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Review

Cross-Industry Principles for Digital Representations of Complex Technical Systems in the Context of the MBSE Approach: A Review

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Abstract: This scientific article discusses the process of digital transformation of enterprises, analyzed as complex technical systems. Digital transformation is essential for businesses to remain competitive in the global marketplace. One of the effective tools for such a transformation is model-based systems engineering (MBSE). However, there is a gap in the practical application of knowledge regarding the uniform principles for the formation of a digital representation of complex technical systems, which limits the realization of the cross-industry potential of digital transformation in the economy. The motivation for this study is to identify common cross-industry principles for the formation of digital representations of complex technical systems that can lead companies to a sustainable and successful digital transformation. The purpose of this work is to identify and formulate these principles through an analysis of publications, using an inductive approach and classifying them by the category of application. As a result of the study, 23 principles were obtained, and the degree of their use in various industries associated with complex technical systems was determined. The results of this study will help to solve the problem of cross-industry integration and guide systemic changes in the organization of enterprises during their digital transformation.

Keywords: model-based systems engineering; MBSE; digital twin; digital representation; digital transformation; complex technical system; system of systems; system cross-industry principles; life cycle

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1. Introduction

The high socio-economic significance of digital transformation determines the relevance of the research topic. Recently, businesses have realized the importance of digital transformation for sustainable development, especially for enterprises in the real sector of the economy [1]. In 2018, only 33% of representatives of manufacturing companies considered digital transformation as a necessary process, but by 2020, this number had almost doubled to 64%. Currently, companies in various industries are investing significant amounts of money, ranging from 3% to 10% of revenue, in digital transformation and related initiatives [2]. Europe can add EUR 2.5 trillion to GDP in 2025, boosting GDP growth by 1 percent a year over the next decade through the use of digital technologies [3]. The digital transformation market size is set to reach USD 2669.48 billion by 2030 [4]. Companies are interested in improving the efficiency of the process of digital transformation [5]. Digitalization has a significant positive impact on increasing the value of companies through the formation of assets [6], risk assessments [7], promotion of innovation [8], the increase in operational efficiency [9], and the reduction in the risk of a collapse in stock prices [10]. There is an urgent need to take advantage of new digital technologies to adjust how companies respond to external economic conditions based on real-time information [9,11].

An emphasis on the aspect of digital transformation associated with systemic organizational restructuring in the real sector of the economy is especially important, as this sector plays a crucial role in overall economic growth [12]. The use of advanced system engineering methods based on digital technology, modeling, and analysis of big data is necessary to ensure competitive advantages [13]. Digital transformation is the driving force of the economy at the present stage, highlighting the potential impact of this study on a wide range of industries [13,14]. By proposing new principles for creating a digital representation of complex technical systems, this study can make a significant contribution to the digital transformation of the economy and the integration of various industries.

As an object of study, the authors propose a digital representation of a real object. The use of a model-based systems engineering (MBSE) approach makes it possible to effectively build such a representation based on the system model of an enterprise, adequately describing it in the form of interconnections of system components [15]. However, currently, there is a lack of detailed descriptions regarding the principles of creating a digital representation of an object based on MBSE. Bridging this gap is the focus of the authors' attention. At the same time, there is evidence that the MBSE approach is indeed an effective tool for forming an adequate digital representation of a real system in the physical world [16]. The formation of a digital representation of a complex technical system is illustrated in Figure 1.

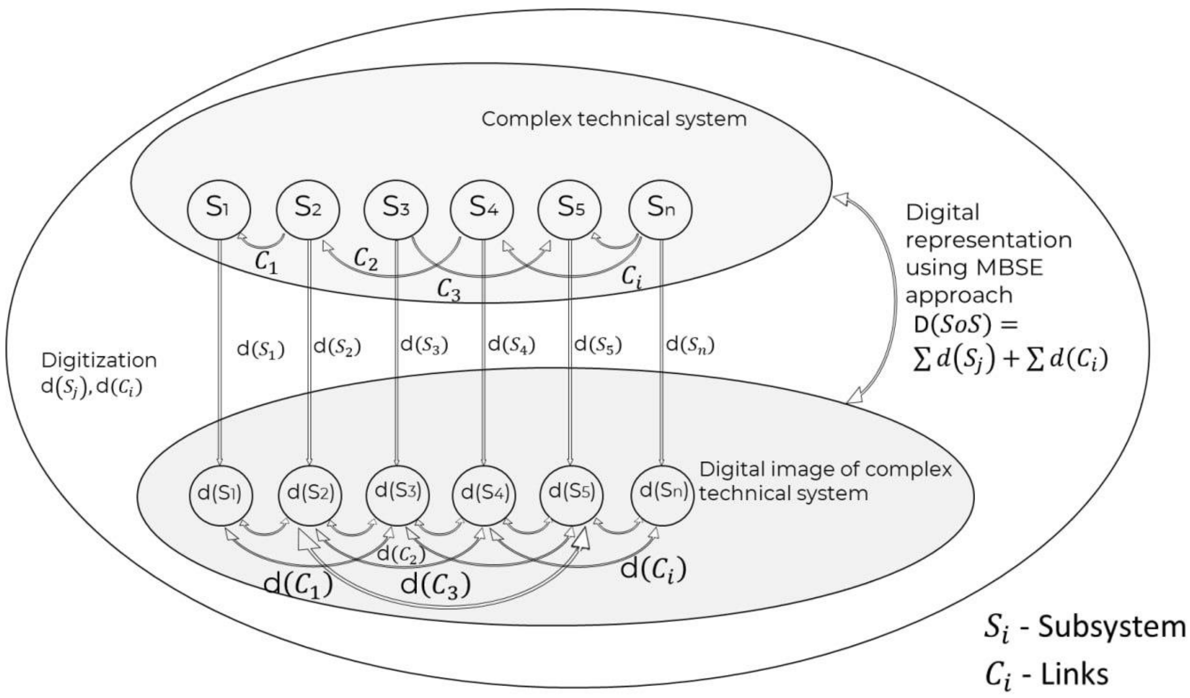

Figure 1. Digital representation of a complex technical system. The diagram shows objects, processes, and relationships between them in a complex technical system in the process of digitalization. The process of digital representation refers to the digitization of system elements (components and connections) separately and the creation of digital models of individual systems, including all elements and connections within it. The process of digitalization, from the position of the MBSE approach, can occur when all subsystems and connections between them at all necessary levels of decomposition are formed into a single model.

The authors have identified a knowledge gap in the absence of common cross-industry principles for the formation of a digital representation of complex technical systems for digital transformation. The lack of such system principles, formulated in a uniform manner, is seen as an obstacle to the standardization of formats of digital representations of organizations as complex systems. This, in turn, is an obstacle to organizing effective interactions between enterprises of various industries, as well as enterprises of the same industry but of different sizes. The formulation of general system cross-industry principles for the formation of a digital representation of complex technical systems is expected to reduce transaction costs, contributing to the solution of many socio-economic problems [17,18].

The gap which is bridged by this article is a lack of identification and formulation of general system cross-industry principles for the formation of a digital representation of enterprises in various industries analyzed as complex technical systems for its digital transformation. To bridge this gap, the authors have identified the following tasks:

1. A review of publications related to the description of the digital representation of complex technical systems in various industries.
2. Identification of common features of the descriptions of complex technical systems in the formation of their digital representation and formulation of the identified features in the form of principles.
3. An analysis of the applications of the identified principles for digital representations of systems and formation of appropriate recommendations for application of these principles for creation of a digital representation of the representation of complex technical systems.

