Journal of Infrastructure, Policy and Development 2024, 8(14), 7983.
https://doi.org/10.24294/jipd7983

Article

Model-based system engineering approach for existing industrial enterprise digital transformation

Vladimir Badenko[1,*], Vladimir Yadykin[2], Elena Tishchenko[3], Galina Badenko[1], Luka Akimov[1], Victor Barskov[4]

[1] Civil Engineering Institute, Peter the Great St.Petersburg Polytechnic University, 195251 St.Petersburg, Russia
[2] Advanced engineering school "Digital Engineering", Peter the Great St.Petersburg Polytechnic University, 195251 St.Petersburg, Russia
[3] Faculty of Economics, Moscow State University named M.V. Lomonosov, 119991 Moscow, Russia
[4] Energy Institute, Peter the Great St.Petersburg Polytechnic University, 195251 St.Petersburg, Russia
*** Corresponding author:** Vladimir Badenko, badenko_vl@spbstu.ru

CITATION

Badenko V, Yadykin V, Tishchenko E, et al. (2024). Model-based system engineering approach for existing industrial enterprise digital transformation. Journal of Infrastructure, Policy and Development. 8(14): 7983. https://doi.org/10.24294/jipd7983

ARTICLE INFO

Received: 14 July 2024
Accepted: 19 August 2024
Available online: 20 November 2024

Abstract: The article presents an answer to the current challenge about needs to form methodological approaches to the digital transformation of existing industrial enterprises (EIE). The paper develops a hypothesis that it is advisable to carry out the digital transformation of EIE based on considering it as a complex technical system using model-based system engineering (MBSE). The practical methodology based on MBSE for EIE digital representation creation are presented. It is demonstrated how different system models of EIE is created from a set of entities of the MBSE approach: requirements—unctions—components and corresponding matrices of interconnections. Also the principles and composition of tasks for system architectures creation of EIE digital representation are developed. The practical application of proposed methodology is illustrated by the example of an existing gas distribution station.

Keywords: model-based systems engineering; system architectural model; digital representation; digital transformation; complex technical system; existing industrial enterprises; gas distribution station

1. Introduction

The modern development of the economy requires for industrial enterprises (IE) transition to manufacturing, which is based on the mass introduction of information technologies and digital models of both individual products and the IE infrastructure as a whole (Ghobakhloo and Fathi, 2019; Kaiser et al., 2023). This transition is commonly referred to as the fourth industrial revolution within Industry 4.0 concept (Cimino et al., 2023; Fang et al., 2023; Matarazzo et al., 2021; Schlemitz and Mezhuyev, 2024; Veile et al., 2020). The digital transformation for existing industrial enterprises (EIE) that have been operating since the last century, is a more serious problem than for new ones (Chen et al., 2024; Skare et al., 2023). To take all the advantages of digital technologies during EIE digital transformation, it is necessary to create a digital representation of EIE in the virtual (digital) world and to connect it with a physical object in the real world with two-way information links (**Figure 1**). This representation is often called a "digital twin" (DT), but the scientific community has not yet come to a common understanding of what an IE DT is and this issue continues to be widely discussed (Liu, et al., 2024; Tong et al., 2024). Thus, ideally, we are talking about the creation of an EIE digital twin and forming an EIE digital asset (Fett et al., 2023; Kukushkin et al., 2022; Psarommatis and May, 2023; Yadykin, et al., 2021). Modern approaches to product manufacturing involve the creation of IE digital representation based on introducing digital technologies throughout all steps of IE life cycle: from design to operation, balancing all criteria: technological, economic, environmental and social (Bai et al., 2020; Bolshakov et al., 2023a; Varriale et al., 2024). However, for an EIE, it is sometimes more economically advantageous to create a new enterprise instead of modernizing the old one (Gajo and Akyuz, 2023).

It is advisable to use system engineering methods for the creating of the EIE digital representation, because EIE is a complex technical system (Badenko, et al., 2021; Bolshakov, et al., 2023a). When considering such systems, many specialists, including the US Department of Defense and NASA, distinguish the "system" and "system of systems" concepts (SoS) (Elhabbash et al., 2024; Maier, 1998; Swickline et al., 2024). Enterprises are unanimously classified as SoS. This situation defines another problem in EIE digital representation creation, related to the complexity of objects.

