, IoT, and their integration for FM.

Functions	Tools	BIM ToT	BIM + IoT
Communication	426 (W) + 509 (S)	3920 (W) + 28539 (S)	42 (W) + 55 (S)
Finance and Business	293 (W) + 468 (S)	417 (W) + 3413 (S)	8 (W) + 15 (S)
Human Factors	31 (W) + 43 (S)	362 (W) + 974 (S)	4 (W) + 4 (S)
Leadership and Strategy	32 (W) + 242 (S)	18 (W) + 500 (S)	1 (W) + 17 (S)
O&M	557 (W) + 746 (S)	4374 (W) + 24709 (S)	66 (W) + 64 (S)
Project Management	157 (W) + 965 (S)	20 (W) + 1875 (S)	6 (W) + 53 (S)
Quality	33 (W) + 200 (S)	61 (W) + 3767 (S)	1 (W) + 2 (S)
Property Management	57 (W) + 169 (S)	42 (W) + 1087 (S)	7 (W) + 19 (S)
Risk Management	253 (W) + 267 (S)	1084 (W) + 5319 (S)	17 (W) + 75 (S)
Sustainability	709 (W) + 794 (S)	7733 (W) + 33413 (S)	59 (W) + 106 (S)
Technology	370 (W) + 1875 (S)	1219 (W) + 30946 (S)	34 (W) + 104 (S)
FM	237 (W) + 236 (S)	71 (W) + 341 (S)	25 (W) + 81 (S)

Over the years, the AEC-FM industry has mostly concentrated on digital twin research as a technique for managing the entire life cycle of a product. These two concepts, digital twin and product life-cycle management, have emerged as the most significant areas of research. Digital twins are currently employed within the building construction sector throughout the duration of a project, highlighting the significance of this concept. Each construction project produces intricate data. This substantial volume of data can be effectively utilized for facility management purposes by leveraging contemporary DT research in the AEC-FM sector [21].

The use of DTs in the AECFM industry has resulted in the development of cognitively enabled digital twins, which represent the building as a physical asset. A digital twin project aims to improve building information models, data processing, and efficiency in information management. Gathering and interpreting data are two of the most difficult activities in a project life cycle. Effective information management is crucial in digital twin research and critical analysis of digital twin technology in the Architecture, Engineering, Construction, and Facility Management (AEC-FM) industry [13].

Digital twins can provide immediate and accurate information about the state of assets, allowing for the identification and precise location of potential problems. They also assist in decision-making processes. Data monitoring can effectively anticipate the future conditions of machines and facilitate appropriate maintenance measures, thereby enabling predictive maintenance. This approach empowers users with the ability to determine the location, timing, and likelihood of potential failure. This form of maintenance results in cost reductions and prevents any disruption to building services. The integration of IoT and BIM to develop a digital twin and enable predictive maintenance is a vast and unexplored domain [22].

Regarding crucial documents, such as the Employer's Information Requirements (EIR), in the Building Information Modeling (BIM) process, they pose a significant challenge. Individuals frequently experience uncertainty regarding the initial steps and express a sense of being inundated by the extensive volume of material they must peruse to comprehend the basics and fully grasp their responsibilities. This is typically seen in the lack of the early integration of facility managers into projects [23].

At the beginning of any project that is targeted at the use its asset and the application of facilities management to it, an EIR should be prepared using the Building Information

Modeling (BIM) process. The EIR defines a client's objectives, expectations, and specific requirements for the project. This clarity ensures that all stakeholders, including the project team and those involved in the BIM process, have a clear understanding of what must be achieved.

By clearly defining the requirements and expectations upfront, the EIR helps identify potential risks related to information management and BIM implementation. This proactive approach allows for the development of strategies to mitigate these risks and reduce the likelihood of issues arising during the project [24].

In conclusion, preparing an EIR before commencing a project, especially in the context of BIM, is essential for establishing clear expectations, aligning BIM's implementation with project objectives, mitigating risks, and promoting efficient collaboration among stakeholders. This sets the foundation for successful BIM implementation and helps ensure that the project delivers the desired outcomes [25].

An important purpose of this research is to explain to all stakeholders how BIM benefits facility managers, because if the top at any institute has a complete vision for the use of BIM, it will be easy to go through the process of operating and maintaining any asset. The use of BIM technology offers a wide range of advantages in several areas of facility management, which is further elaborated upon [26].

Automating the process of data transfer and updating a 6D BIM model facilitate prompt and efficient access to information regarding all building components. As a result, the need for labor-intensive data entry processes to transfer attributes to a Computerized Maintenance Management system (CMMS) is eliminated, thereby saving time when retrieving the necessary data.

By incorporating building information modeling, facility management professionals can play a more influential role in the initial phases of a project, leading to enhanced outcomes.

Understanding BIM data can be challenging because of the extensive quantity of information it encompasses, including schedules and asset details. However, improved data management is possible through the integration of BIM with FM platform, such as a computer-aided facility management (CAFM) system, which enhances capabilities.

In complex projects, time extensions resulting from multiple causes related to different stakeholders at different project phases constitute construction delays. The causes of such delays are related to project partners, including contractors, clients, designers, investors, suppliers, supervisors, laborers, and the government [9].

The establishment of maintenance procedures relies on historical trends determined by utilizing the comprehensive data stored using BIM, which include service history, specifications, and contract information. BIM enables thorough building analysis, particularly in areas focused on sustainability measures such as LEED-EBOM. In addition, BIM can assess several energy options to significantly reduce environmental effects and operational expenses via building information modeling (BIM) for road infrastructure [27].

3. Problem Statement

Facility managers commonly encounter the issue of limited access to information. During the operational period of a facility, the availability of readily accessible information required for efficient processing of work orders is typically limited. Nevertheless, the full potential of BIM in facilitating the provision of comprehensive and superior information for facility management objectives has not yet been fully achieved. The primary obstacles to implementing BIM in FM activities are not technological in nature but stem from existing work processes and organizational structures, including issues such as the absence of well-defined roles and duties, as well as the lack of specific EIRs.

The process of exchanging information between BIM and FM systems is complex, and an adequate understanding of the specific requirements for using BIM in FM is currently lacking. Uncertainty about what information must be provided, when it should be provided, and who is responsible for providing it is included. Although numerous studies on BIM for FM have been conducted in recent years, only a limited number have thoroughly documented the entire process of developing and delivering asset information using BIM, adhering to predetermined information requirements, and exploring its implications for actual large-scale projects.

Furthermore, the interoperability of BIM and FM technologies is limited, mostly because of significant differences in their life cycles. Standardized data libraries and open systems are required. In Table 2, a comparison is made between the traditional approach to the facilities management of any building and the new approach using BIM and DT, especially for megaprojects.

Table 2. Traditional and new approaches in FM.

Title	Traditional Approach	Using BIM and Digital Twin
Information Accessibility	Description: relies on scattered and paper-based documentation, making it challenging to access comprehensive and up-to-date information about the building.	Description: BIM and digital twins provide a centralized repository of comprehensive and real-time information, improving accessibility for facility managers, maintenance teams, and stakeholders.
	Challenges: limited accessibility and potential for outdated information.	Advantages: enhanced access and real-time data updates.
Data Entry and Updates	Description: facility management involves manual data entry and updates, leading to errors, inconsistencies, and delays in reflecting changes in building configurations.	Description: automation with BIM and digital twins ensures that changes to the building are automatically updated, reducing manual data entry errors and ensuring data accuracy.
	Challenges: data inaccuracies and time-consuming processes.	Advantages: increased efficiency and reduced errors.
Collaboration and Communication	Description: isolated information and lack of collaboration between design, construction, and facility management teams.	Description: BIM fosters collaboration by providing a common platform for stakeholders to access and update information throughout the building's life cycle.
	Challenges: inefficiencies, miscommunication, and difficulty in sharing information.	Advantages: improved communication and efficient collaboration.
Maintenance Practices	Description: facility managers struggled with inefficient maintenance practices due to a lack of detailed and real-time information about the building's components.	Description: BIM and digital twins enable proactive and efficient maintenance practices by providing detailed information on the condition of building components.
	Challenges: reactive maintenance, and increased downtime.	Advantages: predictive maintenance and reduced downtime.
Analytical Capabilities	Description: the traditional method of analysis requires a lot of effort and many documents with the risk of human mistakes in drawing conclusions.	Description: BIM and digital twins enable advanced analytics, allowing facility managers to simulate, analyze, and optimize building performance.
	Challenges: hard to make a decision.	Advantages: improved decision making and optimization.
Life-Cycle Management	Description: lack of sufficient information on all stages of the project using one software application.	Description: BIM and digital twins support the entire life cycle of a building, from design and construction to operations and decommissioning.
	Challenges: ensuring a seamless flow of information across different phases can be challenging due to diverse data sources and formats.	Advantages: comprehensive life-cycle management and historical data access.
Cost Savings and Efficiency	Description: managing costs efficiently throughout the life cycle is challenging due to varying levels of human manpower and documentation methods used among stakeholders.	Description: the use of BIM and digital twins contributes to cost savings through improved operational efficiency, reduced downtime, and better-informed decision making.
	Challenges: limited ability to adapt to dynamic project conditions.	Advantages: increased cost-effectiveness and operational efficiency.
User Experience	Description: it is always hard to provide all stakeholders with a complete vision for the project in all stages.	Description: digital twins can enhance the overall user experience by personalizing building environments based on occupant preferences.
	Challenges: large amount of effort with less satisfaction.	Advantages: increased satisfaction and improved productivity.

4. Research Methodology

The primary research deficiency addressed in this study is the absence of data from actual examples concerning the creation and provision of asset information in BIM, specifically with regard to owner-specified information requirements. Specifically, there is a lack of a unified characterization of the process for delivering asset information. This includes information requirements, major activities, information flows, scope of each stakeholder, and tools used. Additionally, there is a lack of connectivity among the many difficulties highlighted in this process. The research aims and objectives are as follows:

1. Conduct an in-depth review of the current research to identify the challenges organizations encounter when implementing Building Information Modeling (BIM) to optimize Facility Management (FM) processes and maximize benefits.
2. Define the concept of a "digital trio" within the context of the role of Facilities Management (FMs) in the BIM process and explore how this framework can enhance organizational workflow and improve efficiency.
3. Develop an intuitive digital twin platform that seamlessly integrates BIM and IoT technologies to facilitate FM applications in buildings. Users can easily upload BIM models to foster the implementation of FM practices.
4. Design a user-friendly interface for a digital twin platform accessible to engineers and specialists. Provide scenario-based tools to address potentially critical situations encountered in various building environments.
5. Advocate for the early involvement of owners, operators, and vendors in projects using the digital trio framework and emphasize the collaborative creation of EIRs to preemptively mitigate challenges during the construction and operational phases.
6. Validate the digital twin platform with BIM/FM experts to refine and ensure its effectiveness.