The authors propose to form a digital representation of all components of the systems and the relationship between these components based on new unified principles. The approach of the authors differs from those previously developed in that the authors identify unified cross-industry principles of system modeling for the formation of digital representations of a system.

2. Literature Review

2.1. Industry 4.0 and the Increased Complexity of Systems

Industry 4.0 refers to the fourth industrial revolution, which is characterized by the integrated adoption of advanced technologies such as the Internet of Things, artificial intelligence, and digital twins in production [19,20]. The interconnection of these technologies contributes to the creation of complex networks and data flows, which, in turn, require complex algorithms and software to manage and optimize their performance. The trend is to create smart factories with increased efficiency, flexibility, and resilience. Companies operating in the real sector of the economy inevitably face the processes of growing globalization and the widespread introduction of digital technologies. Research indicates that companies need to leverage new digital technologies to adjust their responses to external economic conditions based on real-time information [9,11]. The introduction of digital technologies significantly impacts the value of companies, including asset formation [6], risk assessment [7], innovation promotion [8], operational efficiency improvement [9], and reducing the risk of stock price collapse [10]. In many ways, the lack of policy and incentives for implementation, not just the lack of technology, hinders an economic justification for digitalization [21]. As a result, enterprises and industries face the challenge of navigating a complex network of interconnected systems. This complexity has not only transformed industrial processes but has also created an urgent need for qualified specialists capable of effectively managing and maintaining these dynamic, multifaceted systems. Studies have shown that the ability of companies to make decisions related to financial investments is influenced by management characteristics [22,23], corporate governance [24,25], institutional factors [26,27], and external conditions such as the uncertainty of economic policies [28,29]. In many ways, the lack of adoption policies and incentives, rather than the lack of technology, makes it difficult to prove the business case for digitalization [21].

2.2. Digital Solutions and Digital Representation of Systems

Today, the main problem is that traditional engineering methods can no longer cope with the representation of such complex systems, as the complexity of the system grows faster than the capabilities for their effective management [30]. Jack Welch said it best:

"when the rate of change inside the organization becomes slower than the rate of change outside, the end is near" [31,32]. This thesis was discussed as early as 2006 [33], and by 2022 [34], the urgency of solving this issue had become even more relevant. To describe such complex systems, companies need to accelerate the solving of problems associated with digitalization of production, innovation, and acquisition of new skills to remain competitive and achieve success [35–37]. The timely implementation of digital solutions not only advances the product, project, and company, but also enables a quick and adequate response to external changes [9]. To implement digital solutions, it is necessary to transfer physical systems to a digital (virtual) space. This transfer includes the formation of hierarchies of digital subsystems and the corresponding digital representation. The digital representation of the product provides a clear understanding of the structure, functionality, and interactions of the product, which is necessary for its successful development or operation [30]. The creation of an appropriate digital product representation accompanies the product design stage or, in the case of an existing product, the digitalization stage of the product. This stage includes defining the requirements for the product and creating views about the product. The digital representation provides the basis for accurate representation, effective communication, and seamless integration with other systems. The correct digital representation ensures that the attributes, properties, and functionality of the system are accurately represented in the digital product, allowing it to function effectively and fulfil its purpose [31]. A well-defined digital representation facilitates effective communication between the various components of a digital product, ensuring uninterrupted data exchange and reducing the risk of misinterpretation or errors [32,33].

2.3. The MBSE Approach as a Tool for Creating a Digital Representation of a System

Considering the challenges outlined above related to the introduction of digital technologies in companies, it is important to apply a holistic approach that combines technical and organizational solutions. Systems engineering can help in this regard by providing a structured approach to the design, analysis, and management of complex systems that includes both technical and organizational aspects. From a systems engineering perspective, it is promising to consider a manufacturing enterprise as a complex technical system [15]. To manage complex technical systems, it is necessary to have clear, adequate system representations or specifications of components and their interrelationships, functions, and requirements [38]. Decision makers need a method for making better decisions than simply answering the question "should I choose option A or B?" [39]. One approach to describing components and their relationships, functions, and requirements is the MBSE approach. Particular attention should be paid to critical functional interactions between system components and system interfaces, and whether the system can be assembled, integrated, and tested with a minimum level of risk [40,41]. The MBSE approach can be an effective tool for creating a digital representation of a system.

The MBSE approach supports the product lifecycle, which makes it possible to successfully support the process of digital transformation for companies. There are examples of various enterprises around the world benefiting from this approach [42]. According to the International Council on Systems Engineering [43,44], the MBSE approach is a formalized modeling application that supports system requirements, design, analysis, validation, and verification from the conceptual design stage to the development and implementation stages of the life cycle. Therefore, it can be chosen as a method to support digital adoption in companies that use a model-based approach to analyze and manage processes. This paper also posits that MBSE offers a holistic approach to systems engineering based on an evolving system model, including system definition, design, validation, and configuration management. Such a model serves as a "single source of truth" about an enterprise as a system of systems (SoS) or a complex technical system [45,46] (these terms will be used synonymously hereafter). The effectiveness of MBSE stems from the fact that this approach supports the transition from design using highly specialized models (subsystems) to the formation of a single system model to support decision making in all life cycle stages.

MBSE application methodologies allow one to view enterprises from the perspective of an SoS and understand how the various subsystems within the relevant SoS should interact. An important characteristic of MBSE is the possibility of forming an adequate ontology based on the system requirements, which can be used to unambiguously describe the relationships between different subsystems to support the life cycle of an SoS [21]. The most important task to be solved by MBSE is the involvement of a wider range of people in the creation of a single, comprehensive system model, which is used not only by technological subsystems but also by economic, logistical, judicial, legal, and other subsystems. This is a key factor for success in digital technologies. Therefore, MBSE deals with identifying the possibility of the occurrence of collisions and incorporating empirical points of view so that non-expert stakeholders can distinguish between patterns and make timely and meaningful decisions [46].

It is important to note that while MBSE is indeed a prevalent and well-regarded methodology for creating a digital description of complex technical systems, the field of systems engineering is vast and multifaceted [16]. There are other methods, such as enterprise systems engineering (ESE), system of systems engineering (SoSE), software systems engineering (SSE), cyber-physical systems engineering (CPSE), social systems engineering (SSEn), and others. This study focuses on MBSE and does not consider other approaches to systems engineering. While other systems engineering methodologies also hold relevance, the choice of MBSE for this study offers focused and valuable insights into one of the most employed methodologies for managing system complexity.

2.4. Digital Representation as a Stage of Creating a Digital Twin

As mentioned in Section 2.1 of this study, the development of complex technical systems often involves the use of artificial intelligence, machine learning technologies, the Internet of Things, big data, distributed ledgers, and blockchain technologies. A special place in this series is reserved for digital twins, as they can function not only as an individual technology but also as a product of technology application. Digital Twin technology was included in Gartner Inc.'s top 10 strategic technology trends of 2017. This technology is the outcome of the continuous improvement of product development methods and engineering activities [47]. The evolution of these methods began with manual drawings and specifications, then gradually progressed to computer-aided design and finally to model-based system design. Over time, these "ideological twins" transformed into sets of mathematical models, describing real-world objects or their individual properties with varying degrees of accuracy [48]. The digital twin concept allows for the creation of a virtual image or a digital representation of real-world equipment, devices, or systems, ensuring maximum synchronization between the real and virtual worlds. A digital representation of the full life cycle of a product, from the design stage to maintenance, can provide businesses with a predictive analysis of potential problems [49].