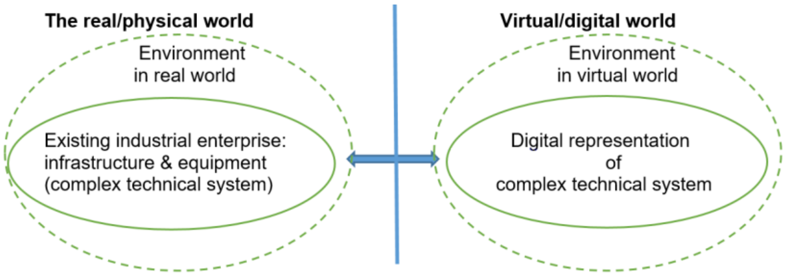

Figure 1. Complex technical systems in the real (physical) and virtual (digital) worlds.

Thus, the task of EIE digital representation creation is urgent and requires a special methodological approach. The authors suggest that this task should be carried out on the basis of system engineering tools and its modern version of a model-based system engineering (MBSE) (Henderson et al., 2024; Madni and Sievers, 2018; Papavasiliou et al., 2024). In general, engineering includes methodology, methods of representation, tools and processes for the creation and application of artificial objects (Henderson and Salado, 2021; Vernadat, 2014). The practical application of MBSE in a development of digital representations of technical objects has shown that different models (verbal, expert, mathematical, digital, intellectual) are effectively complement each other. Therefore, an urgent task is to form practical methodological approaches to the systematic and effective integration of mentioned different models (Bolshakov et al., 2023b; Tikayat Ray et al., 2023). MBSE is originated and developed as a response to these challenges, allowing combination and use of various types of models in engineering (Henderson et al., 2024; Madni and Sievers, 2018; Younse et al., 2022). According MBSE, we propose to arrange a reference structure of system engineering models on the principle of development sequence: verbal (logical-semantic models)—ontological models—architectural models—parameterized architectural models—mathematical models—computer models (**Figure 2**). Verbal (logical-semantic models) represent selected significant semantic elements of information in the form of keywords and identify relationships between them. Ontological model is a breakdown structure of terms and concepts. Architectural models are a representation of main

MBSE entities (requirements, functions, components) by breakdown structures and their interconnections in a matrix form. Parameterized/attributed architectural models expand architectural models with quantities and qualities characteristics (attributes) of entities. In mathematical models, information about entities is represented in mathematical symbols and expressions that formulate relationships between entities attributes. Computer models represent mathematical models in as a set of data and program code to be executed in a computer environment. Each subsequent model type is harmonized with the previous representations, inherits and complements them with new additional properties and characteristics.

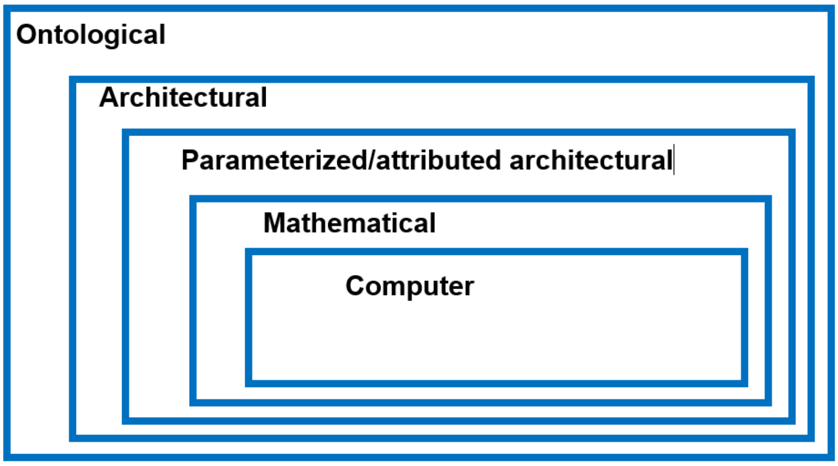

Figure 2. The basic reference structure of MBSE models.

The systems engineering community has turned to MBSE to improve an efficiency in a managing complexity, maintaining consistency, and ensuring systems development process traceability (Madni and Sievers, 2018; San Cristóbal et al., 2018; Swickline et al., 2024; Voth and Sturtevant, 2022). If MBSE is used for digital-based manufacturing transition, the reengineering methodology will be successful for performing the stages of a reverse engineering and restructuring (Henderson et al., 2023; Huang et al., 2020; Madni and Purohit, 2019). MBSE, according Madni and Sievers, 2018, is a holistic system engineering approach centered on the evolving system model, which serves as the “sole source of truth” about the system. Despite the fact that MBSE is beginning to find wide application in many industries, there is still an insufficient information about specific achievements that realize all MBSE advantages (Bemmami and David, 2021; Cameron and Adsit, 2018; Henderson and Salado, 2024; Schummer and Hyba, 2022).

