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Operation Principles of the Industrial Facility Infrastructures Using Building Information Modeling (BIM) Technology in Conjunction with Model-Based System Engineering (MBSE)

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Featured Application: Developed research may be applied to the digitization of the operation of industrial objects.

Abstract: The current industrial facility market necessitates the digitization of both production and infrastructure to ensure compatibility. This digitization is presently accomplished using Building Information Modeling and digital twin technologies, as well as their integrated usage, which enhances convergence and adds further value to facility assets. However, these technologies primarily focus on the physical components of industrial facilities, neglecting processes, requirements, and functions. To address these gaps, the inclusion of the Model-Based System Engineering approach, a proven benchmark in systems engineering, is essential. This inclusion is the main objective of this research. This article outlines methods and principles for integrating Model-Based System Engineering into the informational modeling of existing industrial facilities to address current market gaps. It offers practical steps for such integration and compares it to other methods, positioning Model-Based System Engineering as a pivotal tool for enhancing the value of industrial facility digital assets. The main findings include the proposal of BIM and MBSE integration, which aims to create a competitive advantage for industrial facilities by improving customer service and operational efficiency, requiring collaboration from various stakeholders.

Keywords: building information modeling; model-based system engineering; industrial facilities; factory of the future; facility management

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1. Introduction

Digital transformation is the process of rewiring the work of an enterprise using the latest digital technologies and solutions to increase the competitiveness of production, manage operations, interact with customers, and create new business models [1,2]. In particular, the digital transformation of the industrial facility infrastructures (IFIs) is an integral part of Industry 4.0 and is critical to their competitiveness [3–5]. Therefore, the digital transformation of existing industrial enterprises should include BIM (Building Information Modeling) technology [6]. BIM plays the role of a key tool for the effective management and visualization of building and infrastructure data [7]. BIM also helps to streamline planning, collaboration, and communication processes between different project participants, improves coordination, and reduces the risk of errors and conflicts [8]. Technologies for data analysis, forecasting production processes, and optimizing resource use within the framework of the digital transformation of the enterprise must be aligned with BIM technology [9].

The operation of industrial facility infrastructures using the synergistic approach of Building Information Modeling (BIM) and Model-Based System Engineering (MBSE) holds immense relevance in today's industrial landscape. Firstly, this integrated approach streamlines facility management by providing a comprehensive digital representation of the entire infrastructure, facilitating efficient monitoring and maintenance. Secondly, BIM and MBSE ensure data accuracy and reliability, reducing operational errors and enhancing the overall efficiency of industrial systems.

Furthermore, this combination promotes sustainable practices by enabling the real-time data analysis and prediction of resource consumption, such as energy and water, thereby aiding in cost reduction and environmental conservation [3]. Lastly, BIM and MBSE's automation capabilities expedite routine tasks, optimizing the operation of industrial facility infrastructures and ensuring they perform as intended throughout their lifecycle. In essence, the integration of BIM and MBSE is a powerful means to improve the operational effectiveness, sustainability, and overall management of industrial facilities.

The goal of digital transformation, outlined in the latest book *McKinsey Rewired: A McKinsey Guide to Outcompeting in the Age of Digital and AI* (Wiley, 20 June 2023), should create a competitive advantage via continuous deployment at scale (deploying) technologies to improve customer experience and reduce costs [3]. Digital technologies allow you to optimize and automate production processes. In addition, it is expected that the result of digital transformation will be an improvement in operational efficiency: digital solutions allow you to collect and analyze large amounts of data on production operations. During this process, it becomes possible to identify bottlenecks in production processes, as well as predict and prevent failures and accidents.

Currently, BIM is an object-oriented technology [8,10,11]. BIM technology is currently used to digitize information about IFIs, including their geometry, materials, construction, etc.—i.e., only components. Researchers have declared that the development of BIM technologies is moving towards the creation of more complex and detailed models [12–14] that can provide information on various aspects of design, construction, and operation [10,15–18]. However, if you do not also begin to formalize and digitize the requirements, functions, and processes in IFI, then there is a problem of incomplete information for modeling when building a system model of the enterprise. Such an approach can be provided in conjunction with the methodology of system engineering, and its current state—MBSE (Model-Based System Engineering).

For example, if we do not formalize and digitize the client's requirements for IFI as a whole, we may miss important details that can significantly affect its functionality. Comparatively, without digitizing the infrastructure components and the production part of a building or structure, such as ventilation, electricity, or water supply systems, we will not be able to adequately model and analyze their interaction and performance [10,19,20]. Without digitizing IFI requirements, such as room utilization, cross-departmental collaboration, or user needs, we will not be able to adequately model and evaluate the effectiveness and usability of IFIs.

Until now, BIM, as a design tool, assumed that requirements, functions, and processes are not formalized or digitized; they are only in the head of the design subject based on regulatory documents and customer requirements.