According to the classic concept introduced by Michael Greaves, a digital twin is a set of virtual information structures that fully describe a potential or actual real manufactured product from the microscopic to the macroscopic geometric level. Based on the concept of digital twins, digital marketing author Lior Kitain identified four stages of the concept's development, which are clearly presented in the figure below [50] (Figure 2):

- The first stage implies that there is only a real object or process.
- In the second stage, "mirroring" occurs, where a digital version of the real object or process is created, describing the real counterpart with varying degrees of accuracy.
- The third stage begins when a connection is established between a real object or process and their digital version.
- In the fourth stage, there is a convergence and even an intersection of a real object or process with their digital versions.

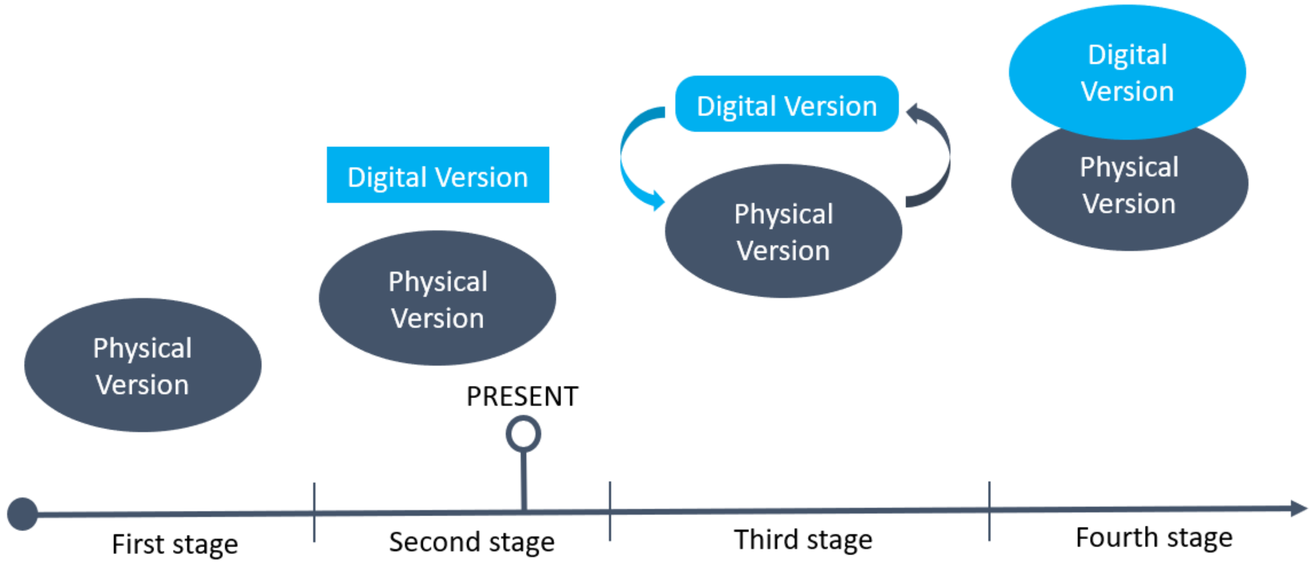

Figure 2. Stages of the concept development of digital twins [50].

In this study, the authors focus on the second stage of digital twin development, where a digital representation of a complex system is created. This digital representation is a "mirroring" of the physical system in the virtual world.

2.5. Cross-Industry Principles for Digital Representation

Based on the above, the MBSE approach can be one of the most effective tools for creating a digital representation of a system [51]. Its application provides a systematic way of collecting, analyzing, and transmitting system requirements, specifications, and projects using models [52,53]. A digital representation of a system is necessary for its effective functioning during the digital transformation process. Literature sources confirm this, emphasizing the importance of standardization, interoperability, and information exchange. The standardization of the process for creating digital representations of systems helps to ensure consistency and compatibility, simplifying system management and maintenance in a digital environment [54]. Adherence to uniform principles facilitates interaction between different systems and ensures seamless data exchange and communication between various components, increasing the overall efficiency of the system. Unified principles for constructing digital representations of systems contribute to effective information exchange, which is necessary for collaborative decision making and management during digital transformations [55].

Therefore, this work aims to reveal the principles of creating a digital representation of a complex technical system. The list of principles discovered can be expanded and refined in future research. Clarifying and supplementing the identified principles in further research will positively impact the results of applying digital representations of systems.

The authors argue that cross-industry principles for developing digital representations of complex technical systems are necessary to ensure consistency in the processes of digital transformation across different sectors of the economy. While different approaches to creating and describing models of complex technical systems in specific industries have been formulated in the literature, general principles that are universally applicable have not been established. The authors believe that this is a significant obstacle to the development of organizations and the overall economy.

By adopting a systematic approach to the development of digital representations of their enterprises during the digital transformation process, companies can achieve greater interoperability and consistency across various systems and subsystems, which is crucial for unlocking the full potential of digital technologies.

3. Materials and Methods

To identify cross-industry principles for digital transformation of industrial manufacturing based on an analysis of publications, an inductive approach was used, considering the recommendations presented in studies [56,57]. The review process was carried out in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Articles were selcted using keywords such as "systems engineering", "MBSE", "systems digital transformation", and "systems digital twin". The authors believe that these keywords reflect the interdisciplinary nature of digital transformation and the complexity of designing and managing complex technical systems in various industries. Additionally, these keywords reflect the requirement for a holistic approach to systems development and the integration of various engineering disciplines into a single system model. The Scopus database was used as the primary source of information. This database was chosen due to its extensive coverage of the literature.

The search strategy included a combination of keywords and Boolean operators. The following search string was used:

("systems engineering" OR "MBSE" OR "systems digital transformation" OR "systems digital twin") AND (publishing date: 2000–2022) AND (cite rating: 20+).

This search string was designed to capture all articles that discuss any of the four mentioned concepts (systems engineering, MBSE, systems digital transformation, and systems digital twin) within the specified publication date range (2000–2022) and with a citation rating of at least 20.

No language or publication type restrictions were applied to ensure a comprehensive search. The search was last conducted on 22 September 2022.

The initial search identified 96 articles. These articles underwent further screening and analysis as described in the following sections.

Other databases mentioned in previous reviews [58–60] were also used, such as EBSCO Business Source Complete (BSC), IEEE Xplore, Web of Science, Science, and Information Systems Association (AIS). In these databases and in the lists of references (with restriction on the date to 2018–2022), we found 388 more articles in addition to the Scopus database. After eliminating duplicates, 416 articles remained for screening. The authors also discarded papers that were not related to technical systems, including papers in medicine and the social sciences. In total, after screening and elimination of duplicates, 108 articles were selected for a detailed analysis. The search algorithm is shown in Figure 3.