The digital transformation of EIE is one of the most important phenomena of the 21st century and is determined by new technologies driven by Industry 4.0 concept (Fang et al., 2023; Matarazzo et al., 2021). However, existing reengineering methodologies use ideal business processes collected using subjective information from interviews with industry experts or company’s documentations, rather than actual processes collected based on real data (Weerakkody et al., 2021). MBSE solves this contradiction, and its tools will serve as the basis for planning digital transformation and provides manufacturing companies with simple and effective implementation plans (Henderson and Salado, 2024; Huldt and Stenius, 2019). At the same time, there are lot of evidences that digital twin technologies, together with MBSE, provide effective continuous updating of system models throughout EIE entire life cycle (Badenko, et al., 2021; Laing et al., 2020; Yang et al., 2023). This trend is confirmed by the fact that in Russia in 2022 and in China in 2023, national standards "Digital Twin of Products" were introduced, which provided an ontological description of the terms and concepts of digital twins, as well as general provisions and requirements for the development and application of digital twins (Kukushkin et al., 2022).

In general, it should be noted that although system engineering has been developing for quite a long time, its practical application is still lagging behind (Bretz et al., 2019; Huldt and Stenius, 2019; Meißneret al., 2021; Verbruggen and Snoeck, 2023). In a recent publication (Henderson at al., 2024), in particular, it is noted that successful stories, studied during MBSE implementations, are one of the key ways to disseminate best practices and recommendations for MBSE. Based on the literature and interviews with practitioners in this study, there is likely still a lack of understanding or confusion about what MBSE is and how to implement MBSE in practice. Therefore, the development of practical methodology for systems engineers, that describe techniques and steps for creation of EIE digital representation is relevant

Often the existing practical recommendations are either narrow-profile and focused on newly created facilities, or too general (Buschhaus et al., 2024; Hennig and Szajnfarber, 2023; Henderson and Salado, 2024). The growing understanding of needs to develop practical recommendations for expanding the introduction of new digital technologies, in particular digital twins, is actively forming new methods and tools of digital system engineering that allow ensuring the proper level of adequacy (Bone et al., 2019; Campo, et al., 2022; Henderson et al. 2023; Madni et al., 2019). Also it is interesting to note as verbal models created within the framework of MBSE using ChatGPT, took their place in system engineering methods development (Mitola and Prys, 2023; Titus, 2024; Zhang and Yang, 2024).

An object for this research is an existing industrial enterprise (EIE), that is not often found in publications. The paper objective is to present practical methodology for development of an adequate EIE system architecture, which can serve as the basis for the EIE digital representation creation and in a future for a EIE digital twin. EIE digital representation based on MBSE will ensure the integration of process and events models, consolidating information into an accessible centralized source (Guide, 2024; INCOSE, 2023) for predicting EIE behavior. According methodology proposed the EIE and its digital representation will have a single system architecture model. The authors consider an urgent task of developing a sufficiently universal practical methodology. The methodology has been developed on a base of the MBSE principles as a practical tool for system engineers. To illustrate the proposed methodology, a problem of digital representation creation of a standard gas distribution station (GDS) is considered. Such facilities are an integral part of any gas distribution network worldwide. The example is a typical one and can be used as a reference for projects for creation of EIE digital representations in a number of energy and mechanical engineering sectors. The versatility of the proposed methodology allows it to be used in other industries and countries.

2. Materials and methods

The materials for this work were documents from The International Council on Systems Engineering (INCOSE) in practicular last Released 6 May 2024 (Guide, 2024) and published case studies of specific projects. Materials from projects implemented at Peter the Great St.Petersburg Polytechnic University (Russia) and Moscow State University named M.V.Lomonosov (Russia) were also used (https://ncmu.spbstu.ru/article/publikacii-ncmu). When developing the practical methodology, the method of analysis and synthesis of the activities of systems engineers was used.