The understanding of IFI information modeling at the moment rested on its development as an understanding of the technology that describes the *objects* of the physical world: building structures, engineering networks, landscaping elements, etc. [16,21,22]. If BIM developed systematically, then not only objects of the physical world would be digitalized. The principles of application of BIM described in ISO 19650 [23] are currently insufficient for a modern industrial enterprise because they consider digital technologies for buildings and structures not consistent with the digital technologies of the enterprise, such as manufacturing technologies. At the same time, production technologies are evolving very quickly in Industry 4.0, and BIM technologies describe more conservative entities. Therefore, new principles of the operation of the infrastructure of industrial enterprises are required—a necessary basis for an enterprise that seeks to defend itself competitively in the market. At the same time, it is obvious that in the gas_cal world, there are not only objects. Physical *objects* and their systems can perform certain *functions*, such as electricity, gas, and water supply, ensuring the strength of structures, maintaining certain microclimate parameters, and others [2,4,17]. In addition, within the framework of a building or structure, various *processes* can take place: air conditioning, the movement and heat dissipation of equipment and people, dynamic loads from equipment, and others. Finally, any existing industrial enterprise assumes the requirements for IFI, ranging from the economical and investment characteristics of the project to the requirements of production or design parameters. It should not be forgotten that in addition to the *objects*, *functions, processes*, *and* requirements of the physical appearance of IFI, there are *relationships* between these entities. For example, microclimate *requirements* affect the *processes* of heating, ventilation, and air conditioning and, at the same time, depend on them. And the *functions* performed via building structures and engineering networks directly depend on the parameters of these *objects*. Modern approaches require that all digital technologies of the enterprise develop harmoniously since, at the moment, they are quite isolated from each other.

BIM technology cannot evolve in a vacuum to be in demand, as it requires the interaction and collaboration of various stakeholders. The smooth integration of BIM into the process of the digital transformation of an enterprise is successful only when all participants in the process actively interact and exchange information in a single digital environment. Only such cooperation allows you to maximize the potential of BIM. Without collaboration and data sharing, BIM technology will not be able to realize its full potential and be in demand.

Consequently, the **purpose** of this study is the principles of the joint application of BIM technologies and MBSE via the decomposition and subsequent formalization and digitization of the *requirements*, *functions, components, processes, and relationships* between them related to a certain IFI. This study has the following **objectives**:

- To analyze the literature in the field of digital operation of industrial enterprises and identify current gaps in this area (state of the art);
- Identify challenges based on the need to formalize and digitize requirements, functions, and processes within IFI;
- To propose a conceptual model and principles of the operation of the infrastructure of industrial enterprises using BIM technology in conjunction with MBSE;
- To identify practical steps and considerations for the implementation of the proposed conceptual model for the operation of the infrastructure of industrial enterprises using BIM technology in conjunction with MBSE;
- Identify the limitations of the proposed transformation model and suggest possible improvements;
- Show the limitations of the proposed model and the advantages of the proposed approach over the existing ones;
- Offer directions for further research.

There is a need to create IFI information models in accordance with the MBSE methodology, with the corresponding transformation of BIM technology. The technology itself must respond to the challenges that arise in the modern world. Therefore, the research question is how to optimize the management of facility assets using BIM and MBSE. The main study objective is to formulate a conceptual model and principles of the operation of the infrastructure of industrial enterprises using BIM technology in conjunction with MBSE.

2. Materials and Methods

The methodology of this research is represented as the process of forming the concept and principles of implementing BIM to improve the operation of industrial buildings as it is shown in the Figure 1. Let us break down this method in more detail:

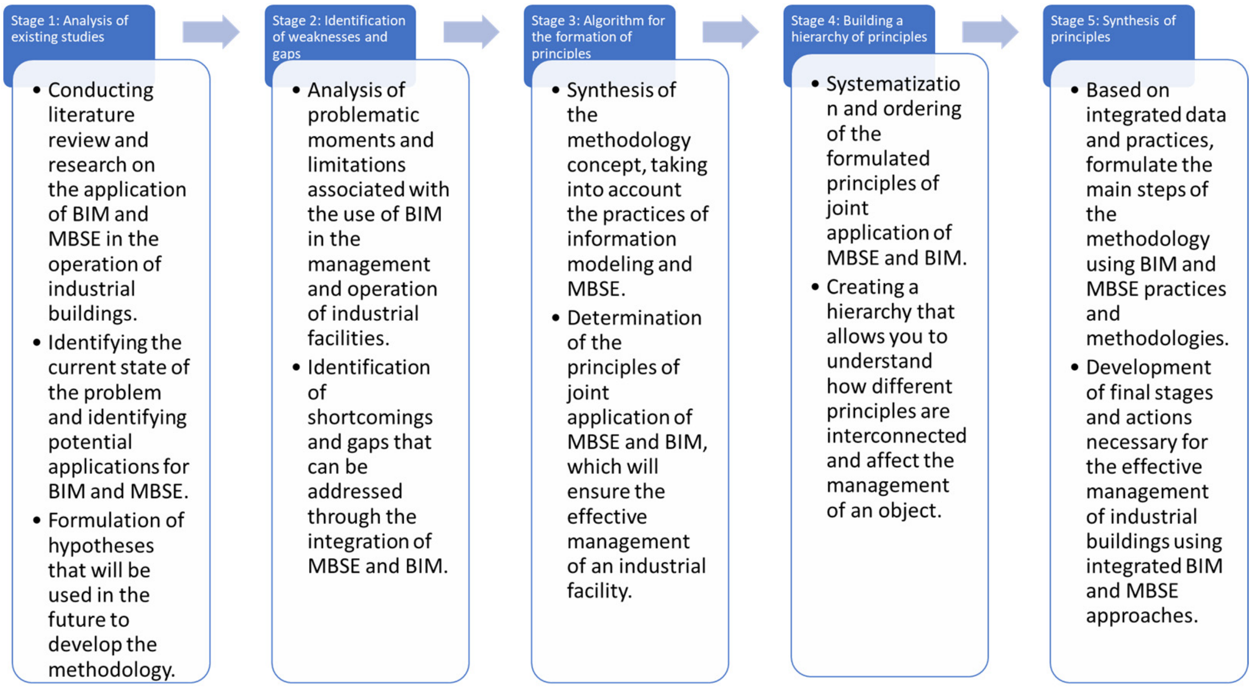

Figure 1. MBSE implementation for BIM.