In the analysis stage, the information was initially collected and classified according to the problems posed in the publications and the results obtained. Then, the articles were classified according to the main research areas that are presented in the analyzed publications:

- Business processes;
- Production;
- Mechanical engineering;
- IT sector;
- Energy;
- Civil engineering;
- Military sector;
- Aerospace industry.

These categories were selected after an initial review of the articles. Subsequently, each article was analyzed in detail to identify the features of application (principles) of the approach used and to identify whether systems engineering and system modeling were mentioned in it. The principles discovered were included in the general list if they differed from those already identified in previous articles and had characteristics that could supplement or clarify any of the previously listed principles. In some cases, there was a direct indication of the use of a specific principle, but more often, actions were described within the framework of the MBSE approach. Based on the description of such an activity, it was concluded that it corresponded to one principle or another. To justify inclusion in the list, a quote was provided for each identified principle, based on which a conclusion was made about its use. In addition, the authors considered enough industries to confirm the accuracy and universality of our principles.

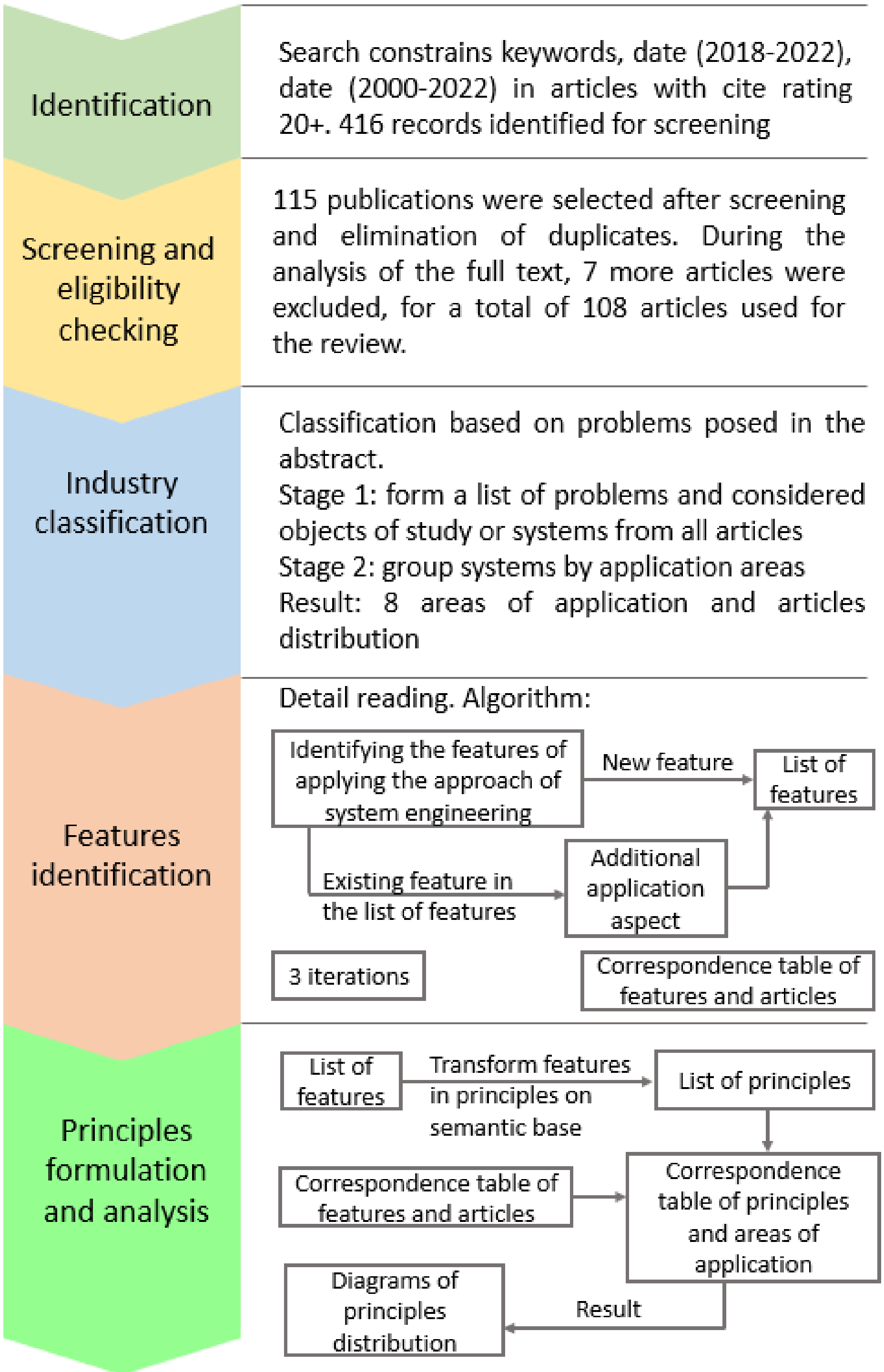

Figure 3. Search algorithm.

After the analysis and collection of identified principles, they were combined according to the proposed way of using the principle. These principles were then adapted to the process of digital transformation of a complex technical system. During adaptation, for each principle, the authors considered whether there were significant features in its application to describe the digital representation of complex technical systems. If such features were indicated in the publications, the authors formulated and classified them in the context of the task of digital transformation being solved. Thus, cross-industry principles were identified and formulated and an appropriate set of recommendations for the formation of digital representations of complex technical systems was drawn up. On this basis, directions for further research also were formed.

As a basis for further analyses, the authors used four well-known and recommended principles for applying the MBSE approach [60,61]:

- The MBSE method should be used semantically, with each concept assigned values within the system and the created digital representation of the real system.
- MBSE should comply with metamodeling criteria, including general rules for building models, such as object types, object parameters, and how to establish relationships between objects.
- Modeling should be carried out ontologically, with certain rules for describing the creation of models, including the types of objects, parameters of objects, and rules for relations between objects.
- The object of modeling should be a certain system and the subject of modeling can be various participants related to this system.

The authors chose these four principles as the main ones based on the monograph [46] and the INCOSE book [43]. While more principles are mentioned in these works, the ones the authors chose are consistent with the general lines of these works [62,63]. These principles were initially adopted based on theoretical results, assuming that they may not be mentioned in publications concerning the theoretical foundations of the MBSE approach. At the same time, the authors analyzed these principles on an equal basis with the others in terms of their inclusion in the articles and their meaning. The authors did not include the basic statements that the MBSE approach defines and models a system, that systems include elements and the relationships between them, and other similar statements related to the definition of the MBSE approach itself as a principle. The authors assume that these statements are generally accepted and, therefore, are not subject to analysis.

4. Results

As a result of the literature analysis, cross-industry principles for system modeling to form a digital representation of complex technical systems were identified. For ease of understanding, all principles are summarized in a single list (Table 1).

To compare the distribution and determine the most used principles across all industries, a summary chart was created (Figure 4). The chart shows the industries mentioned in the studies, with the horizontal axis representing the principles mentioned in research papers. Fragments related to different industries are highlighted in color.

The chart is in a stacked bar chart format, where the total height of the columns corresponds to the ratio of the number of articles that use the principle to the total number of articles considered (100%), which reflects the degree of use of each principle. Each column is divided into shares of using the direction of the principle. For clarity, the color of each share corresponds to the ratio of the number of articles where that principle was revealed to the total number of articles where that principle was revealed (with 100% being the full height of the column).