MBSE-based digital representation projects start with a domain ontology creation (Elhabbash et al., 2024; Lu et al., 2021; Sanfilippoet al., 2019). Ontology consist of basic concepts definitions reference books that are used during the creation of EIE system architectures. Such models are textual descriptions of system model entities in a unified form of reference books, hierarchically structured entities (requirements, functions, components and processes) (Browning, 2015; Henderson et al, 2024; INCOSE, 2023; Lu, 2021; Purohit and Madni, 2021).

System modeling treats the EIE as a system. It starts with the architectural modeling of the system and covers, first of all, the compilation, analysis and synthesis of reference books of requirements for the EIE and its functions and components, including its interconnections using interlevel and intralevel dependency matrix (Purohit and Madni, 2021). The concept of requirements for target objects is part of the key principles used in system engineering (Boehmet al., 2012; Bolshakov et al., 2023b; Madni and Sievers, 2018). The requirements reflect, in the form of compact text entries, the engineer's ideas about what the EIE should correspond to, its goals, the value of the EIE as an artificially created system, the functions, the criteria and limitations that the EIE must meet. When documenting requirements, an unambiguous indication in the imperative mood is recommended and formulated according to SMART (Specific, Measurable, Achievable, Relevant) rules, essential at the selected level of hierarchies of consideration, traceable and available for analysis. Requirements are presented in the form of an indexed hierarchically ordered directory, which we will call requirement models or Requirement Breakdown Structure (RBS). Requirements are validated (assurance of their correctness is provided, for example, through expert assessments) and verified (verification of correctness is provided, for example, through tests).

The requirements representation and modeling policies are as follows:

- The description is carried out within the given subject area boundaries, for example, EIE physical and technical components;
- Requirements records are placed in a reference table, in which indexing reflects requirements hierarchical ordering and its taxonomy;
- Requirements attributes are set taking into account their measurement units;
- The text records of the requirements comply with the SMART rules.

Identification of the EIE physical components is conducted in such a way to ensure of the EIE requirements and functions fulfillment. In practice, a significant part of the components is identified on the basis of existing components with the addition of new innovative components during reengineering, taking into account alternative options for the EIE physical architecture. Text records about components are arranged in the form of an indexed hierarchically ordered set of physical components, which we will call physical architecture of EIE or Component Breakdown Structure (CBS). The records about physical components, as well as the requirements, are validated and verified.

System engineering involves taking into account, documenting and balancing the interconnections of the EIE entities (requirements, functions and components). This reflects the essence of a system approach to the modeling and design of technical objects. For the EIE entities relationships modeling, entity interconnectivity matrices are formed according to the selected levels of the object hierarchy. Such design structure matrices (DSM), also called the dependency structure matrices, have become a widely used modeling framework across MBSE applications (Browning, 2015; Hennig and Szajnfarber, 2023; Purohit and Madni, 2021; Rehberg and Brem, 2024; Sharon et al., 2013). In this matrix-based approaches for MBSE, the system architecture is represented as a $N \times N$ square matrix in which the rows and columns represent the N entities while the body of the matrix represents the interactions between the entities. These matrices should also be considered as structured text models of the EIE in the form of a text records database about the structure of the entities and their relationships. Thus, all models of EIE behavior should be based on EIE entities interactions (Guide, 2024). The general methodological approach proposed by the authors within the framework of MBSE to structuring of EIE representation in the form of system architecture models set is shown in **Figure 3.**

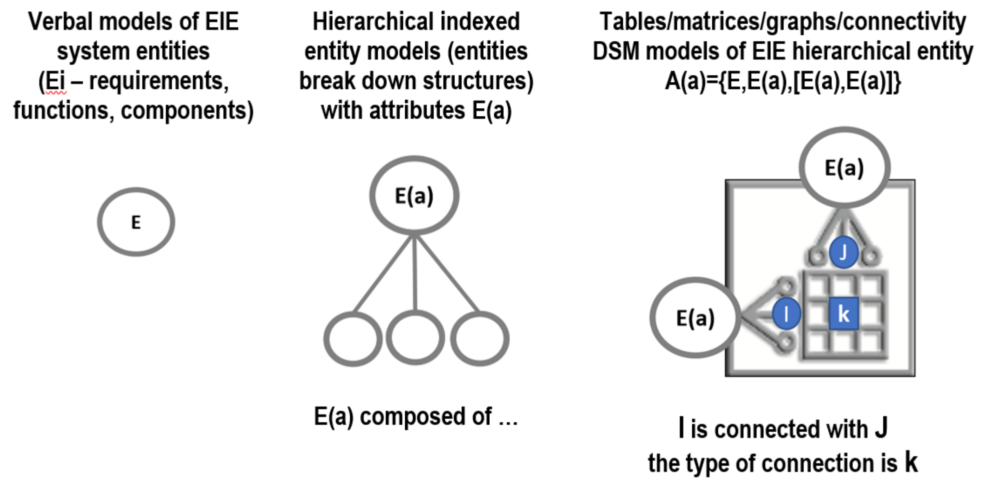

Figure 3. A structured representation of EIE in the form of architectural models A(a) = {E,E(a),[E(a),E(a)]}.