Stage 1: In the initial phase, the analysis of existing studies involves a comprehensive review of the current state of research in the field of BIM technology and its application in industrial building management. This analysis provides a foundation for understanding the existing body of knowledge.

Stage 2: Building on the insights from Stage 1, Stage 2 involves the systematic identification of the gaps and limitations in the current use of BIM technology for industrial facility infrastructure (IFI). These gaps serve as critical points of focus for the research to address specific challenges in the field.

Stage 3: The development of an algorithm for the formation of principles represents a crucial step in this research methodology. This algorithm is designed to guide the creation of a set of principles that will underpin the integration of BIM and MBSE for enhanced operational efficiency.

Stage 4: Once the principles are identified, Stage 4 focuses on building a priority structure for these principles. This hierarchy will help in organizing and prioritizing the principles based on their significance and interrelationships, ensuring a coherent and systematic approach.

Stage 5: The synthesis of principles, as outlined in Stage 5, is the process of combining and refining the identified principles to create a comprehensive framework for the sustainable management and operation of industrial buildings. This synthesis ensures that the principles work together synergistically.

The overarching goal of this methodology is to establish a sustainable and efficient system for managing and operating industrial buildings, harnessing the advantages of BIM and MBSE technologies. By addressing the existing gaps and developing a well-structured set of principles, this methodology aims to optimize processes and enhance overall efficiency within the realm of industrial facility infrastructure management.

3. State of the Art

Literature Review

The current breakdown of BIM articles by year is shown in the graph below (Figure 2).

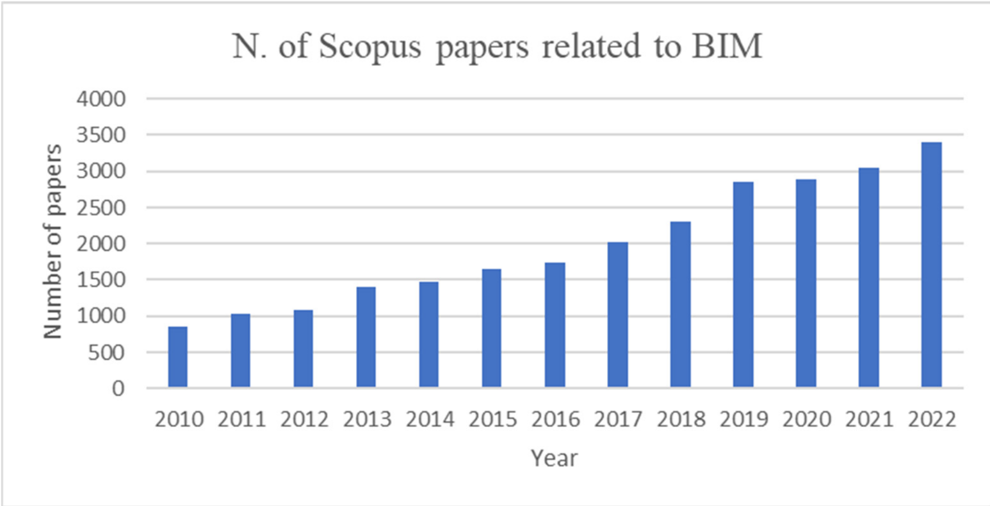

Figure 2. Publication activity for BIM.

BIM is a powerful tool that can be used with MBSE, System Engineering (SE), System Information modelling (SIM) within Digital Transformation of facilities. Distribution of related articles is presented on Figure 3.

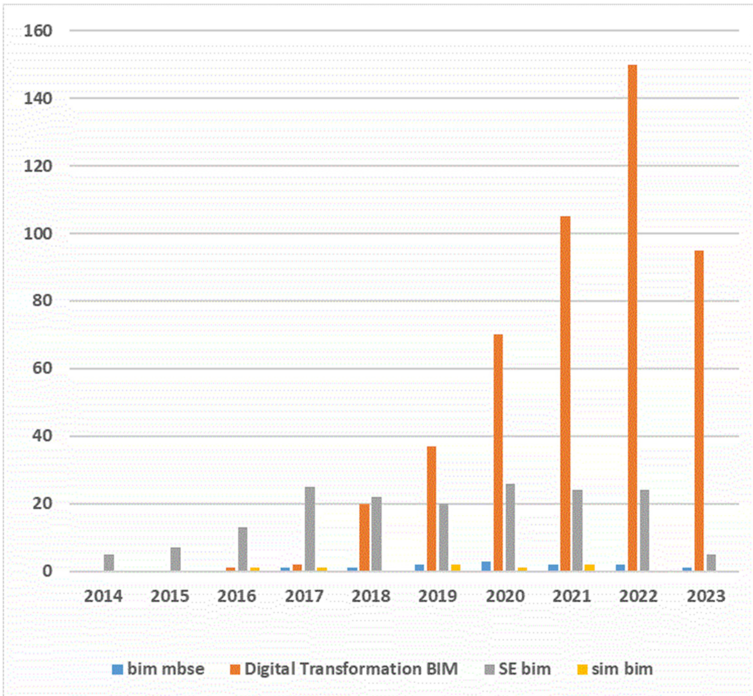

Figure 3. Distribution of articles by keywords containing "BIM" and integration with selected methodologies.