The following charts (Figure 5) show the percentage of usage of the principles in each direction, allowing for identification of the most and least used principles in industry.

Table 1. Cross-industry principles for the formation of a digital representation of complex technical systems.

System of systems level principles	Metamodeling Ontology Semantics Stability Hierarchy Unified standards Interoperability Transformability Iterative principle Systematic verification Lifecycle
Subsystem level principles	Subjectivity principle Reverse functional Independence Networking principle Externalization Minimization Systematic validation Reusing Visualization 3D model usage "Black box" Generativity

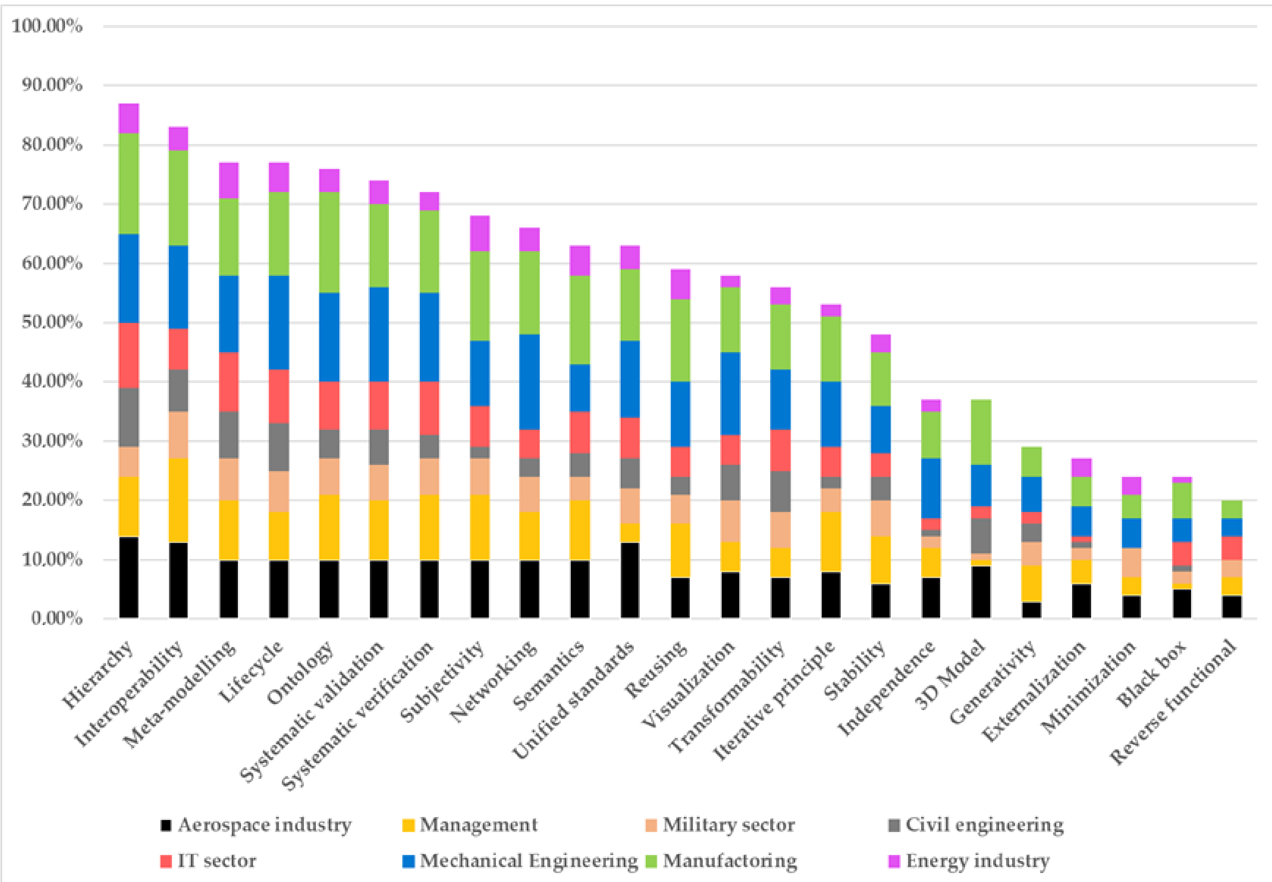

Figure 4. Identified principles and areas of application.