For system models descriptions, it is recommended to use, according to three pillars of MBSE tools: tool, method, language (Khandoker et al., 2022), specially developed languages. The most common among the languages for creating system models is undoubtedly SysML (Fang et al., 2023; Shoshany-Tavory, et al., 2023; Swickline et al., 2024). However, when developing the EIE system architecture models, one of the most important requirements is accessibility for understanding by all stakeholders. Therefore, sometimes it is more convenient to use simpler software, for example, MS Excel. This approach will be used in the rest of the manuscript.

Thus, a general scheme for the EIE digital representation creation of can be seen in **Figure 4**, which shows a framework of the proposed methodology in the form of an iterative process. The essence of the proposed mrthodology to EIE digital transformation is in the iterative processes supporting that forms the basis of the MBSE methodological approach: Verbal models → Architectural models → Parameterized architectural models → Mathematical models → Computer models → Digital models.

During the implementation of the proposed methodology, the representation of the connectivity (interconnections) of the EIE entities for a system model in the form of the DSM is particularly difficult. When filling out the DSM, the system engineer must overcome the systemic contradiction: "describe minimally, but enough." For the EIE, it is proposed to use the following classification of types of interconnections:

- by physical interactions;
- by spatial constraints;
- by material and energy flows;
- by information flows;
- by system restrictions;
- according to the logic of the interaction of physical components.

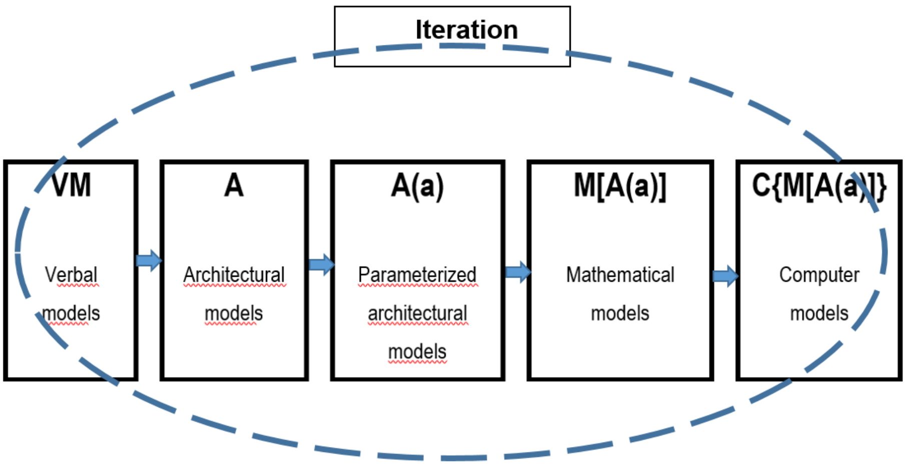

Figure 4. The process of developing a digital representation of EIE.

When adding attributes to architectural models (**Figure 4)**, it is recommended to use the following parameters: spatial, physical, managerial, economic, risks, Technological Readiness Level (TRL analysis) and others. The parameters of architectural models can be both quantitatively measurable and qualitative, compiled on the basis of expert assessments (Strong-Neutral-Weakness, SNW analysis). **Figure 5** shows a representation of the architectural model supplemented by quantitative (a1) and qualitative (a2) parameters. This allows the system engineer to evaluate options for system architecture models quickly.

A – architectural model (RBS, CBS)	RBS	CBS	a – architectural model parameters
RBS	DSM (RBS, CBS)	DSM (RBS, CBS)	A(a1) =[RBS(a1)]
			A(a2) =[RBS(a2)]
CBS	DSM (PBS, CBS)	DSM (PBS, CBS)	A(a1) =[CBS(a1)]
			A(a2) =[CBS(a2)]

Figure 5. Architectural model representation supplemented by quantitative and qualitative parameters.