A large number of articles are devoted to DT. However, the following aspects should be noted:

1. The place of BIM technology is not clearly marked.
2. A unified methodology for transformation has not been defined.

The greatest success in digital transformation has been achieved in the aerospace industry. BIM does not occupy the place that we believe it should occupy in the process of digital transformation. Instead, the methodology of system engineering and MBSE is used to a limited extent, while system engineering has become very widespread in related industries.

The state of the art in implementing Building Information Modeling (BIM) and Model-Based System Engineering (MBSE) in the management of industrial facilities represents a cutting-edge approach that is revolutionizing the way such facilities are planned, constructed, and operated.

- Digital Twins: BIM has evolved to include the concept of "digital twins". This involves creating a real-time digital replica of the industrial facility, allowing for the monitoring of its performance, condition, and operational data. Digital twins are instrumental in predictive maintenance and optimizing efficiency.
- Lifecycle Management: BIM and MBSE are increasingly being applied across the entire lifecycle of industrial facilities. From the early design and construction phases to ongoing facility management and even eventual decommissioning, these technologies provide a unified platform for managing data and information.
- Interoperability: The industry is making significant strides in improving interoperability among various BIM and MBSE software platforms. This ensures that data can seamlessly exchange between different stages and stakeholders, improving collaboration and data accuracy.
- IoT Integration: Integration with the Internet of Things (IoT) is becoming commonplace. IoT sensors are embedded in industrial facilities to gather real-time data on equipment performance, environmental conditions, and energy consumption, which are then incorporated into the BIM and MBSE models.
- AI and Machine Learning: Artificial intelligence and machine learning algorithms are employed to analyze the vast amounts of data generated via BIM and MBSE. This data-driven approach allows for predictive analytics, helping to optimize facility operations and maintenance.
- Regulatory Compliance: BIM and MBSE are increasingly being used to ensure compliance with safety and regulatory standards. This is crucial in industries with strict safety and environmental requirements, such as chemical processing, energy, and manufacturing.
- Sustainability and Energy Efficiency: BIM and MBSE are instrumental in designing and managing sustainable energy-efficient facilities. They enable detailed analyses of energy consumption and environmental impact, leading to more eco-friendly and cost-effective designs.
- Remote Monitoring and Control: The integration of BIM and MBSE allows for the remote monitoring and control of industrial facilities. This is particularly relevant in situations where facilities are geographically dispersed or where access is limited.
- Data Security and Privacy: As the reliance on digital technologies increases, ensuring the security and privacy of sensitive facility data becomes a paramount concern. State-of-the-art solutions incorporate robust data security measures to safeguard critical information.
- Education and Training: As these technologies become more prevalent, there is a growing emphasis on educating professionals in their use. This includes training programs and certifications to ensure that the workforce is equipped with the necessary skills to implement BIM and MBSE effectively.

The state of the art in implementing BIM and MBSE in industrial facility management is marked via a holistic approach that encompasses the entire facility lifecycle, leverages advanced technologies like IoT, AI, and digital twins, and prioritizes sustainability, safety, and data security. It represents a paradigm shift in how industrial facilities are designed, built, and operated, with a strong emphasis on data-driven decision making and efficiency optimization. Distribution of articles by keywords "Digital Twin MBSE" is presented in the Figure 4.

According to the current research, the gap in implementing BIM in IFI management is that mostly only *objects* of physical objects are digitized, not taking the *processes, requirements, and functions* under consideration.