Figure 1 illustrates the research methodology, which begins with reviewing the state of the art in previous research and analyzing the data, found in two databases, Web of Science and Scopus, on digital twins in the AEC-FM industry. Suitable filtration was applied using the VOS viewer for data analysis.

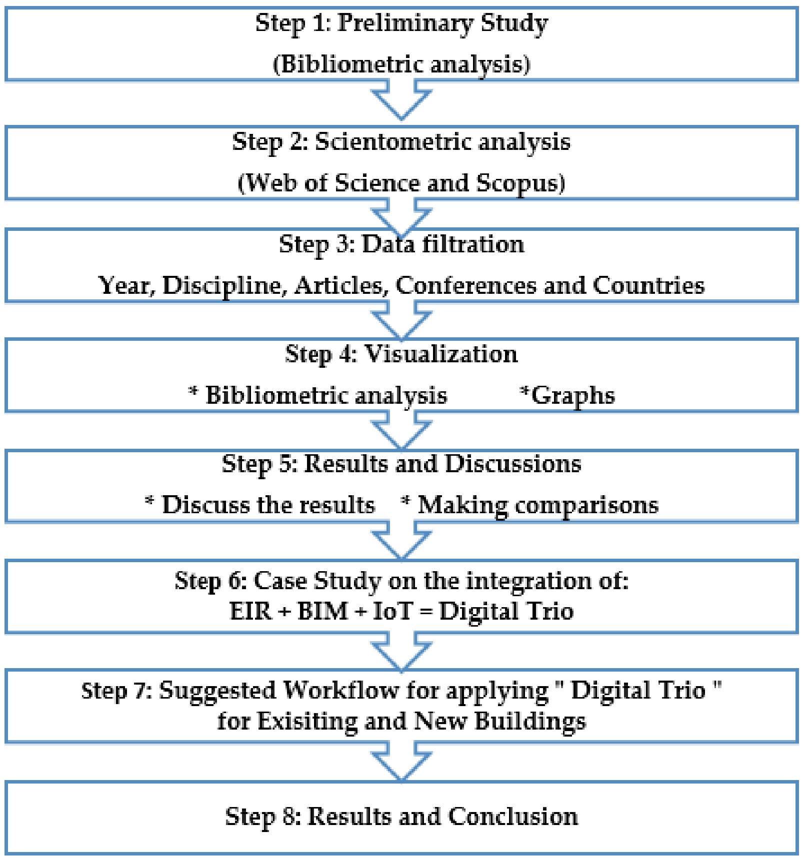

Figure 1. Research methodology.

Subsequently, a case study of a digital twin platform that integrates EIR, BIM, and IoT in the facility management of a city under the new concept of a "digital trio" is presented. This includes the involvement of operators and vendors at the project's inception. A roadmap for applying the digital trio workflow to both existing and new buildings is provided, followed by the results and conclusion.

4.1. BIM Process

Owing to the complete absence of well-established case studies and empirical evidence, the application of BIM in FM is viewed with uncertainty by stakeholders. Tangible empirical proof is required by facility managers to promote BIM to owners. In addition, the lack of endorsement for cost reductions in FM through BIM serves as an additional obstacle to its implementation.

4.1.1. Vendors' input into EIR

Lack of Technical Feasibility: The technical feasibility and limitations of software and tools, of which vendors possess deep knowledge, may not be considered if vendors are not included in an EIR's preparation. Requirements that are technically infeasible or inefficient may be set without their input, as follows:

- Suboptimal Tool Selection: The optimal selection of tools and software might not be made without vendor involvement. Vendors who are capable of advising on the most suitable solutions that can efficiently meet the demands of a project might offer more effective or economical alternatives;
- any FM platform: Critical insights into the alignment between a tool's capabilities and the requirements might be missing if vendors are excluded. Such exclusion can lead to misalignment, causing delays and increased costs owing to necessary adjustments or changes of tools during the project;
- Inefficient Workflows: Without vendor guidance during an EIR's preparation, workflows might be designed that are not optimized for the tools being used, leading to reduced efficiency and possibly affecting the quality of the project;
- Increased Risk of Noncompliance: The risk that specified standards and practices may not be fully supported by the software increases if vendors are not involved in drafting the EIR. Compliance issues may arise particularly if the software does not support certain standards or data formats.

To ensure the successful execution and delivery of a project, vendors must meticulously address a comprehensive array of technical requirements during the preparation of the EIR. By thoroughly preparing for these technical requirements in advance, vendors can ensure that they are well equipped to meet the project's demands, deliver high-quality results, and fulfill client expectations. This proactive approach enhances project outcomes and promotes a structured and efficient project execution process. In Table 3, explanations of the requirements and potential consequences and negative effects are provided, which make the use of the digital trio concept a must.

Table 3. Vendors' technical requirements and potential consequences.

Title	Technical Requirements in EIR	Consequences if Not Applied	Effect
Technical Documentation and Specifications	Prepare detailed technical documentation, including specifications, installation guides, user manuals, and maintenance instructions.	Misunderstandings, incorrect installations, and improper use of systems.	Increased errors, higher maintenance costs, extended project timelines, and reduced overall project quality.
BIM Compliance and Standards	Ensure all deliverables comply with relevant BIM standards such as ISO 19650 [28]. Develop BIM models that meet the specified level of detail (LOD) and level of information (LOI).	Inconsistent and incompatible data and coordination issues.	Project delays, cost overruns, potential rework due to misaligned models and information.

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Table 3. *Cont.*

Title	Technical Requirements in EIR	Consequences if Not Applied	Effect
Data Management and Exchange	Establish protocols for data management, including naming conventions, file formats (e.g., IFC and COBie), and data exchange procedures. Set up a common data environment (CDE) for collaboration and data sharing.	Data loss, inconsistencies, and difficulty in data retrieval.	Inefficient project execution, miscommunication among stakeholders, and potential legal disputes over data discrepancies.
Quality Assurance and Control	Implement a quality assurance plan with procedures for verifying the accuracy and completeness of deliverables. Conduct model-checking and clash detection processes to ensure data integrity.	Defects and errors can go unnoticed until the late stages of the project.	Increased rework, compromised project integrity, higher costs, and diminished client satisfaction.
Security and Data Protection	Implement measures for data security, including encryption, access control, and secure data transfer methods. Ensure compliance with data protection regulations.	Data breaches and unauthorized access to sensitive information.	Legal penalties, loss of client trust, financial losses, and potential project termination.
Software and Tools	Confirm the availability and compatibility of all software tools and platforms to be used. Ensure team proficiency with the required software.	Incompatible or outdated software can hinder collaboration and data exchange.	Reduced productivity, increased likelihood of errors, and project delays.
Integration and Interoperability	Prepare for integration with existing systems and infrastructure. Ensure the interoperability of software and hardware components through standardized interfaces and protocols.	Siloed systems and data fragmentation.	Inefficient workflows, increased manual intervention, and higher operational costs.
Training and Competency	Conduct training programs for team members to ensure proficiency in required tools and methodologies. Prepare training materials and schedules for project stakeholders.	Improper use of tools and technologies, reducing overall project efficiency.	Increased error rates, lower productivity, and potential safety hazards.
Project Planning and Scheduling	Develop a detailed project plan including timelines, milestones, and resource allocation. Use project management tools to track progress and manage tasks.	Unrealistic timelines, resource conflicts, and missed deadlines.	Project delays, cost overruns, diminished project quality and stakeholder satisfaction.
Communication and Collaboration	Set up communication channels and collaboration platforms for efficient coordination with stakeholders. Define roles and responsibilities and establish protocols for issue resolution and decision making.	Misunderstandings and misalignment among project stakeholders.	Increased conflicts, duplicated efforts, and inefficient project execution
Hardware and Infrastructure	Ensure the availability of necessary hardware, such as workstations, servers, and networking equipment. Verify the hardware's performance requirements for the software and tasks.	Performance bottlenecks and inability to run necessary software.	Reduced efficiency, increased downtime, and potential project delays.
Regulatory Compliance	Ensure all deliverables and processes comply with relevant industry standards, codes, and regulations. Obtain the necessary certifications and approvals before starting the project.	Legal issues and project halts.	Legal penalties, increased costs for modifications, and damage to reputation.
Risk Management	Identify potential risks and develop mitigation plans. Continuously monitor and manage risks throughout the project life cycle.	Unforeseen issues and crises during the project.	Project delays, cost overruns, and potential project failure.
Support and Maintenance	Establish a plan for ongoing technical support and maintenance services. Ensure availability of support staff and resources for issue resolution.	Unresolved technical issues and system downtimes.	Increased operational disruptions, higher maintenance costs, and decreased system reliability.
Environmental and Sustainability Considerations	Implement practices supporting environmental sustainability, such as waste reduction and energy efficiency. Prepare documentation to support environmental assessments and compliance with sustainability.	Environmental damage and noncompliance with regulations.	Legal penalties, increased operational costs, and negative impact on the company's reputation and social responsibility goals.

4.1.2. Use of FM in AEC and by Owners

After reviewing expert opinions and visions, a clear misunderstanding was found among the stakeholders on projects, as follows:

- Design firms often perceive BIM as a tool for issuing schematics and drawing detailed designs. This limited perspective results in the minimal use of BIM technology postconstruction during the operational stage, often without coordination. During the design process, equipment data are unavailable until the project is awarded to a contractor, preventing designers from applying real dimensions or tagging the final information on all elements.
- In most construction companies and projects, BIM is utilized only when mandated by the owner, owing to insufficient awareness of BIM among the team or management. Furthermore, a well-prepared BIM model is required before construction work commences, necessitating a considerable time investment, particularly at the outset of the project. Project managers often resort to using 2D tools to accelerate site progress during critical phases; however, this leads to numerous coordination issues, resulting in wasted time and increased costs.
- Owners play a critical role in implementing BIM in projects and should envision its use during the operational phase. However, many projects lack the preparation of the Employer's Information Requirements (EIR) before initiation, leading to a misalignment of the vision for using BIM in facility management. Often, owners assign project managers who lack experience in and understanding of BIM, causing the project to lose its full benefits.
- The operators responsible for asset usage have a significant influence on a project's alignment with their requirements. Frequently, owners negotiate with operators during the construction phase, missing the benefits that could be gained if the operators' requirements and vision are incorporated from the beginning.