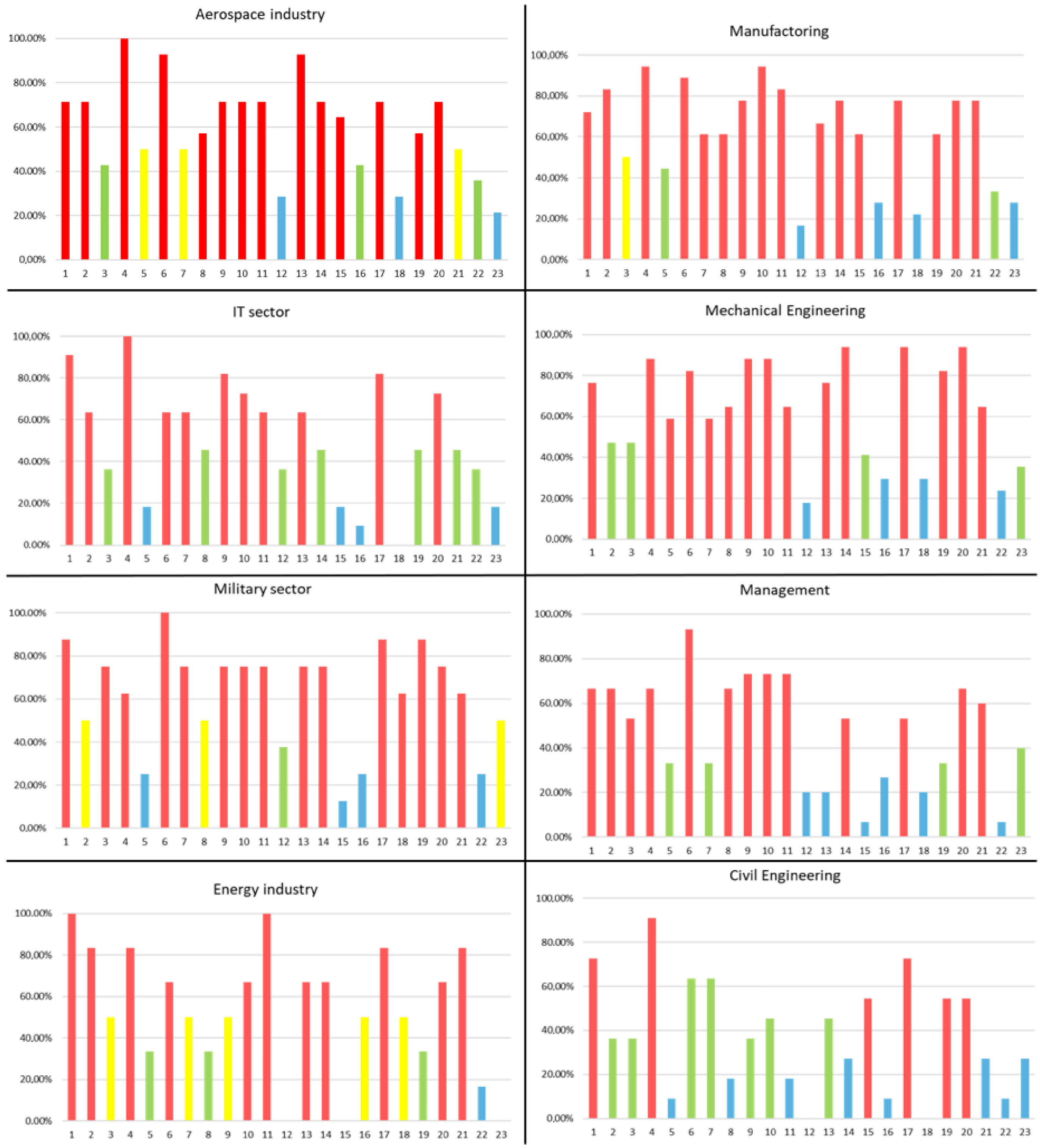

Figure 5. Distribution of principles within each area of application 1—Meta-modeling, 2—Semantics, 3—Stability, 4—Hierarchy, 5—Independence, 6—Interoperability, 7—Transformability, 8—Iterative principle, 9—Systematic verification, 10—Ontology, 11—Subjectivity, 12—Reverse functional, 13—Unified standards, 14—Networking, 15—3D Model, 16—Externalization, 17—Lifecycle, 18—Minimization, 19—Visualization, 20—Systematic validation, 21—Reusing, 22—Black box, 23—Generativity. Legend: Using principles in the industry —more than 50%, —50% (equal), —between 30% and 50%, —less than 30%.

Based on the research results, the following conclusions can be drawn for various industries regarding digital transformation. Aerospace prioritizes hierarchy, interoperability, unified standards, and semantics. Civil Engineering focuses on hierarchy, lifecycle, and meta-modeling. Management emphasizes interoperability, systematic verification, ontology, and subjectivity. In the IT sector, there is a strong focus on hierarchy, meta-modeling, lifecycle, and systematic verification. The military prioritizes interoperability, lifecycle, and visualization. Mechanical engineering highly prioritizes hierarchy, interoperability, systematic verification, ontology, and lifecycle. Manufacturing emphasizes hierarchy, interoperability, ontology, and subjectivity. The energy industry prioritizes meta-modeling, hierarchy, and subjectivity.

In summary, the industries analyzed generally prioritize hierarchy, interoperability, and lifecycle for their digital transformation, with variations in other principles based on the industry's specific needs. Differences across industries lie in the degree to which other principles such as semantics, stability, and systematic verification are applied. This information can help guide the development of digital transformation strategies tailored to each industry's needs and priorities.

Many of the identified principles are based on metamodeling [64–75], which is an origin point that determines the essence and form of creating a suitable model and applying the MBSE approach. At the metamodeling stage, an MBSE implementation plan is drawn up, which describes the planned standards for use, the structure of the model and systems, the roles of the participants, their areas of responsibility, and the semantics of the main concepts as well.

All general concepts used at all levels of decomposition must be defined semantically [66–69,76–78] to ensure the stability and interoperability of the model. This means that all concepts and terms using during model development are compatible with each other and do not have direct contradictions. However, different systems, models, and systems of systems can use different semantic definitions specific to a particular industry. To resolve possible conflicts at the metamodel level, it is recommended to provide a semantic transformation mechanism for information exchange between components with different semantic characteristics and features.

The research in [79] alludes to the principles of semantics and metamodeling. The first step of the study was to develop concepts and their relationships that were gathered in a metamodel. Basically, concepts represent the elements, allowing their description, and formalize a domain. The study details the development of concepts and their relationships, which are subsequently assembled into a metamodel. It portrays concepts as crucial elements that aid in the description and formalization of a domain. While the term "semantics" is not explicitly mentioned, its substance aligns with the description, leading us to infer that the principle is indeed applied in the context of the study.

The **stability of a system** [80–83] generally means that when making small changes to the model or system, the functioning of the system as a whole will not be disturbed. In other words, with small violations of the links between the components of the system the system as a whole, it does not fail. As an example of this in an article [84], it is said that the stability could be technical features that are expected from the system as a whole, such as resilience, flexibility, and interoperability.

An analysis of the application of the approach shows that it is important to provide a **hierarchy**, which involves dividing a system of systems into different levels of decomposition and nesting components within each other [84–88]. Hierarchical modeling involves integrating validated subcomponent-level, component-level, or subsystem-level models into a large-scale system-level model [85]. To determine the boundary conditions of a complex technical system, it is necessary to rise to the level of a hierarchically higher complex technical system and identify the incoming and outgoing data in the complex technical system under consideration, and vice versa to the hierarchical level of the lower complex technical system, and repeat this process iteratively [84–88]. As the model and structure of the system are built, these operations must be repeated and, if necessary, move along the chain to even higher and lower levels of complex technical systems. Depending on the context in which the system is considered, the chain of nesting of systems should be analyzed. In most cases, it is advisable to define no more than two–three such "systems within systems". It is also assumed that, in the general case, any chosen SoS has an SoS of hierarchically higher and lower levels.

The hierarchical chain described above also considers the principle of **independence** [89], which implies that a virtual (digital) and a real object can evolve as a system without directly influencing each other. Reference [89] describes this concept in the context of design and manufacturing using the example of a pipe object. This object, defined by static attributes such as geometry and materials, connects the design and manufacturing worlds, serving as a bridge between the two. The concept functionally divides the work of one model into two parts: one that directly affects the three-dimensional physical components and the second where the system and model operate independently. Thus, when making changes to the system of a virtual object, there is no need to immediately modify anything in the system of a physical object and its components and vice versa.

In the structure of the system and the model, **interoperability** [90–94] of all components, including systems, components, requirements, functions, and processes, should be organized, among which bidirectional links are established. Reference [90] elaborates on this by explaining that interoperability is achieved through the sharing and exchange of various outputs. Each output serves dual roles—it is the product of its origin (creator, provider, or sender) and simultaneously becomes the input for its recipient (receiver, consumer, or destroyer). As such, the term "output" in this context transcends the traditional concepts of inputs or outputs, and is applicable even when it is in transit between two system of systems (SoS). This can be achieved using matrices in the MBSE approach [90] and multi-criteria analyses of the significance of the components and their relationships. Therefore, information and data must be **convertible** [52,64,65,73,95–102] when moving from one industry or system to another. This can be achieved through the use of a single modeling language or common standards for all components, as well as through a meta-model, which, in this case, is a "model of a model" that maps heterogeneous lower-level models through a single higher-level model. In reference [103], the construction of a metamodel and its subsets of relationships are explained. This is then linked to the DEVS (Discrete Event System Specification), thereby facilitating convergence between the two. Additionally, the principle of unified standards is discussed in [86], where it is highlighted that the use of MBSE methodologies can improve communication between internal and external stakeholders through the use of tailored model views and standardized language, as per Walden et al. and Beihoff et al. **Externalization** is also associated with this principle, which is the transfer of knowledge and practices from one area or industry to another within the framework of a common system. In particular, in the article [82], it is stated that "to create the methodological approach of knowledge externalization that complements and supports the textile PDP and its stakeholders, BPM and MBSE have been identified as facilitators of knowledge creation, knowledge sharing, and knowledge utilization between stakeholders".