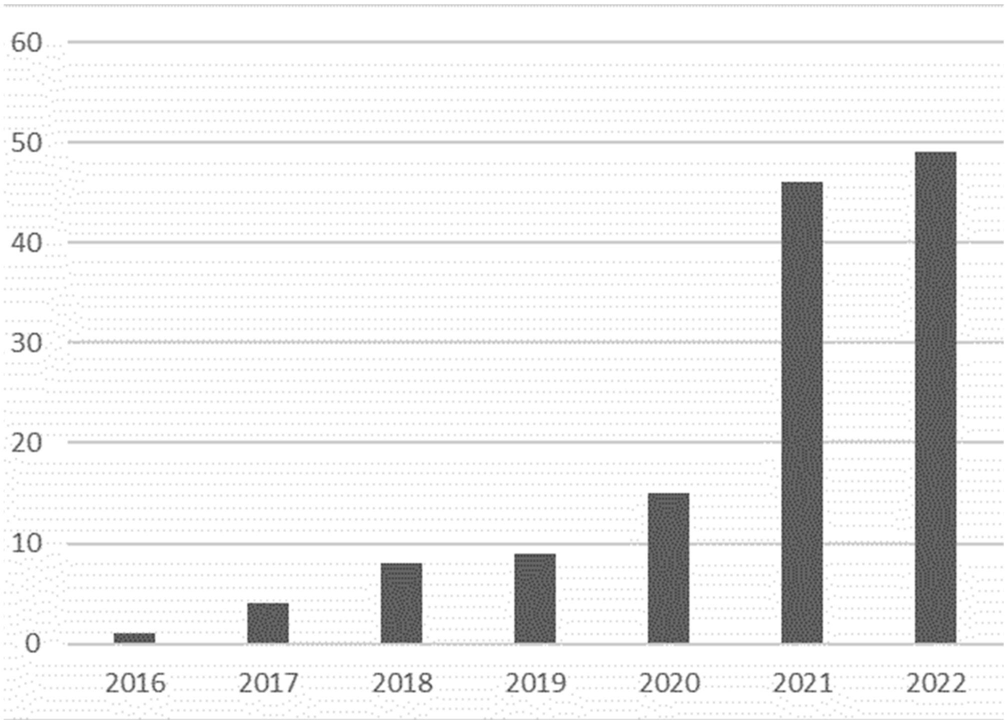

Figure 4. Distribution of articles by keywords "Digital Twin MBSE".

4. Results and Discussion

4.1. Conceptual Model and Principles of Operation of the Infrastructure of Industrial Enterprises Using BIM Technology in Conjunction with MBSE

MBSE, which has proven itself in systems theory and mechanical engineering as an effective tool for the decomposition of complex systems and their analysis, is the current challenge for [24–26]. MBSE allows you to decompose a building or structure, considered a complex system (system of systems), into *requirements, functions, components, and processes*, as well as take into account the *relationships* between them [27]. Such a decomposition significantly increases the adequacy of the BIM model to the physical world [28]. At the same time, using MBSE, there is a transition to a systematic coordinated application of BIM technologies.

Modern BIM technology is being actively introduced into the IFI operation process, offering significant advantages over traditional IFI management methods [29,30]. BIM provides a complete digital two- or three-dimensional IFI model that integrates geometric information with data on the properties and behavior of components.

When BIM is implemented in the operation of IFI, first of all, a single database is created containing all the necessary information about IFI, including geometric configuration, architectural and engineering solutions, materials, equipment, and documentation. This database allows you to manage IFI [31] at all stages of its life cycle, from design and construction to operation and repair.

BIM provides the ability to visualize IFI in real time [32,33]. IFI operating scenarios help to optimize processes and increase efficiency [34].

A BIM system allows you to automate many routine tasks, such as scheduling maintenance and controlling spare parts and inventory. Automating these processes allows you to reduce the number of errors and increase the accuracy of information, as well as reduce the time spent on these tasks.

With the use of BIM in the operation of IFI, it is possible to carry out an effective analysis and forecasting of the consumption of resources such as energy and water. Based on the results of these analyses, it is possible to develop and implement measures to reduce energy consumption and improve the environmental efficiency of IFI. BIM also allows you to create and maintain online IFI documentation, including information about the repairs, replacements, updates, and changes to IFIs.

The ontological model and the semantic model are two different approaches to the representation of knowledge and semantics in information systems. Here are their main differences:

Ontological model: Ontology is a formal description of concepts and the relationships between them in a particular subject area. The ontological model represents knowledge in the form of an ontology that defines classes of concepts, attributes, and relationships. An ontological model is usually used to formalize knowledge and ensure consistency and uniqueness in the subject area. It defines concepts and their relationships but does not always contain detailed semantic descriptions or logical relationships between them.

Semantic model: The semantic model represents knowledge in the form of semantic networks or graphs, where nodes represent concepts and edges represent the relationships between them. In the semantic model, relationships have explicit semantic meanings that describe the relationships between concepts. The semantic model pays more attention to the representation of the meaning and semantics of the data. It can be used for natural language processing, semantic retrieval, or semantic analysis in a text.

Thus, the main difference between the ontological and semantic models is that the ontological model focuses on the formalization of concepts and connections in the subject area, while the semantic model pays more attention to the semantics and meaning of data.

The principles of operating the infrastructure of industrial enterprises using BIM technology in conjunction with MBSE can be formulated as follows (in priority order):

- Data integration and centralization: Create a common centralized information platform that combines data from BIM models and MBSE models to provide a single source of truth about the state of enterprise objects and systems.
- Lifecycle Integration: Integrate design, construction, operations, and change management into a single cycle through consistent BIM and MBSE models to minimize switching between systems and reduce the risk of errors.
- Full visibility and transparency: Ensure that up-to-date data and models are available to everyone involved in the project and operations, allowing you to quickly respond to changes and optimize processes.
- Knowledge and Experience Management: Implement a BIM- and MBSE-based knowledge management system that allows you to retain and transfer knowledge about the design, construction, and operation to ensure business continuity.
- Process Analysis and Optimization: Use BIM and MBSE to model and simulate processes in the enterprise to identify bottlenecks, optimize resources, and improve efficiency.
- Risk Forecasting and Management: Use BIM- and MBSE-based analytical tools to anticipate operational risks and develop strategies and plans to manage them.
- Collaboration and communication: Promote collaboration between different disciplines and project participants, using collaborative BIM and MBSE models as the basis for effective communication and collaboration.
- Flexibility and adaptability: Create flexible BIM and MBSE structures that can adapt to changes in the requirements and conditions of the enterprise, ensuring the long-term sustainability of the system.
- Staff training and development: Train staff to work with BIM and MBSE to maximize the potential of technology and provide skills for effective infrastructure management.
- Regulatory Compliance: Maintain compliance with processes, data, and models to regulations and standards that ensure quality, safety, and industry compatibility.