4.1.3. Using FM in Operations and Maintenance

In building operations and maintenance (O&M) management, the decision to utilize BIM technology is influenced by the progress of the operational team, as well as by the asset owners and the recruited management personnel. Should the building operator decide to implement Building Information Modeling (BIM) technology for O&M, a substantial capital investment is necessary to achieve cost savings and enhance efficiency in the O&M process, deviating from conventional building O&M approaches.

4.1.4. Quality of BIM Models

Upon project completion, owners face the challenge of evaluating the informational quality of BIM models for facility management. Inaccuracies in BIM are significant issues when owners begin to use as-built models received from contractors. Health checks of these models often show less than 50% of the required quality for use in operations and maintenance, frequently lacking the application of the actual material submittals and equipment used in the project.

4.1.5. Contractual Framework Among Stakeholders

The deployment of BIM presents contractual challenges, particularly when it comes to integrating FM and BIM. There is an urgent need to develop BIM for FM specifications and terms in contracts with the functions and needs of FM and O&M. The traditional contract terms should be revised to match the deliverable FM-BIM, especially when using IOT in the operations stage. This prevents wasting time and effort. Clear terms in any contract should specify all requirements in the BIM execution plan.

4.1.6. Cost

A common misconception is that BIM is more expensive and time-consuming for all projects. However, while 3D models require a significant time investment at the outset of the project, they ultimately save time and effort compared to 2D models. Although 2D models may initially seem faster to produce, they often lead to coordination issues and site progress delays, resulting in costs that exceed the expected budget. The capabilities of the manpower and management vision of all stakeholders directly influence the time and cost of BIM use in any project.

4.1.7. Economic Situation

The protracted conflict in Ukraine has diminished the prospects for growing and developing economies for a post pandemic economic rebound. Construction enterprises have experienced a substantial rise in operating costs due to the situation in Ukraine, characterized by soaring gasoline prices and heightened material expenses.

Supply chains, which were already experiencing considerable disruptions due to the global pandemic, have been further destabilized by the conflict in Ukraine. As a result, costs have increased, shortages of goods and project timeframes have been extended, often by a large amount. The disruption of transportation routes and lack of international collaboration could have a significant impact, leading to more disruptions in the supply chain. The availability of materials and equipment leads to many changes in the design and construction process, which makes it more difficult to prepare a complete vision for the procurement of the required equipment and materials, directly influencing the FM.

Tracking technology has attracted the attention of researchers for several years, especially after COVID-19. Many researchers have emphasized the benefits of using BIM technology in the construction industry. This study aims to establish an integrated tracking system to analyze workers' workplace behavior using a BIM environment.

5. Bibliometric Review of the Research

A co-occurrence keyword analysis was conducted using both the authors' keywords and index terms. The analysis was based on the bibliographic data obtained from the Scopus database. The map consists of labels linked to circles, and the dimensions of both are contingent upon the weight of the object, with certain dimensions being concealed to prevent overlap. Every object is presented with a distinct color that indicates the cluster to which it is associated.

After applying the VOS model to the Web of Science's publications, the data were cleaned to ensure the semantic meaning of the keywords. The VOS viewer graph illustrates the evolving academic discourse in Building Information Modeling (BIM), with a notable increase in the emphasis on the integration of "digital twin" and "facility management" in recent years.

The timeline, indicated by the color gradient, shows the progression of the research focus from August 2021 to April 2022, with warmer colors representing more recent contributions.

Key terms, such as "digital twin", "facility management", "BIM", and "integration", are interconnected with robust lines, indicating strong and growing relationships among these concepts. The node for "digital twin" is closely aligned with "BIM", signifying digital twin's rising importance as a method of virtual representation in BIM processes, as shown in Figure 2.

With VOSviewer, overlay visualization was performed for the individuation of the average publication year of the DB's material, as shown in Figure 3. The visualization is similar to the network visualization but differs in the items' colors. In this case, each item is associated with the color of its average publication year. The map confirms the increases in the words' occurrences in recent years, particularly in 2021 and 2022 [26].

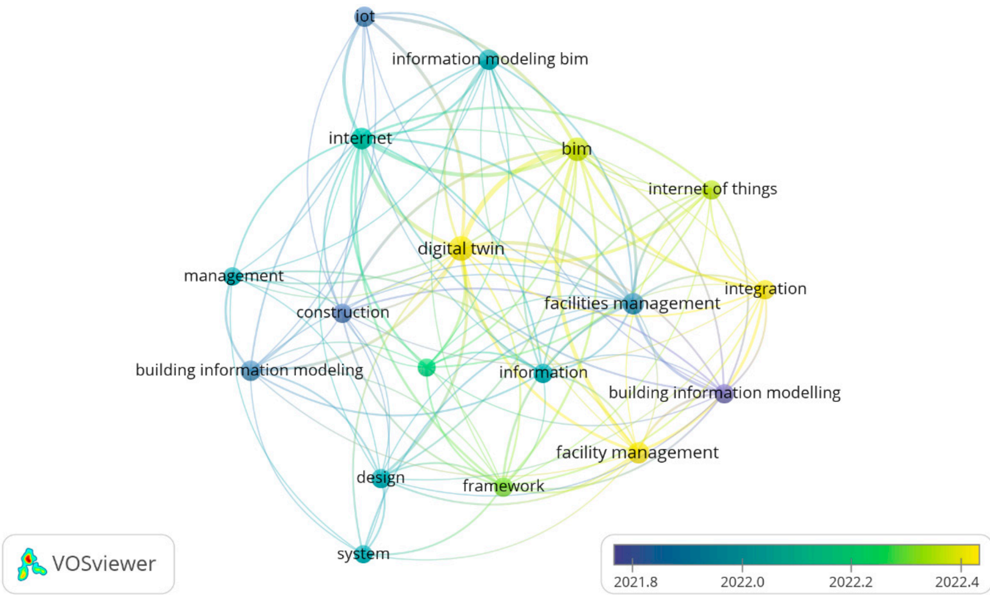

Figure 2. Keywords network map analysis.

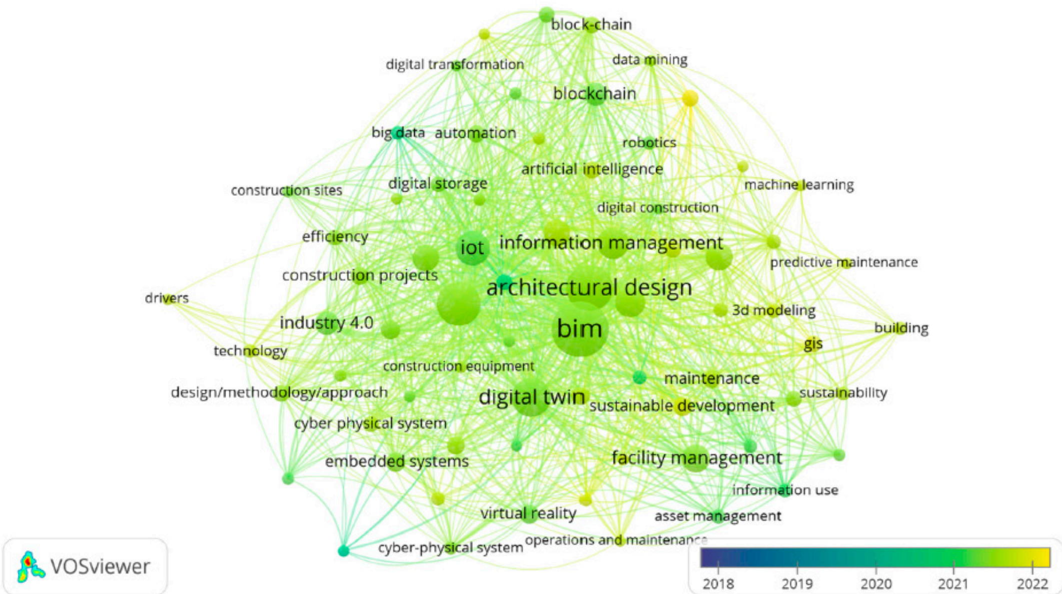

Figure 3. Co-occurrence network map temporal overlay performed with VOSviewer.

6. Case Study

A case study was prepared for the megaproject "New Administrative Capital" in Egypt. The proposed city is situated 45 km (28 miles) east of Cairo, adjacent to the Second Greater Cairo Ring Road, in a predominantly undeveloped region halfway to the maritime city of Suez. According to the proposed designs, the city will serve as Egypt's new administrative and financial hub, accommodating primary government offices, ministries, and foreign embassies. With a total area of 700 square kilometers (270 sq. mi), the population of this region is currently 6.5 million people, but this is projected to potentially reach 7 million. The project consists of residential, commercial, entertainment, and administrative buildings in addition to infrastructure and landscape works.

The main aim is to prepare a platform that collects data, via connected sensors, on targeted, required activities occurring in compounds or cities to observe, monitor, and control any issues that might be faced or lead to problems that might cause danger to either life or property.

Sensors were positioned in selected areas and connected with the Scada system's control room by programming the reads from the screens that appear on the platform through gauges and numbers.

The platform, as shown in Figure 4, also connects the BIM model LOD500, which contains the data of each machine and instrument, with the Scada system and integrates all follow-up data into the 3D model to show the location of any problems using warning messages if the reading from a sensor exceeds the limit, which help users deal with the warning according to the protocol for each situation.

Figure 4. Digital Trio platform interface.

6.1. Digital Trio Platform

The main aim is to prepare a web platform that collects data from vendors, consultants, and operators and that will be connected to sensors on targeted, required activities operating in compounds or cities to monitor, track, and control any issues that might arise or lead to problems that could endanger life or property. Figure 5 explains the process of integration among stakeholder through the digital trio platform to control all required parameters.