The principles described above, similar to all others, should be applied iteratively [104–109], i.e., cyclically repeating operations after making changes to the real system and model and obtaining new information. For example, this may involve navigating up and down the hierarchical chain of systems to analyze incoming and outgoing data, combining real and virtual test data, adapting a product model based on real experience, and adjusting real usage based on simulation data. Any such processes should be continuously performed to improve accuracy and provide adequate feedback. For instance, reference [65] discusses this principle in the context of the staged introduction of MBSE. The iterative approach offers insights into various facets of MBSE, advocating for a blend with existing processes where necessary, rather than a wholesale change in working methods, thereby ensuring non-disruptive integration.

Together with **iterative** repetition of operations at each stage, **verification** [89,92,110,111] of the model and the upper-level system is necessary. This means checking whether the model and the SoS still correspond to the principles and rules defined by semantics and the meta-model, or if there are any deviations. Verification and validation are mentioned in almost every article on MBSE. For instance, reference [73] stresses that with the growing maturity of model-based design and construction, there is an accompanying rise in the need for system-centric methodologies and toolsets. These aid in supporting system integration, requirement management, verification, validation, and configuration management, which are crucial if model-based information is to effectively assist in the operation of complex civil building infrastructure projects.

Continuous **validation** is a key principle mentioned both in MBSE theory and in publications [39]. Validation, in contrast to verification, aims not to check the entire complex technical system and its model for compliance with general rules and its theoretical correctness, but to check (test) the characteristics of individual components of the model. In particular this includes checking for compliance with the ontology, checking for compliance with the behavior of the model and the real object, and maintaining connectivity with other system components.

To verify and validate a complex technical system for safety and stability, the principle of **reverse functionality** is used [112–115]; the state of a complex technical system is built, in which the performance of functions is disrupted or not performed, failures occur, processes do not work in the standard mode, and components are broken. In this case, the result can be achieved by building connections between the system and the "anti-system", between functions and anti-functions, and between processes and anti-processes. Through these connections, it is possible to determine the mechanisms for the occurrence of an emergency and the connection of this mechanism with other components and possible sources of occurrence. The principle of inverse functionality is considered as one of the stages in the application of MBSE, as outlined in [113]. This suggests that the second step involves generating functional failure modes and other related failure modes and effects analysis (FMEA) data defined by or specific to customer-required data needs. The task of failure mode generation could be as straightforward as converting a functional statement into an anti-function statement to describe a failure mode.

Ontology is a special case of metamodeling of a particular considered subsystem or system component [34,46,66–69,80,100,108,116–120]. When constructing an ontology, the rules for a given component, its semantics, information about it, and its attributes are determined. The use of ontology, in essence, is referenced in [121], where a knowledge repository is described as a central component of the methodology. This repository accumulates expertise, experiences, patterns, and reference models, promoting the reuse of experiences by enhancing their model with best practice patterns or by avoiding repetition of past errors. The primary goal is to improve efficiency during the commissioning design and execution phases. As the work primarily revolves around models, the most crucial elements of the knowledge repository are patterns and reference models.

One of the main principles of the application of MBSE, which also provides interoperability, is the principle of **subjectivity** (context) [34,81,94,96,99,122–125]. Following this principle, a complex technical system is modeled, developed, and used in different contexts from different points of view with respect to specific tasks and industries. At the same time, the complete system combines all these contexts into a single whole unit. This approach reduces resources and time, since aspects that are not essential to this task are not considered and different aspects can be considered at the level of model definition. It directly follows the principle of network organization (**networking**) [79,92,115,122,126]. According to this principle, when developing a model and describing a complex technical system, it is necessary to involve specialists from various industries. A depiction of the application of these two principles can be found in [121]. The authors propose enhancing the coordination and integration of activities from all stakeholders involved in the design and realization phases of a complex system. The aim is to bridge the gap between systems engineering processes, model-based systems engineering practitioners, and actors involved in the integration, verification, or validation of the system. Each participant focuses on their specific objectives, such as requirements engineering, architectural design, and integration, verification, or validation of the system.

A special role is played by the application of the principle of minimization [39,70,89,127–132]. According to this principle for solving specific problems, information should be provided in the minimum necessary volume. For example, the graphical description should be as clear and understandable as possible and as minimalistic as possible, while the system representation should remain holistic. Following the minimization principle makes the reduction the time of analytics, model development, data reading, and workplace automation of resources possible, since the time resource often plays a more significant role than an additional increase in accuracy (adequacy). One can find an application of this principle in [85], where the authors caution against merging various datasets indiscriminately. They argue that a smaller, "clean" design matrix sometimes proves more useful than a larger "ill-conditioned" or imbalanced dataset. At the same time, a graphical representation (visualization) of a specific task is itself significant for teamwork and the use of this part of the model [99,104,133]. The authors of [121] provide an example of a visualization principle, emphasizing that the visualization method should allow for data viewing and analysis results while preserving important relationships between the information and illustrating the behaviors of the concerned processes.

The "**black box**" principle also belongs to the category of subsystem-level principles [99,104,133]. In accordance with this principle, when developing and using models, in the first steps, only the input and output data of a specific subsystem or its components are used, without considering the processes occurring inside the subsystem. In subsequent stages, if necessary, a "white box" is used, where the internal structure inside a component or subsystem is described in detail. Reference [79] mentions this black box principle, elucidating its objective to express functional requirements relative to the system of interest's (SoI) behavior in terms of input/output functions across various fields, facilitate communication of system black box behavior through a simple language, enable system analysis through simulations, and enhance traceability by linking requirements to behavior and modes. This approach supports the redefinition and sharing of requirements to be met by the SoI without ambiguity.

In many publications, the system **life cycle** is the focus [21,52,68,79,93,99,116,120,134–139]. To the regular matrices of the MBSE approach, a time matrix, which represents various system states as they change, and life cycle scenarios in the form of successive branched chains of events are added. This is an important component of a single system model because it allows for managing changes in the system both at the stage of its formation and during subsequent changes. The life cycle principle is articulated in reference [121], emphasizing the importance of establishing this link at the earliest possible stage from the initiation of the design project to ensure efficient and significant interaction between the subsequent phases.

The consideration of the life cycle and the principle of minimization lead to the principle of **reuse** [76,78,99,120,126,131,140,141] of the developed fragments of the model and the revealed structures of systems. This is most relevant for products whose role in the life cycle is identical or similar. Reference [121] illustrates this usage, it outlines how a pattern, a set of models, and related information offer a tried-and-tested solution to a recurring problem and enable engineers and architects to relate a problem to a pre-validated solution. This solution can then be partially reused for analogous issues. This also implies the principle of **generativity** [52,68,73,76,82,83,87,114,142,143], which means the use of systems of development scenarios to obtain the widest possible range of its possible states in an automated way and the subsequent selection of optimal states from this spectrum. In this case, generation is carried out recursively at different levels of the system hierarchy [144] according to similar algorithms with different parameters.

At the same time, following the principle of independence, there is a certain set of mandatory system components that is common to any level of nesting and hierarchy and is tied to real physical objects. The key link here is the **3D model** [68,78,89,102,120,122,129], which serves as a bridge between the real and digital world. When working with complex technical systems, it is almost always necessary to use a 3D model as a link or a common base spatial reference to develop a single system model. Reference [68] illustrates this point, it explains how 3D simulation models allow workers to gain an in-depth understanding of the tasks required to achieve a specific setting.