These principles will help provide a more integrated, efficient, and sustainable approach to managing the infrastructure of industrial enterprises using BIM and MBSE.

The Figure 5 illustrates the place of BIM in digital transformation based on the interconnections between the physical and digital worlds.

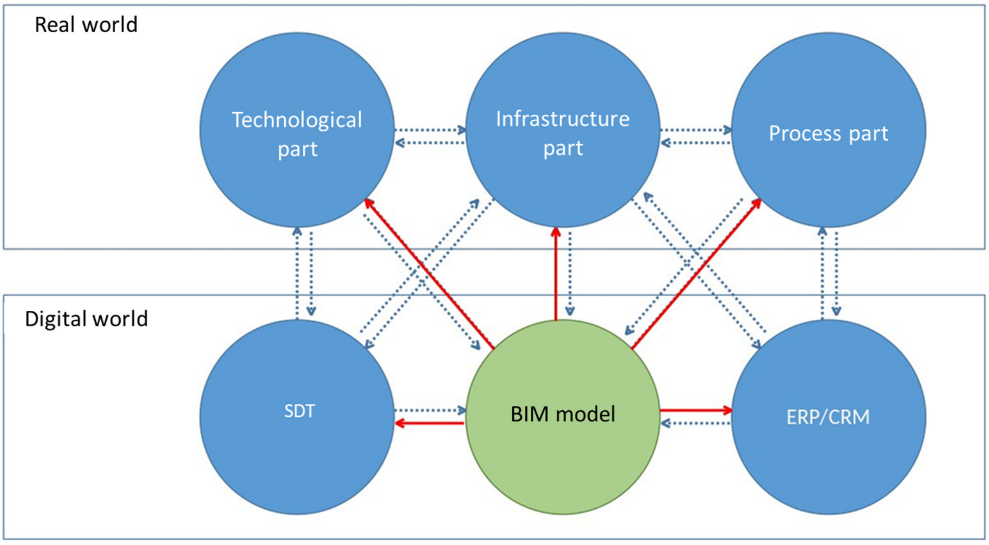

Figure 5. The role and place of BIM in digital transformation: the relationship between the digital and real world.

Based on the MBSE approach, IFI should be considered in terms of a number of requirements, functions, components (systems and subsystems in accordance with the construction information classifier), and processes. To identify relationships, the method involves the compilation of pairwise matrices RBS-FBS, RBS-PBS, RBS-WBS, FBS-PBS, FBS-WBS, and PBS-WBS.

At the same time, it is proposed to distinguish the following entities in an enlarged way:

- Requirements (RBS); Requirements for the reliability of structures;
- Functional requirements;
- Requirements for space-planning solutions;
- Cost requirements;
- Functions (FBS);
- Project Initiator (Investor–Owner/Order);
- Gen. contractor;
- Contractor;
- Contractor (Operation);
- Components (PBS);
- According to the Construction Information Classifier;
- Processes (WBS);
- Projection;
- Construction;
- Exploitation;
- Disposal (demolition).

In industrial facility infrastructures (IFIs), which encompass both production and production infrastructure, digitalization involves the integration of Building Information Modeling (BIM) and digital twin (DT) technologies. The approach to maintaining buildings, structures, and life support systems via information modeling technologies centers on the creation of a digital asset—an enterprise's digital resource capable of generating economic benefits. This digital asset comprises a set of digitized requirements, functions, components, and processes.

The proposed method aligns with Model-Based System Engineering (MBSE), an operated building that can be viewed as a complex technical system, often referred to as a "system of systems". Digitalizing operations is a vital component of the construction industry's broader digital transformation. The graphical representation of the MBSE method is illustrated in the figure below, featuring digital depictions of individual systems and their interconnections (Si and Cj). However, genuine digital transformation is only achieved via the digitalization and integration of subsystems and their connections.

Another significant challenge pertains to the substantial resource consumption and extensive computational time required for efficient research models, as well as uncertainties stemming from simplifications in these models. While certain simplifications and idealizations may not significantly affect a specific model's operation, their cumulative impact in a consolidated model can lead to substantial errors. A potential solution to this issue involves developing well-fitted simplified models that can be integrated into a unified model. Even with their inherent simplifications, within a sufficiently large system and with extensive data utilization, these simplified models can naturally rectify each other.

In the classical MBSE approach, the process involves gathering a comprehensive set of data about the system, categorized into requirements (R), functions (F), components (W), and processes (P) as it is shown in Figure 6. Subsequently, pairwise matrices of influence are generated to depict the relationships between the system's functions, processes, components, and their corresponding requirements. The intersections of columns and rows in these matrices indicate the connections between the various elements.