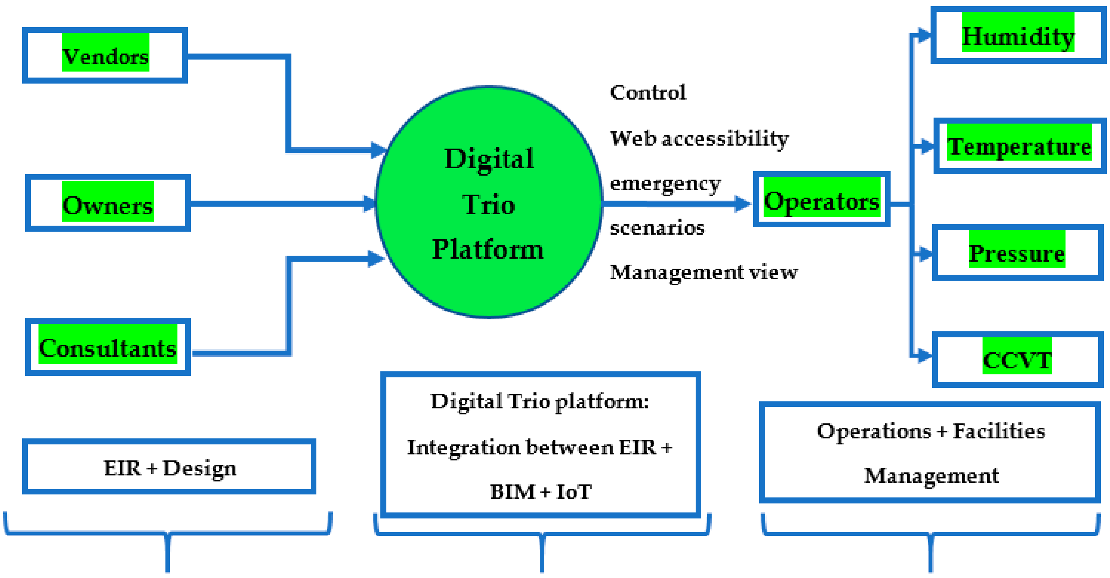

Figure 5. Digital trio process.

6.2. Humidity

As illustrated in Figure 6, the integration of sensors in main halls with the platform's interface to conduct humidity measurements is crucial in large-scale buildings. The left section of the platform displays the sensor locations, allowing for the real-time monitoring of humidity levels. This setup is essential for preventing issues such as condensation, mold growth, mildew, staining, slippery surfaces, and the deterioration of equipment and building materials. Effective humidity management ensures the structural integrity of buildings and reduces maintenance costs. The integration of sensors with a humidity measurement platform is particularly important in large-scale buildings for the following reasons.

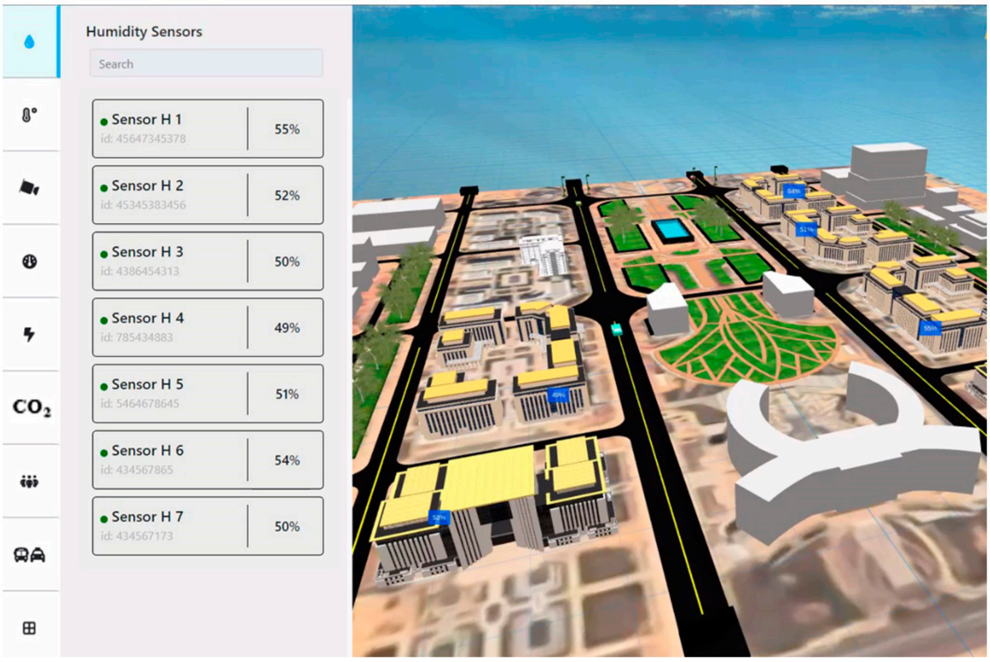

Figure 6. Digital trio platform interface for humidity.

- Indoor Air Quality (IAQ): Proper humidity control is crucial for maintaining good indoor air quality. It helps prevent conditions that can lead to health issues, such as mold growth and proliferation of allergens;
- Comfort and Occupant Well-Being: Maintaining optimal humidity levels enhances occupant comfort and well-being. Appropriate humidity levels can prevent respiratory issues, skin irritation, and other health problems caused by excessively dry or humid conditions;
- Energy Efficiency: Humidity control can improve the efficiency of HVAC systems. HVAC systems can operate more effectively by maintaining appropriate humidity levels, leading to energy savings and lower operational costs;
- Quality Preservation of Stored Products: For moisture-sensitive products, such as food and beverages, pharmaceuticals, and electronics, monitoring humidity levels is essential to prevent degradation and ensure quality preservation;
- System Performance and Maintenance: Continuous humidity monitoring helps identify potential issues with HVAC and other environmental control systems. The early detection of abnormal humidity levels can prompt timely maintenance, prevent significant problems, and extend the lifespan of equipment;
- Regulatory Compliance: In specific environments, such as healthcare facilities, laboratories, and food storage areas, humidity control is necessary to meet regulatory standards. Proper monitoring ensures compliance and protects the integrity of stored goods and processes;

- Data-Driven Decision Making: collecting and analyzing humidity data provide valuable insights into environmental conditions, helping building managers make informed decisions about system adjustments, maintenance schedules, and potential building modifications.

6.3. Temperature

Measuring the temperature within a building is a critical task requiring immediate attention. Figure 7 presents the platform interface, featuring gauges connected to sensors placed at strategic locations throughout the building. This system offers several benefits, including enhanced comfort, improved energy efficiency, and overall optimization of building performance. The key benefits of temperature measurement in buildings include the following:

- Comfort and Occupant Well-Being: monitoring indoor temperature ensures comfortable environments for occupants and enhances their well-being;
- Energy Efficiency: Temperature measurements are vital for energy conservation. Analyzing temperature data helps identify HVAC inefficiencies, optimize settings, and implement energy-savings strategies, resulting in cost savings and environmental benefits;
- HVAC System Performance: monitoring temperature variations allows for the early detection of HVAC issues, such as inadequate airflow or equipment malfunctions, enabling timely maintenance and improving system performance and equipment lifespan;
- Indoor Air Quality (IAQ) Management: temperature control affects humidity levels and indoor air quality, helping to prevent condensation and mold growth;
- Data-Driven Optimization: analyzing temperature data over time reveals patterns and trends, enabling energy savings, optimizing equipment schedules, and assessing building modifications;
- Regulatory Compliance: In regulated environments such as healthcare facilities and laboratories, temperature monitoring ensures compliance with standards, safeguarding stored goods and sensitive processes.

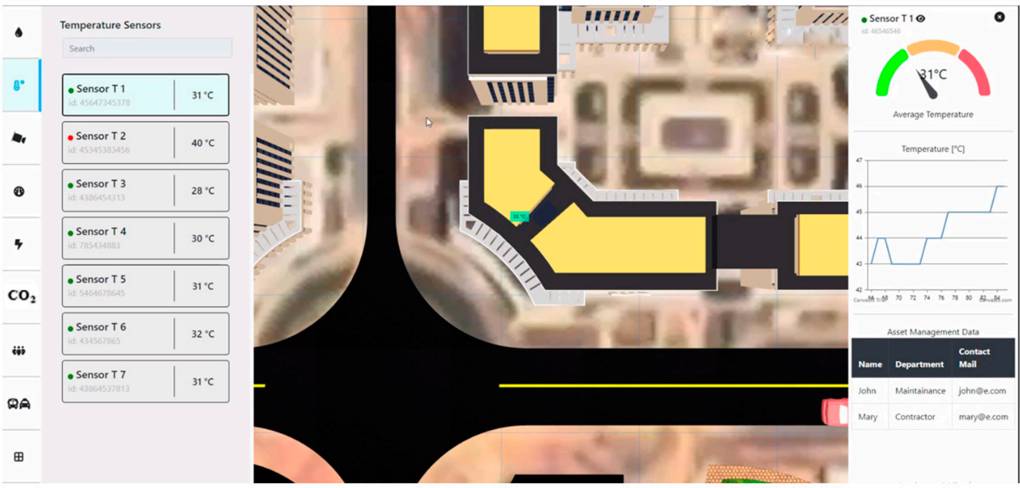

Figure 7. Digital trio platform interface for temperature measurements.

6.4. Pressure

Pressure measurements in infrastructure are critical for ensuring system performance, safety, regulatory compliance, leakage detection, system balancing, equipment maintenance, and effective system design. As depicted in Figure 8, comprehensive network control facilitated by sensors that provide necessary readings is particularly valuable for detecting hidden issues, especially underground. The following points summarize the importance of monitoring pressure in any urban infrastructure.

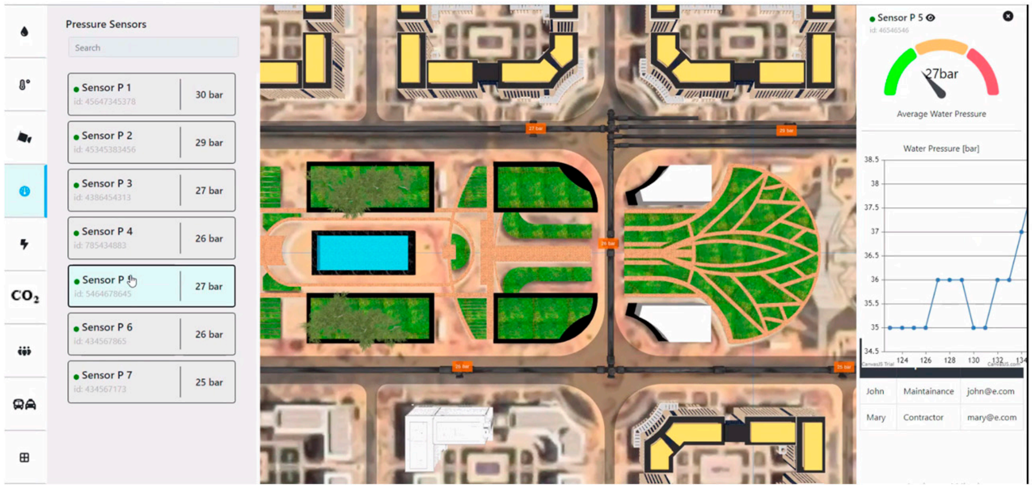

Figure 8. Digital trio platform interface for pressure measurements.