Thus, based on a comprehensive analysis of the publications related to the description of digital representations of complex technical systems in various industries, common features of the description of complex technical systems were successfully identified. The identified features were formulated in the form of cross-industry principles for the formation of a digital representation of enterprises in various industries analyzed as complex technical systems (see Table 1).

5. Discussion

5.1. Additional Recommendations for Applying the Principles Formulated above to Develop a Digital Representation of Complex Technical Systems

This section is primarily devoted to additional recommendations, which are partially presented in the previous section, for applying the principles formulated above to develop a digital representation of complex technical systems.

Based on the reviewed publications, it can be concluded that the more complex the system and its model are, the more principles are used. However, applying these principles requires a certain level of digital maturity within the company [145,146]. Companies can achieve levels 4 and 5 of digital maturity (autonomous production and autonomous organization) by developing a single system model according to the MBSE methodology. To reach these levels, companies must first undergo significant digitalization of processes and objects (level 1), selective implementation of advanced analytics (level 2), and interdisciplinary optimization (level 3).

All the identified principles in the article should be used in accordance with the description presented in the results. However, their application to creating a digital representation of complex technical systems requires specific considerations. It is recommended to implement the principle of metamodeling and use platform solutions to combine heterogeneous models and manage complex technical systems. Semantics ensure the stability of a complex technical system by clarifying concepts in a new, transformed environment. If digital technologies cannot create a digital representation of any part of a complex technical system, it is recommended to apply the principle of independence until the necessary technologies become available. The connection between the model and the physical world should be based on 3D models. With proper development of digital technologies, testing on physical objects should be minimized. Automated mechanisms for verification and validation should be provided. The ontology of a complex technical system must be dynamic, with an automated update based on new scientific and practical knowledge. Networking should be organized for a complex technical system and life cycle management on a permanent single platform. Generation and reuse should be critical principles in the final stages of development. The remaining principles are mandatory for consideration in system modeling based on MBSE, although they do not have specific applications.

For a more comprehensive collection of the fundamental principles of systems engineering, the authors recommend referring to INCOSE reports [43,44]. They do not believe that the principles outlined in this article conflict with those outlined in these reports. However, the reports focus more on the fundamental principles of systems engineering, on which there is consensus in the MBSE community, and the principles in this article are more of a generalization of the observational practice of applying them for creating a digital representation of a system using the MBSE approach. Therefore, proving cross-industry principles and reaching a consensus on their application may be the subject of further research.

5.2. Commonality in Digital Transformation

The research in [14,147] also raises questions about the need for commonality in digital transformations. The literature review in [14] identified and analyzed eighteen confirmed digital maturity models and frameworks which describe various dimensions that should be considered for a digital transformation strategy. The main result of the work was the identification of action fields, along with optional additional dimensions, which should therefore be discussed in all digital transformation strategies. The study reveals that a clear conceptualization of the impact of digital transformations on incumbent firms' business models was missing [147]. This study aimed to approach these research gaps by exploring the impact of digital transformations on the overall business model of incumbent firms across different industries, thereby examining the nature of this impact to provide detailed information about how this impact can be conceptualized and what it means for an incumbent firm.

The authors' research and the cited research both contribute to the broader discourse on digital transformation by identifying universal principles or dimensions and addressing gaps in the current knowledge. However, while the cited studies focus on digital transformation strategies and impacts on business models, this study takes a more technical approach by focusing on the development of digital representations of complex technical systems using the MBSE methodology. References [14,147] share some similarities in terms of recognizing the need for common principles or action fields in the context of digital transformation and the identification of gaps in current conceptualizations of digital transformations. Our study and the literature review in [14] underscore the importance of establishing universal principles or action fields that can guide digital transformation across various industries.

5.3. Problems in Applying the MBSE Approach

MBSE is suitable for creating custom models of complex technical systems that can select and describe the relationships between components, functions, processes, and requirements according to the concepts of systems engineering [148]. MBSE supports an effective approach for providing definitions, communication, clarity, and adaptability within systems engineering projects, as well as assessing the cost, evolution, implementation time, and security requirements [51]. These factors work together to reduce errors and facilitate faster decisions throughout the entire life cycle of the product.

Regarding the problems in applying the MBSE approach to the digital representation of enterprises, existing reviews primarily indicate issues with verifying and validating models, maintaining a balance between the complexity of models and the need to maintain their performance, and problems with semantics and the universalization of modeling languages. There is a significant gap in the data regarding successful implementation of the MBSE approach in digital transformation practices, as well as in the ability to identify potential problems related to such implementations [46]. According to a recent study [85], an effective examination of the behavior of a real production system requires the use of substantial resources and significant computation time by models, but there are also uncertainties due to simplifications in model development. Single simplifications and idealizations may not have a significant impact on the operation of a particular model. However, when combined in a single model, they can have a multiplicative effect and result in errors. The solution to this problem can be the use of the MBSE approach when developing approaches to validation, verification, and calibration when integrating simplified models into a single model, including the possibility of considering indirect influences on results from different factors. Thus, one of the most important tasks, which has been analyzed in many publications, is verifying the models used. A recent study [69] established ten paths to successful verification using the MBSE approach.

6. Conclusions

Based on an analysis of the successful application of the MBSE approach for building system models, eight areas were identified in which the MBSE approach can be used to develop a digital representation of technical systems: business processes, production, mechanical engineering, the IT sector, the energy sector, civil engineering, the military sector, and the aerospace industry. Then, based on an analysis of the features for building a system model in the process of creating a digital representation of enterprises in various industries, 23 corresponding cross-sectoral principles for the formation of digital representations of complex technical systems were formed and classified in Table 1.

Using universal cross-industry principles to develop a digital representation of complex technical systems can help companies ensure a successful and sustainable digital transformation. By taking a standardized and systematic approach to digital transformation, companies can achieve greater interoperability and connectivity between different systems, which is critical in realizing the full potential of digital technologies. These principles are recommended as practical guidance for companies and organizations when developing their digitalization strategies. By following universal principles, companies can capitalize on the collective knowledge and experience of the industry, digitally building on existing workforce knowledge and experience, avoiding common mistakes, and ensuring that their digital transformation efforts are aligned with best practices and industry standards.

The resulting distribution (Figure 2) of application of the identified principles in various industries is recommended to be used as an indication of possible necessary directions for systemic changes in the organization of work within these industries and within individual enterprises. The analysis showed that principles such as independence, reverse functionality, externalization, 3D model use, and "Black box" are the least used but no less valuable than the others. This means that their application and implementation in each industry require additional research.

Further directions for research primarily include practice-oriented studies of functioning interdisciplinary models built according to the MBSE methodology. Another promising direction may be the search for an industry or activity that can serve as a universal system and the basis for a single model to which all other industries and sub-models can be tied.

Based on the foregoing, research is relevant to clarify the problems and limitations associated with the digitalization of manufacturing companies in the context of MBSE. There is a risk that digitalization, which requires extensive changes in business processes, will face serious difficulties due to the inability of enterprise management to change generally accepted business models of production. At the same time, insufficient attention is paid to the digitalization of relationships, processes, functions, and requirements and the creation of appropriate digital representations.

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