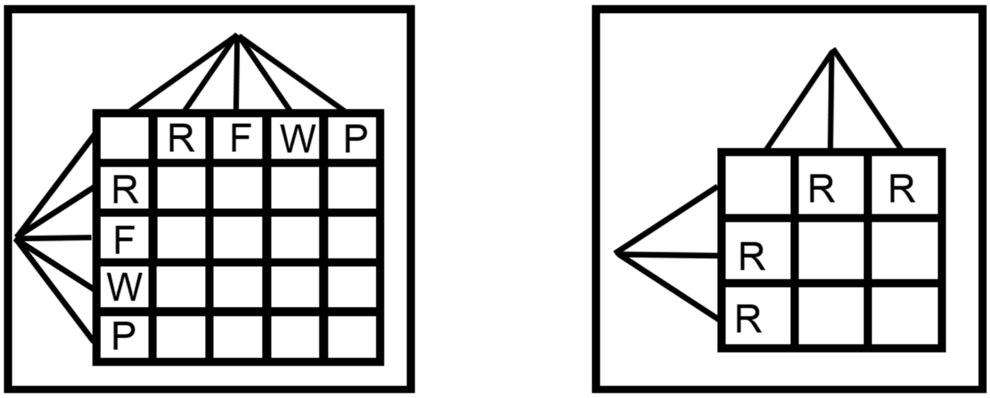

Figure 6. MBSE matrices.

We propose to add two more categories to the classic version: the system and the product. Then, we determine the following:

- The system is the element in question;
- Requirements are the boundary conditions for the system;
- Functions are what the system is capable of doing (it has the function of photographing, and photographing is a process);
- Components are how components implement the functions of the system;
- Processes are what the system does;
- The product is a separate result of the system.
- MBSE involves using a model to describe problems and determine the optimal solution.

4.2. Practical Steps and Considerations for the Implementation of the Proposed Conceptual Model for the Operation of the Infrastructure of Industrial Enterprises Using BIM Technology in Conjunction with MBSE

An algorithm for applying the MBSE method to create a digital image of a complex system based on IFI, presented in the digital world in the form of a BIM model:

- Define the purpose of the MBSE model;
- Set SoS boundaries;
- Identify the lifecycle stages that exist in the SoS;
- Define system requirements breakdown (RBS);
- Define component decomposition (PBS) and function decomposition (FBS);
- Process the breakdown definition (WBS);
- Define the list of attributes (a) used to define the system;

- Form the semantic definitions and their assignment to the concepts used in the model;
- Parameterize the components, functions, requirements, and processes;
- Analyze hierarchies for SoS requirements;
- Construct the matrices of relationships between RBS, FBS, and PBS;
- Rank the importance of relationships;
- Define the boundaries of relationship modeling (determine which relationships are modeled in the digital world);
- Identify the components, functions, requirements, and processes required for modeling;
- Define standards and ensure model interoperability and form a platform solution;
- Define the model ontology for individual systems and components;
- Model the components, functions, and processes;
- Conduct relationship modeling (parameterized meta-model);
- Determine a decision-making strategy based on the display of changes in the physical world in the digital world and scenario modeling (generativity);
- Determine the methodology for verification and validation of the SoS model;
- Perform a verification of a single SoS model (iterative);
- Perform SoS model validation (iterative);
- Repeat the iteration.

4.3. Limitations of the Proposed Model and the Advantages of the Proposed Approach over the Existing Ones

Limitations of the proposed principles:

- Complexity of implementation: Creating and maintaining a centralized information platform requires significant investments in IT infrastructure, software, and staff training.
- Compatibility with existing systems: Integration with existing data management and storage systems can be difficult due to differences in data formats and structures.
- Data Quality Dependency: The effectiveness of the system will depend on the relevance and accuracy of the data in the BIM and MBSE models. Poor-quality data can lead to errors and unreliable analyses.
- Complexity of changes: Making changes to established BIM and MBSE models can be complex and require significant effort, especially in the later stages of the life cycle of an object.
- Barriers to staff skills: Working with BIM and MBSE may require new skills for employees, which can be a challenge when transitioning to a new methodology.

Advantages of the proposed approach over the existing ones:

- Improved visibility and control: A centralized information platform provides all project participants with access to up-to-date data, improving coordination and reducing the risk of errors.
- Lifecycle integration: Combining BIM and MBSE reduces switching between systems at different stages of the lifecycle, which reduces time delays and improves consistency.
- Process optimization: The ability to analyze and simulate processes using BIM and MBSE can lead to improved operational efficiency and resource optimization.
- Risk management and predictability: The use of analytical tools based on BIM and MBSE allows you to more accurately assess risks and develop strategies for their management.
- Collaboration and communication: Common BIM and MBSE models facilitate more effective communication between project participants and different disciplines.
- Adapting to change: Flexible BIM and MBSE structures make it easy to make changes to the system, which is important in the face of changing requirements.
- Knowledge retention: The implementation of a knowledge management system based on BIM and MBSE allows you to preserve and transfer experience, which ensures the continuity of the enterprise.
- Compliance: The approach promotes easier compliance with regulations and standards, which contributes to improved quality and safety.

5. Directions of Further Research

Future research will focus on the deep interintegration of three key methodologies: BIM, MBSE, and Analytical Hierarchy Process. The intersection of these methods is an area of active research effort to improve the management, design, and operation of complex systems, including buildings and infrastructure.

The progressive integration of BIM, MBSE, and the hierarchy analysis method is aimed at creating synergies between them. This will allow you to effectively structure projects, manage their life cycle, and make informed decisions based on many aspects. This line of research promises to significantly improve the way complex system processes are integrated and optimized, with the potential to greatly increase the efficiency and reliability of engineering solutions in the future.