- System Performance: pressure measurement helps assess the efficiency and functionality of fluid or gas flow in infrastructure systems;
- Safety: monitoring pressure levels helps to prevent equipment failures, leaks, bursts, and other hazardous situations;
- Compliance: pressure measurement ensures adherence to regulatory standards and requirements;
- Leakage Detection: monitoring pressure drops helps detect and locate leaks, conserve resources, and reduce the environmental impact;
- System Balancing: pressure measurement allows for optimal pressure levels across different zones, improving system performance and energy efficiency;
- Equipment Maintenance: pressure monitoring helps identify abnormal variations, enabling timely maintenance and preventing equipment failure;
- System Design: accurate pressure measurements can inform infrastructure design and planning for effective system operations and reliability.

6.5. CCTV

One of the primary functions of the digital trio platform is to monitor every hall, place, and street within a city and detect issues, such as fights, fires, or car accidents, using controlled cameras that record all activities. As depicted in Figure 9, the platform enhances the security, safety, operational efficiency, and incident response capabilities in buildings by providing real-time surveillance. The right section of the platform interface displays live camera feeds from targeted locations, enabling comprehensive monitoring. The key functions of implementing CCTV control within the platform are as follows:

- Crime Deterrence and Prevention: the presence of visible CCTV cameras acts as a deterrent for potential offenders, thereby decreasing incidences of theft, vandalism, and unauthorized entry;
- Incident Detection and Response: CCTV cameras provide continuous real-time surveillance, enabling immediate detection of security breaches;
- Evidence Collection and Investigation: recorded CCTV footage is crucial for investigating incidents or criminal activities, assisting in the identification of involved individuals, reconstructing the sequence of events, and supporting law enforcement and security teams;
- Safety and Emergency Management: CCTV systems monitor areas susceptible to accidents or safety risks, such as fire-prone zones or overcrowded spaces, aiding in timely

responses, efficient crowd management during emergencies, and safe evacuation of occupants;

- Operational Monitoring and Efficiency: CCTV cameras can observe operational processes, allowing for the identification of areas requiring improvement. By analyzing traffic patterns and observing key locations, building managers can optimize staffing, streamline operations, and improve customer service;
- Remote Monitoring and Control: Many CCTV systems offer remote access capabilities, facilitating surveillance and control from a central location or via mobile devices. This enhances proactive surveillance, enables rapid response, and allows for the simultaneous monitoring of multiple sites;
- Loss Prevention and Asset Protection: CCTV surveillance is instrumental in protecting valuable assets, equipment, and inventory by monitoring sensitive areas to detect and deter theft, unauthorized access, or tampering, thereby reducing financial losses and ensuring asset security;
- Liability and Risk Management: CCTV footage provides objective evidence in liability disputes or potential legal claims, helping to establish the sequence of events, providing accurate information, and safeguarding the interests of the building management and occupants involved.

Figure 9. Digital trio platform interface for CCTV.

7. Results and Discussions

Following the explanation of the benefits of utilizing the digital twin platform, a roadmap for two building cases—an existing governmental building and a new building—is presented. The platform's user-friendly interface allows for comprehensive control by management and administrative teams for both types of buildings. This capability presents a significant opportunity to enhance building performance and reduce the running costs.

7.1. Road Map to Apply the Digital Trio Platform in Existing or New Buildings

7.1.1. Methodology for Preparing the Digital Trio Platform for Existing (Governmental) Buildings

It is well recognized that while the application of digital twins in the facility management of governmental buildings or any existing building offers many benefits, there are also major challenges that need to be addressed for its successful implementation. Some of the main challenges are listed in Table 4.

Table 4. Challenges in applying a DT platform in an old building.

No	Challenge	Description
1	Old Buildings	Many of governmental offices are established in old buildings that were used for another purpose, which means that there are no full data available, like plans, equipment catalogs, and information on assets.
2	Data Integration	Inefficient project execution, miscommunication among stakeholders, and potential legal disputes over data discrepancies.
3	Data Integration	Governmental buildings often have various systems and equipment from different manufacturers and vendors. Integrating all data from different sources into one digital twin platform can be very hard and requires standardized of data formats and protocols.
4	Accuracy and Quality of Data	The accuracy of the digital twin model depends on the quality of the data input. Inaccurate or outdated data can lead to building a wrong vision and making poor decisions. Ensuring data accuracy and arranging documents is a challenge, especially when dealing with legacy systems.
5	Initial Setup and Cost	Creating a comprehensive digital twin model requires a significantly huge investment in terms of technology, sensors, data collection infrastructure, and software development. Governmental budgets and procurement processes might pose challenges in acquiring the necessary resources.
6	Technical Expertise	Developing and maintaining a digital twin platform requires expertise in fields such as IoT, data analytics, software development, and building systems. Government agencies might face challenges in recruiting or training staff with the required skills.
7	Data Privacy and Security	Government buildings often house sensitive information, and ensuring data privacy and security in the digital twin environment is crucial. Implementing robust cybersecurity measures to protect both the physical and virtual aspects of a building is challenging.
8	Interoperability	Digital twins may need to interact with other systems and databases within the governmental organization. Ensuring that the digital twin platform is compatible and can seamlessly integrate with existing systems can be challenging due to differing technologies and protocols.
9	Scalability	Governmental organizations often manage multiple buildings across various locations. Scaling a digital twin platform to cover a wide range of buildings while maintaining consistency and efficiency can be challenging.
10	Change Management	Implementing a digital twin platform requires a shift in workflows and processes. Employees may resist change or require training to adapt to the new technology, which can pose challenges to adoption.
11	Regulatory Compliance	Government buildings must adhere to various regulations and standards. Integrating these compliance requirements into the digital twin model and ensuring ongoing compliance monitoring can be complex.
12	Maintenance and Updates	Digital twin platforms require ongoing maintenance and updates to ensure they remain accurate and aligned with real-world changes. Ensuring regular updates without disrupting operations can be challenging.
13	Vendor Lock-In	Depending on third-party vendors for digital twin solutions can lead to vendor lock-in, limiting flexibility and potentially increasing costs in the long run.
14	Return on Investment (ROI) Demonstrations	Establishing a clear ROI for digital twin implementations can be challenging, especially when the benefits may be realized over the long term or are difficult to quantify directly.

Addressing these challenges requires careful planning, collaboration among different stakeholders, continuous training, and commitment to embracing technological advancements in facility management. While challenges exist, the potential benefits of using digital twins in existing building management make this effort worthwhile.

Creating a digital trio for existing governmental buildings involves several key steps and considerations, including data acquisition, modeling, and integration with existing systems. The following is a more detailed explanation of each of these aspects:

- Data Acquisition and Data Sources: identify the various data sources that will be used to create the digital trio platform. These include sensors, IoT devices, historical data, BIM data, and geographic information system (GIS) data;
- Sensor Deployment: sensors and data collection devices are installed in the building to gather real-time data. These sensors include temperature sensors, humidity sensors, occupancy sensors, and security cameras;
- Data Quality: Ensure data quality by regularly calibrating and maintaining the sensors. Inaccurate or inconsistent data can lead to errors in digital trio platforms;
- Data Types: collect data on various aspects of the building, such as temperature, humidity, energy consumption, occupancy, structural data, and security data;
- Data Security and Privacy: address data security and privacy concerns by implementing encryption, access control, and compliance with relevant regulations;
- Data Modeling: if available, incorporate BIM data, which provide a detailed 3D model of the building's architecture, infrastructure, and systems. This can serve as a foundational element of digital trio platforms;
- Semantic Modeling: create a semantic model that represents the components, systems, and relationships within a building. This involves defining the ontology and taxonomy of the DT;
- Time-Series Data: handle time-series data for monitoring and predictive analytics. This includes historical data and real-time data streaming from sensors;
- Machine Learning and AI: Implementation of machine learning algorithms and artificial intelligence for data analysis and predictive capabilities, for example, predictive maintenance models can help anticipate when equipment fails;
- Visualization: develop a user-friendly interface for visualizing the digital trio. This may include 3D models, dashboards, and data visualizations.

Figure 10 shows the procedures for applying the DT platform's workflow to existing buildings. In summary, the integration of a digital twin platform in an existing building can provide full control of the FM as follows:

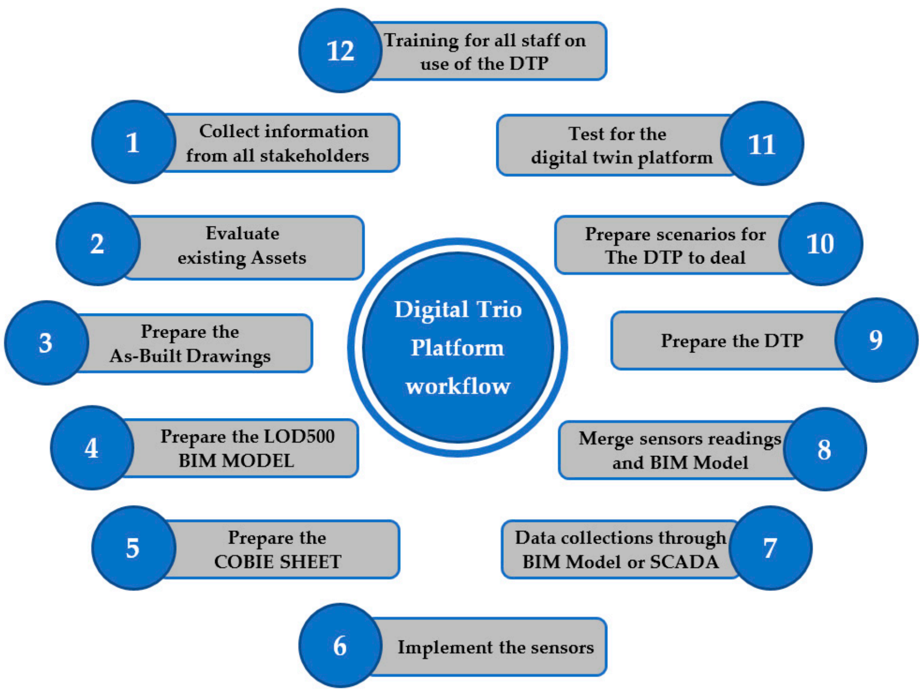

Figure 10. Digital trio platform's workflow for existing building.

7.1.2. Methodology for Preparing a Digital Trio Platform for New Buildings

Applying a facility management digital trio platform in a new building is generally easier than in an existing building for several reasons, as follows:

- Design Integration: new buildings are often designed using digital tools that can be easily integrated with a digital trio platform. This means that the digital trio can be developed alongside the building using the same models and data used for construction;
- Sensor Integration: in a new building, the sensors and IoT devices necessary for a digital trio can be included in the design and built into the structure. This seamless integration ensured comprehensive data collection from the start;
- Data Availability: for a digital trio to be effective, it requires data. New buildings can be designed to collect and feed data into a digital twin from day one;
- Technological Compatibility: New buildings can be constructed using the latest technology to ensure compatibility with modern digital trio platforms;
- Planning and Budgeting: When a digital trio is part of the original plan for a new building, it can be budgeted and implemented in the most efficient way;
- Customization and Optimization: With new construction, the digital trio can be customized and optimized during the design phase, ensuring that it meets all the specific needs of the building;
- Regulatory Compliance: New buildings will be designed to comply with current regulations, including those that may relate to digital systems and data handling.

Figure 11 shows the procedures for applying the DT platform's workflow to new construction. In summary, the integration of a digital twin platform in a new building can be more straightforward, as it can be planned and implemented from the ground up, whereas retrofitting an existing building to accommodate such technology can be more challenging and resource-intensive.

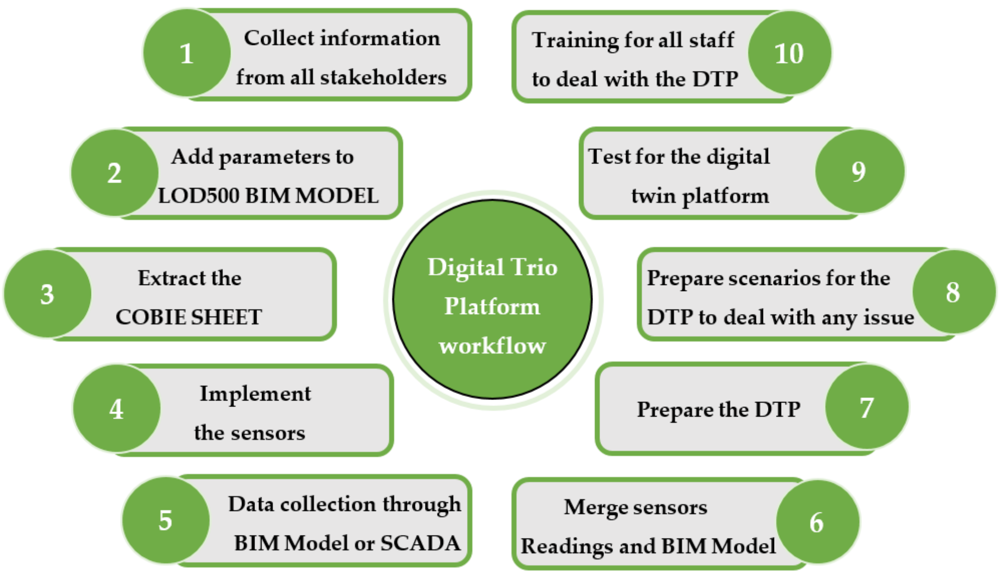

Figure 11. Digital trio platform's workflow for a new building.

7.2. Framework for Establishing DT

The new vision for the digital trio emphasizes the early involvement of operators in projects, as shown in Figure 12, even before the owner makes a selection. It advocates for the inclusion of a specialist in the preparation of the Employer's Information Requirements (EIR) and the Building Execution Plan (BXP) prior to the conceptual stage. This proactive approach aims to prevent the shock of necessary changes to meet operator requirements post-construction, a situation that traditionally occurs toward the end of a project.

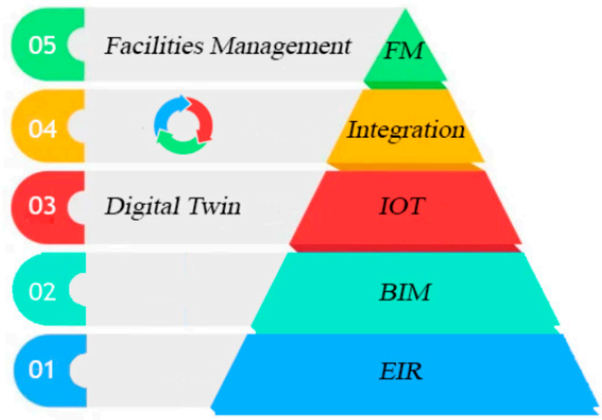

Figure 12. Digital trio chart.

Figure 13 is the proposed workflow diagram and illustrates the research methodology for the implementation of a digital twin in facility management, specifically within the context of BIM, as follows:

- Owner/Operator: This is with whom the process starts, likely with the building's owner or operator identifying the need for a digital twin and initiating the process;
- Collect Survey Results: The first task is to collect survey results, which could refer to the collection of data on the current state of the building or facility;
- Specify the Main Gaps: on the basis of the survey results, the main gaps in information or performance are identified. This is a critical step in understanding what needs to be addressed using the digital twin;
- EIR: As a result of identifying gaps, improvements are made to the EIR, which dictate what information needs to be collected and exchanged throughout the process;
- BXP BIM Execution Plan and DBIM Models: a consultant then develops a BIM Execution Plan (BXP) and Detailed BIM (DBIM) models. This involves planning how the BIM process will unfold and creating detailed building models;
- 3D Coordinated Model and As-Built Model: the contractor, possibly with the help of specialized subcontractors, uses the execution plan and models to create a 3D coordinated model of the building as it is to be built (or as it exists, in the case of an existing building);
- AIM (Asset Information Model): the Asset Information Model (AIM) is developed, which contains detailed information about the assets within the building and is crucial for the management of the facility;
- IoT: IoT plays a role in this workflow by providing a network of sensors and devices that collect real-time data from the building;
- Digital Twin: This is the culmination of the previous steps, whereby AIM and IoT are combined to form the digital twin, a virtual representation of the physical building that is dynamic and data-rich;
- Facilities Management with Smart Automated Operation: Finally, the digital twin is used for advanced facilities management, enabling smart automated operations of the building systems, likely aimed at improving efficiency, reducing costs, and enhancing user experience within the building.

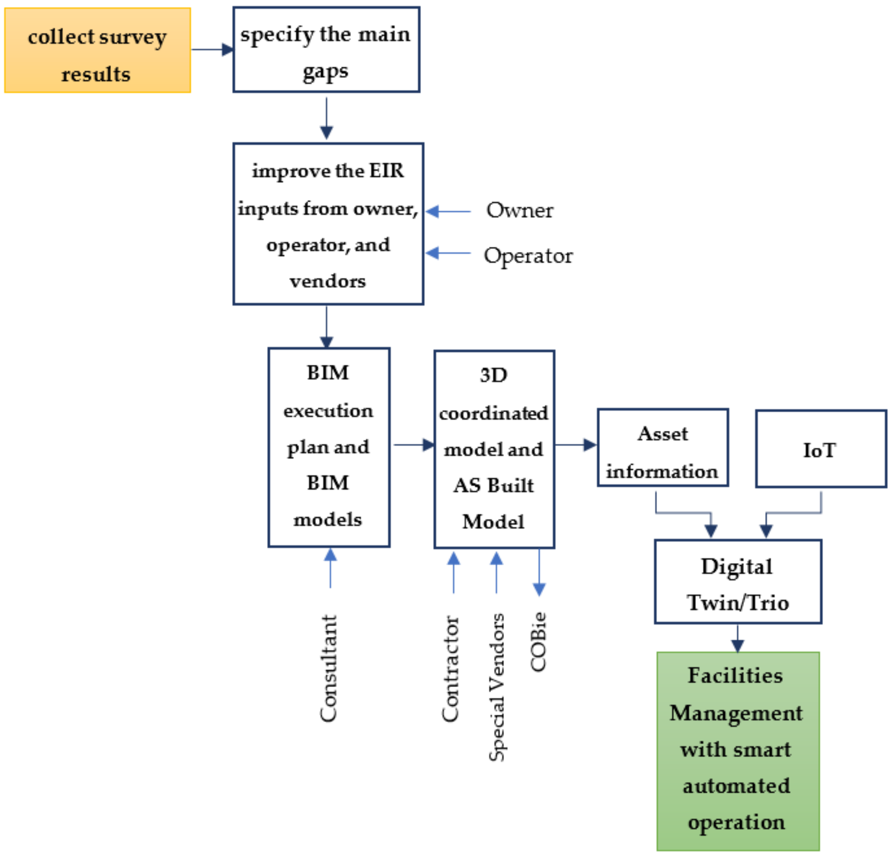

Figure 13. Digital trio workflow.

7.3. Methodology for Assessing Building Conditions [29,30]

The methodology for assessing building conditions using digital twin technology involves a systematic and comprehensive approach to gathering, analyzing, and utilizing data for the creation of a detailed virtual model of a building. This methodology includes several phases: pre-assessment preparation, data collection, digital twin model creation, data analysis, reporting, and continuous monitoring.

1. Pre-Assessment Preparation
    - Objective Definition: clearly define the objectives of the assessment, such as identifying structural issues, improving energy efficiency, and planning maintenance activities;
    - Team Assembly: form a multidisciplinary team of experts, including structural engineers, architects, IT specialists, and facility managers;
    - Documentation Review: review existing building documentation, such as architectural drawings, maintenance records, and previous inspection reports, to establish a baseline understanding of the building.
2. Data Collection
    - Sensor Deployment: Install sensors and IoT devices throughout the building to collect real-time data on structural health, environmental conditions, and energy consumption;
    - Nondestructive Testing (NDT): use nondestructive testing techniques, such as infrared thermography, ultrasonic testing, and ground-penetrating radar, to assess hidden conditions without causing damage;
    - 3D Laser Scanning: conduct 3D laser scanning to capture precise geometrical data of the building's physical structure;
    - Drone Surveys: utilize drones for aerial surveys to capture data on hard-to-reach areas, such as rooftops and facades;

- Material Sampling and Laboratory Testing: collect samples of building materials for laboratory analysis to determine their condition and properties.