This study on integrating Building Information Modeling (BIM) and Model-Based System Engineering (MBSE) into the management of industrial infrastructure offers valuable insights for future research in various domains. Here are some practical implications and potential research avenues that need to be considered:

- Interdisciplinary Collaboration: The integration of BIM and MBSE often requires collaboration between professionals from different backgrounds, including civil engineering, systems engineering, and information technology. Future research should explore effective strategies for promoting interdisciplinary collaboration and knowledge exchange in industrial infrastructure projects.
- Standardization and Interoperability: Ensuring that BIM and MBSE systems can communicate effectively is a key challenge. Future research can focus on developing and evaluating standardization protocols and interoperability standards that facilitate seamless data exchange between these two technologies.
- Data Management and Integration: Managing large datasets generated via BIM and MBSE systems is critical. Research can delve into innovative data management techniques and tools, including data storage, version control, and data integration strategies, to optimize information flow in industrial infrastructure projects.
- Cost–benefit Analysis: Investigating the cost-effectiveness and return on investment of integrating BIM and MBSE in industrial infrastructure management is essential. Future studies should analyze the long-term financial implications of this integration and identify areas where cost savings and efficiencies can be realized.
- Technology Adoption and Training: Research should explore the factors affecting the adoption of BIM and MBSE in the management of industrial infrastructure. This includes assessing the training needs of professionals and the development of effective training programs to ensure the workforce is well prepared to utilize these technologies.
- Risk Management: Assessing the potential risks and challenges associated with the integration of BIM and MBSE is crucial. Future research can investigate risk mitigation strategies and contingency plans to address issues that may arise during implementation.
- Project Lifecycle Management: Future studies should explore how BIM and MBSE can be applied throughout the entire project lifecycle, from design and construction to operation and maintenance. This involves investigating the benefits of continuous information flow and decision support across all phases.
- Performance Measurement and Optimization: Developing performance metrics and methodologies for assessing the effectiveness of BIM and MBSE integration in improving the management of industrial infrastructure. Research can also focus on optimization techniques to enhance decision-making based on real-time data.
- Sustainability and Environmental Considerations: Investigating how the integration of BIM and MBSE can facilitate sustainable practices and environmental impact reduction in industrial infrastructure projects. This includes evaluating how these technologies can support energy-efficient designs and resource conservation.
- Case Studies and Best Practices: Collecting and disseminating case studies and best practices that showcase successful implementations of BIM and MBSE in industrial

infrastructure management. These real-world examples can offer valuable insights and guidance to industry professionals.

In conclusion, the integration of BIM and MBSE in industrial infrastructure management presents numerous research opportunities across various aspects, from technology integration to interdisciplinary collaboration, cost-effectiveness, and sustainability. Future research should address these practical implications to advance the adoption and effectiveness of these technologies in industrial infrastructure projects.

6. Conclusions

Digital transformation is a rethinking of the company's work via the integration of the latest digital solutions to increase competitiveness. An important component of this process for industrial enterprises is the use of BIM technology, a key tool for managing building and infrastructure data [35] BIM streamlines planning, communication between project participants, and coordination, reducing the risk of errors.

The goal of digital transformation is to create a competitive advantage via the deployment of technology to improve customer service and reduce costs. It is also expected to improve operational efficiency by analyzing data and identifying weaknesses in production processes. BIM technology is used to digitize data on infrastructure facilities, but its development requires the cooperation of various stakeholders.

In this way, digital transformation and BIM technology together contribute to the effective management and optimization of production processes in industrial enterprises.

MBSE is an effective tool for analyzing and decomposing complex systems such as buildings and structures. By decomposing into requirements, functions, components, and processes, MBSE improves the compliance of the BIM model with the real system, providing system interaction with BIM technologies.

The implementation of BIM in the operation of IFI brings significant benefits. BIM creates a digital IFI model, combining geometric information with component data, and provides management of the object at all stages of its life cycle. Real-time visualization and virtual scenario simulation allow you to quickly monitor the condition of the facility and optimize its operation.

BIM automates routine tasks, improving data accuracy and reducing turnaround time. BIM also allows you to analyze and predict the consumption of resources, such as energy and water, to develop effective measures to reduce costs. IFI's electronic documentation, including repair and change information, is also managed via BIM.

Building Information Modeling (BIM) and Model-Based System Engineering (MBSE) are both powerful tools for improving the design, construction, and management of industrial buildings. When used together, they can automate routine tasks and enhance data accuracy in various ways. Using automated 3D modeling BIM allows for the creation of detailed 3D models of the building, which can be automatically generated from design and engineering data. This model can include information about architectural, structural, and MEP (mechanical, electrical, and plumbing) systems. MBSE, on the other hand, focuses on creating system models, which can be integrated into the BIM model. This integration ensures that the building systems are correctly designed and can be managed efficiently. By providing data integration and interoperability, BIM and MBSE tools are designed to work with a wide range of data formats and software applications. This integration allows for the seamless data exchange between different stages of the building's lifecycle, from design to construction to operation. It ensures that the most up-to-date information is always available, improving data accuracy. BIM and MBSE tools also provide data validation and error detection which often come with built-in validation checks. They can automatically detect clashes or inconsistencies in the design, helping to maintain data accuracy and reduce rework during construction.

By combining BIM and MBSE, industrial building management can benefit from improved automation of routine tasks, enhanced data accuracy, and better coordination between architectural, structural, and systems engineering components. This integrated approach helps ensure that the building performs as intended and is more efficiently managed throughout its lifecycle.

Thus, the implementation of BIM and the application of MBSE enrich the approach to IFI management and operation, optimizing processes and increasing efficiency.

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