3. Digital Twin Model Creation
    - Data Integration: integrate all collected data, including sensor data, 3D laser scans, drone surveys, and laboratory results, into a unified digital platform;
    - Model Development: develop the digital twin model using advanced software tools that create a dynamic and interactive virtual representation of the building;
    - Calibration: calibrate the digital twin model to ensure it accurately reflects the real-world conditions and behaviors of the building.
4. Data Analysis
    - Structural Analysis: analyze structural data to assess the integrity and performance of the building's components, identifying any weaknesses or potential failure points;
    - Energy Efficiency Evaluation: evaluate energy consumption patterns and identify areas for improving energy efficiency within the building;
    - Predictive Maintenance: use the digital twin model to simulate and predict the performance of building systems, enabling proactive maintenance planning.
5. Reporting
    - Comprehensive Report: compile a detailed report summarizing the findings from the digital twin analysis, including visual documentation, data analysis results, and condition ratings;
    - Recommendations: provide actionable recommendations for maintenance, repair, or replacement of building components, prioritized on the basis of urgency and impact;
    - Cost Estimates: include preliminary cost estimates for the recommended actions to assist in budgeting and planning.
6. Continuous Monitoring
    - Real-Time Monitoring: continuously monitor the building's condition through the integrated sensors and IoT devices, updating the digital twin model in real time.
    - Performance Tracking: track the performance of building systems and components over time to identify trends and potential issues early.
    - Periodic Re-Assessments: conduct periodic re-assessments using the digital twin model to update the building condition information and adjust maintenance plans as needed.
    - By following this comprehensive methodology, the assessment of building conditions using digital twin technology can provide accurate, real-time insights, enabling informed decision making and efficient maintenance planning. This approach ensures the safety, functionality, and sustainability of the building throughout its life cycle.

7.4. Potential Limitations of Using Digital Twins

The implementation of digital twin technology presents several limitations that must be considered, as follows:

- High Initial Costs: The deployment of digital twin technology involves substantial initial investments in software, hardware, and skilled labor, which can be prohibitive for smaller organizations.
- Data Security and Privacy: The reliance on extensive data raises significant concerns regarding data security and privacy, necessitating robust measures to protect sensitive information from cyber threats and ensure regulatory compliance.

- Integration Complexity: Integrating digital twins with existing systems and processes is complex and often time-consuming, requiring compatibility and interoperability across various platforms and legacy systems.
- Data Management Demands: Effective implementation requires comprehensive data management capabilities to handle large volumes of data, maintain accuracy, and ensure real-time updates.
- Technical Expertise: The development and maintenance of digital twins demand specialized technical expertise, posing challenges in recruiting and training qualified personnel.
- Scalability: Scaling digital twin solutions for large or complex projects is challenging due to increased data processing, storage, and analysis requirements.
- Real-Time Data Processing: Ensuring real-time data processing and analysis is critical but challenging, especially for applications requiring instantaneous decision making.
- Model Accuracy: The effectiveness of digital twins depends on the accuracy and reliability of the data and models, with inaccuracies potentially leading to incorrect insights and decisions.
- Organizational Resistance: Adopting digital twin technology often necessitates significant changes to workflows and processes, which can encounter resistance within organizations.
- Ethical and Regulatory Concerns: The use of digital twins, particularly in sensitive sectors, like healthcare and smart cities, raises ethical and regulatory issues that must be addressed to ensure responsible usage and compliance.

Addressing these limitations requires strategic planning, resource allocation, and ongoing training to maximize the potential benefits of digital twin technology.

7.5. Practical Application of Using Digital Trio

- Enhanced Data Integration and Management: The digital trio enable seamless data integration across the life cycles of assets. In manufacturing, for instance, they allow real-time monitoring and predictive maintenance, reducing downtime and extending equipment life. This integration ensures that the physical and digital representations are consistently aligned, facilitating better decision making.
- Optimizing Building Management Systems: Digital twins optimize building operations by providing comprehensive real-time data on HVAC, lighting, and energy consumption. These data help facility managers adjust systems dynamically for improved efficiency and occupant comfort while also enabling predictive maintenance to prevent system failures.
- Urban Planning and Smart Cities: Urban planners use digital twins to simulate and analyze infrastructure, traffic flows, and environmental conditions. These models assist in optimizing city layouts, improving traffic management, and enhancing public services. The ability to test different scenarios helps in making informed urban development decisions.
- Product Development in Automotive and Aerospace Industries: In the automotive and aerospace sectors, digital trios facilitate rapid prototyping and testing of design options under various conditions. This reduces the time and cost associated with physical prototypes and improves the performance and reliability of the final product through continuous real-time monitoring.
- Optimizing Supply Chain and Logistics: A digital trio provide real-time visibility into the supply chain, tracking inventory and transportation routes. This capability helps in identifying bottlenecks and predicting disruptions, thus improving decision making, operational efficiency, and supply chain resilience.
- Personalized Medicine in Healthcare: Digital trios in healthcare create personalized models of patients, integrating data from medical records and health-monitoring devices. These models allow physicians to simulate treatment options and predict outcomes, leading to more tailored and effective healthcare solutions.

- Energy Production and Management: Digital trios optimize energy production and distribution by monitoring the performance of energy assets like wind turbines and power grids. Real-time data help in predicting maintenance needs and optimizing output, thereby improving efficiency and reliability in the energy sector.
- Performance Enhancement in Sports: In sports, digital trios track athletes' physical conditions and performance metrics, aiding in developing personalized training programs. For sports facilities, they optimize operations and enhance the spectator experience, reducing operational costs and improving service quality.
- Precision Agriculture and Farming: Digital trios support precision agriculture by providing insights into crop health, soil conditions, and weather patterns. These real-time data enables farmers to optimize irrigation, fertilization, and pest control, leading to higher yields and sustainable farming practices.
- Disaster Response and Management: In disaster response, digital trios offer real-time information and simulations to plan evacuation routes and deploy resources efficiently. They enhance emergency response by providing a dynamic and updated view of the situation, improving overall disaster management strategies.

7.6. Recommendations for Overcoming Practical Challenges in Implementing Digital Twins for FM

- Investment in Training and Education: Continuous training for facility management staff should be provided to ensure proficiency in BIM tools. Certification programs should be encouraged to enhance skills and knowledge in BIM and FM.
- Standardization of Data and Processes: Clear data standards and protocols must be established to ensure consistency and interoperability across different systems and stakeholders. Detailed BIM Execution Plans (BEPs) should be developed and implemented to outline processes, roles, and responsibilities for BIM use in FM.
- Leveraging Interoperable Software Solutions: Interoperable software solutions that could seamlessly integrate with existing facility management systems and other digital tools should be used. Open standards, such as Industry Foundation Classes (IFCs), should be adopted to facilitate data exchange and interoperability among different BIM applications.
- Enhancement of Data Security and Privacy: Robust cybersecurity measures should be implemented to protect sensitive building information from unauthorized access and cyber threats. Clear data governance policies must be established to manage data privacy and compliance with regulations.
- Planning for Initial and Ongoing Investment: A sufficient budget for the initial implementation of BIM, including software, hardware, and training costs, should be allocated. Ongoing maintenance and updates of BIM systems must be planned to ensure they remain effective and up-to-date.
- Development of Strong Leadership and Support: Strong support from leadership should be secured to champion BIM implementation and allocate necessary resources. Effective change management strategies must be implemented to address resistance and encourage adoption among staff.
- Execution of Pilot Projects and Gradual Implementation: Pilot projects should be initiated to test and refine BIM processes and tools before full-scale implementation. Gradual expansion of BIM use across the organization should be based on lessons learned from pilot projects.
- Fostering Collaboration Among Stakeholders: All relevant stakeholders, including designers, contractors, and facility managers, should be engaged early in the BIM process to ensure alignment and collaboration. The use of integrated project teams should be promoted to enhance communication and coordination.
- Utilization of Real-Time Data and IoT Integration: IoT devices should be incorporated to collect real-time data on building performance, which can be fed into the BIM model

for enhanced monitoring and management. Data analytics should be utilized to derive actionable insights from the real-time data and improve decision-making processes.
- Focus on Continuous Improvement: Feedback loops should be established to continually assess and improve BIM processes based on user experiences and technological advancements. Benchmarking against industry best practices and continuously seeking to adopt and adapt the latest BIM innovations and methodologies should be pursued.

7.7. Results

The integration of BIM, EIR, and IoT for FM in mega construction projects, referred to as the "digital trio", is recommended to be highly effective and necessary to avoid many operational issues.

The digital trio concept necessitates the involvement of all stakeholders, including owners, consultants, contractors, operators, and vendors. This inclusive approach simplifies design, construction, and operational processes. Incorporating material submittals into the design phase and envisioning the building's use can significantly reduce costs by avoiding numerous changes during the construction and operations phases, and it is essential that facility management requirements are included in the EIR from the project's inception to build a future vision for operation of the building.

For existing and new buildings, a roadmap was developed to facilitate the creation of a digital trio platform, which aids in the control and operations of these structures, providing a clear flow chart to gain the maximum benefits of using the digital trio platform.

The digital trio platform provides the advantage of integrating EIR, BIM, and FM with an easy-to-use interface, thereby enabling comprehensive monitoring and detection. This platform connects sensors in critical areas of the building to measure essential parameters, such as temperature, CCTV, humidity, and pressure. In addition, the platform can be easily expanded to include more parameters as required by the operator.

The primary advantages of incorporating BIM, IoT, and EIR in large-scale projects lie in the capacity to streamline facility management procedures, resulting in cost reduction, enhanced energy efficiency, and a prolonged lifespan of the structure or infrastructure. Through the utilization of BIM to generate a digital replica of the structure or infrastructure, facility managers can simulate and scrutinize various situations, enabling them to make better-informed choices regarding maintenance and operations. This can result in enhanced resource use and facilitate the early detection of possible concerns before they escalate into problems.

As shown in Figure 14, using the Integration of EIR, BIM, and IOT in a new expression "digital trio" will lead directly to enhance the operations and maintenance of any building by using the digital trio workflow in order to improve facilities management with smart automated operation in the construction industry.

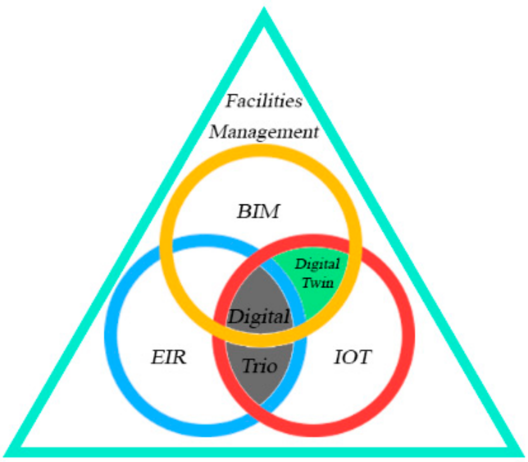

Figure 14. Integration between BIM, EIR, and IoT.

8. Conclusions

The integration of Building Information Modeling (BIM), Employer's Information Requirements (EIR), and the Internet of Things (IoT) for Facilities Management (FM) in mega construction projects, newly expressed as a "digital trio", is identified as highly effective and necessary for mitigating numerous operational issues.

The digital trio concept requires the involvement of all stakeholders, including owners, consultants, contractors, operators, and vendors. This inclusive approach simplifies design, construction, and operational processes. Incorporating material submittals into the design phase and envisioning the building's use can significantly reduce costs by mitigating numerous changes during the construction and operational phases. It is essential that facility management requirements are included in the EIR from the inception of the project to build a future vision for operating the buildings.

The optimal integration of BIM, IoT, and EIR in megaprojects, particularly in Egypt, necessitates a comprehensive approach that includes the following steps:

- Education and Awareness: raising awareness and educating stakeholders about the benefits of these technologies through training programs for architects, engineers, and construction professionals, as well as workshops and seminars for government officials and developers;
- Development of Standards and Guidelines: establishing standards and guidelines for data exchange and interoperability tailored to the Egyptian market in collaboration with international organizations and experts;
- Encouragement of Collaboration and Partnerships: promoting collaboration among stakeholders, including government agencies, private sector developers, and academic institutions, to facilitate successful implementation;
- Implementation of Pilot Projects: demonstrating the benefits of BIM, IoT, and EIR through pilot projects in various sectors, such as infrastructure, industrial, commercial, and residential projects, to gather data and feedback for future implementation efforts;
- Establishment of a Legal Framework: creating a legal framework to regulate data collection, sharing, and usage, ensuring the protection of data and the rights of stakeholders;
- Encouragement of Innovation and Research: promoting innovation and research in BIM, IoT, and EIR to stay updated with the latest developments, potentially through funding initiatives.

By adopting this multifaceted approach, the integration of BIM, IoT, and EIR in megaprojects can be effectively implemented, enhancing project outcomes and operational efficiencies.

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Abbreviations

BIM	Building Information Modeling
BXP	BIM Execution Plan
IoT	Internet of Things
EIR	Employer's Information Requirements
DT	Digital Twin
AEC industry	Architecture, Engineering, and Construction Industry
QA/QC	Quality Assurance/Quality Control
CDE	Common Data Environment
LOD	Level of Development
CCTV	Closed-Circuit Television

References

1. Mannino, A.; Dejaco, M.C.; Re Cecconi, F. Building Information Modelling and Internet of Things Integration for Facility Management—Literature Review and Future Needs. *Appl. Sci.* **2021**, *11*, 3062. [CrossRef]
2. Abd El-Hamid, S.M.; Farag, S.; Abdelalim, A.M. Construction Contracts' Pricing according to Contractual Provisions and Risk Allocation. *Int. J. Civ. Struct. Eng. Res.* **2023**, *11*, 11–38. [CrossRef]
3. Abd El-Karim, M.S.B.A.; Mosa El Nawawy, O.A.; Abdelalim, A.M. Identification and Assessment of Risk Factors Affecting Construction Projects. *HBRC J.* **2017**, *13*, 202–216. [CrossRef]
4. Abdelalim, A.M.; Abo. elsaud, Y. Integrating BIM-Based Simulation Technique for Sustainable Building Design. In *Project Management and BIM for Sustainable Modern Cities; Proceedings of the 2nd GeoMEast International Congress and Exhibition on Sustainable Civil Infrastructures, Egypt 2018–The Official International Congress of the Soil-Structure Interaction Group in Egypt (SSIGE)*; Springer International Publishing: Cham, Switzerland, 2019; pp. 209–238. [CrossRef]
5. Abdelalim, A.M.; Said, S.O.; Alnaser, A.A.; Sharaf, A.; ElSamadony, A.; Kontoni, D.-P.N.; Tantawy, M. Agent-Based Modeling for Construction Resource Positioning Using Digital Twin and BLE Technologies. *Buildings* **2024**, *14*, 1788. [CrossRef]
6. Abdelalim, A.M.; Said, S.O.M. Dynamic Labor Tracking System in Construction Project Using BIM Technology. *Int. J. Civ. Struct. Eng. Res.* **2021**, *9*, 10–20.
7. Akinshipe, O.; Aigbavboa, C.; Anumba, C. The Future of Facility Management: A Case for Digital Twin. In Proceedings of the 13th International Conference on Applied Human Factors and Ergonomics, New York, NY, USA, 24–28 July 2022.
8. Ashworth, S.J. The Evolution of Facility Management (FM) in the Building Information Modelling (BIM). Ph.D. Thesis, Liverpool John Moores University, Liverpool, UK, 2020.
9. Beadle, S. *Employer's Information Requirements (EIR): An Overview of Facilities Management Requirements*; BIFM: Gaborone, Botswana, 2017.
10. Bhaskar, K. Requirements of Construction Scheduling for the BIM Execution Plan: A Literature Review. 2023. Available online: https://pubs.aip.org/aip/acp/article-abstract/2887/1/020062/2906313/Requirements-of-construction-scheduling-for-the?redirectedFrom=fulltext (accessed on 24 May 2024).
11. *CIC BIM Standards*; Construction Industry Council Hong Kong: Hong Kong, China, 2021.
12. Codinhoto, R.; Campos Fialho, B. BIM and IoT for Facilities Management: Understanding Key Maintenance Issues. In *Research Anthology on BIM and Digital Twins in Smart Cities*; IGI Global: Hershey, PA, USA, 2023.
13. Patacas, J.; Dawood, N.; Kassem, M. BIM for Facilities Management: A Framework and a Common Data Environment Using Open Standards. *Autom. Constr.* **2020**, *120*, 103366. [CrossRef]
14. Elhosin, Y.; El Badawy Sayed, A.; Farag, M.A.M.; Abdelalim, A.M. Risk Identification of Building Construction Projects in Egypt. *Buildings* **2023**, *13*, 1084. [CrossRef]
15. Hassanen, M.A.H.; Abdelalim, A.M. A Proposed Approach for a Balanced Construction Contract for Mega Industrial Projects in Egypt. *Int. J. Manag. Commer. Innov.* **2022**, *10*, 217–229. [CrossRef]
16. Hassanen, M.A.H.; Abdelalim, A.M. Risk Identification and Assessment of Mega Industrial Projects in Egypt. *Int. J. Manag. Commer. Innov.* **2022**, *10*, 187–199. [CrossRef]
17. Hosamo, H.H.; Imran, A.; Cardenas-Cartagena, J.; Svennevig, P.R.; Svidt, K.; Nielsen, H.K. A Review of the Digital Twin Technology in the AEC-FM Industry. *Adv. Civ. Eng.* **2022**, *2022*, 2185170. [CrossRef]
18. Hosamo, H.H.; Nielsen, H.K.; Kraniotis, D.; Svennevig, P.R.; Svidt, K. Energy and Buildings. *Energy Build.* **2023**, *288*, 112992. [CrossRef]
19. Hu, W.; Lim, K.Y.H.; Cai, Y. Digital Twin and Industry 4.0 Enablers in Building and Construction: A Survey. *Buildings* **2022**, *12*, 2004. [CrossRef]
20. Khedr, R.; Abdelalim, A.M. The Impact of Strategic Management on Projects Performance of Construction Firms in Egypt. *Int. J. Manag. Commer. Innov.* **2022**, *9*, 202–211.
21. Moreno, C.; Olbina, S.; Issa, R.R. BIM Use by Architecture, Engineering, and Construction (AEC) Industry in Educational Facility Projects. *Adv. Civ. Eng.* **2019**, *1*, 1392684. [CrossRef]
22. Parsanezhad, P. Towards a BIM-Enabled Facility Management: Promises, Obstacles and Requirements. Doctoral Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2019.

23. Rizk Elimam, A.Y.; Abdelkhalek, H.A.; Abdelalim, A.M. Project Risk Management during Construction Stage According to International Contract (FIDIC). *Int. J. Civ. Struct. Eng. Res.* **2022**, *10*, 76–93. [CrossRef]
24. Saback, V.; Popescu, C.; Blanksvärd, T.; Täljsten, B. Framework for Facility Management of Bridge Structures Using Digital Twins. In Proceedings of the IABSE Congress, Ghent 2021: Structural Engineering for Future Societal Needs, Ghent, Belgium, 22–24 September 2021.
25. Shawky, K.A.; Abdelalim, A.M.; Sherif, A.G. Standardization of BIM Execution Plans (BEP's) for Mega Construction Projects: A Comparative and Scientometric Study. *Telemat. Comput. Sci.* **2024**, *12*, 103–129. [CrossRef]
26. Siccardi, S.; Villa, V. Trends in Adopting BIM, IoT and DT for Facility Management: A Scientometric Analysis and Keyword Co-Occurrence Network Review. *Buildings* **2023**, *13*, 15. [CrossRef]
27. United Nations. *Building Information Modelling (BIM) for Road Infrastructure*; United Nations: New York, NY, USA, 2021.
28. *ISO 19650*; Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling. International Organization for Standardization: Geneva, Switzerland, 2018.
29. Boje, C.; Guerriero, A.; Kubicki, S.; Rezgui, Y. Towards a semantic Construction Digital Twin: Directions for future research. *Autom. Constr.* **2020**, *114*, 103179. [CrossRef]
30. Khajavi, S.H.; Motlagh, N.H.; Jaribion, A.; Werner, L.C.; Holmström, J. Digital Twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access* **2019**, *7*, 147406–147419. [CrossRef]