The parameterized system architecture model (PASM) is the EIE holistic ontological textual description, which allows, for example, during the expert strategic sessions to discuss a digital transformation project, possible options for its implementation, etc. The key feature of the PASM is an identification of the key EIE entities interconnections and the parameterization of these interconnections. Based on PASM, a first version of a target matrix of requirements and constraints (Badenko et al., 2021; Kukushkin et al., 2022) is compiled. This matrix is a hierarchical system of interconnected data structures containing formalized requirements for the EIE and its components. Determining interconnection of EIE parameters is the main objective for the architectural stage. Already at this stage, the system engineer can identify possible scenarios (paths) for balancing requirements.

Thus, the developing of the PASM has the following stages:

- A representation of the subject area in the form of a reference book of basic terms and concepts;
- Development of the initial version of PASM;
- An expert discussion of the proposed PASM;
- Making a final decision on PASM.

The proposed methodological approach recommends using the following composition of modeling levels with a transition in the “from simple to more complex” for composition of the characteristics used in them (**Figure 6**):

- System of used terms;
- Typology of modeling strata used;
- Architectural models used in system representations;
- Mathematical models;
- Computer models;
- Digital models;
- Intelligent models (artificial intelligence models);
- Assemblies, digital platforms, and simulation and testing ranges.

Terms	Architectural models of EIE	PASM	Mathematical models	Computer models	Digital models	Intelligent models
Entities reference guides Matrix of entities interconnections						
Assemblies, digital platforms and polygons for simulation and virtual testing						

Figure 6. Composition and positioning of models.

To describe the models of each level, it is proposed to use the following architectural system representations:

- Reference guides of used terms and concepts;
- Typology of used models;
- Model requirements reference guides;
- Reference guides of functions performed by models to ensure compliance with their requirements;
- Reference guides of the composition of the used models that ensure the fulfillment of requirements and functions;
- Interconnectivity of model requirements, model functions, and model composition both within individual strata (analysis level) and between different strata;
- Attributes and ratings of models.

It is proposed to use the characteristics of models from one level at other levels, which makes it possible to link models into a single model system complex:

- Verbal (logical-semantic) models represent significant semantic elements of information in the form of terms and identified relationships between them, creating the basis for the design of architectural models;
- Architectural models systematically represent and organize parameters of mathematical, computer, digital, and intelligent models;
- Mathematical models are transformed in an accepted way into the form of computer models;
- Digital models combine sets of computer models, detail and expand them;
- Intelligent models complement and extend digital models by taking into account large, possibly unstructured data;
- Data and parameters, mathematical, computer, digital, and intelligent models should be linked and mutually positioned with models of the EIE physical architecture.

As a result, the entire composition of models used can be systematically ordered and interconnected. Models are beginning to be considered together with physical objects as full-fledged components of a hybrid representation of the physical and virtual world for the EIE (**Figure 1**). This approach allows a for a systematic and orderly representation of the EIE in various complementary and interpenetrating representations of modeling strata, ensuring and developing all the benefits of the proposed methodology.

Mathematical models of the processes and phenomena in a complex technical system, for example the EIE, in this case are, if we follow the terminology used here, mathematical formulas involving attributes from the PASM. Abstraction levels describe the transition from high-level models to more detailed models. This process can be represented as follows:

- Description of the laws and the rules linking the main components of the EIE digital representation;
- Study of the mathematical problems that mathematical models lead to;
- Verification and validation of all the models;
- Interconnection of the models based on balancing of DSM.

Thus, a digital representation of the EIE and a multi-level matrix of requirements, resources and restrictions are formed, as a system of interconnected structures containing formalized requirements for the EIE.

3. Results and discussion

The proposed methodology has been successfully tested on the example of an existing gas distribution station (GDS). Such facilities are typical for gas networks in many countries around the world. In traditional engineering, a set of technical requirements is formed basing on regulatory requirements and an object operating practice. With this approach, proven technical solutions for changing operating conditions, operational improvements, automation, and optimization of the full life cycle may not provide the declared efficiency of the GDS, and the capabilities of a modern modeling are not fully used.

According to the proposed methodology, at the first step, in accordance with a national regulation and standards (considered as initial data), a semantic representation of the subject area was compiled in the form of a reference guide book of basic terms and concepts. Such reference guide is necessary for the most unambiguous understanding of the semantic content of the words, concepts, and expressions used. Thus, in accordance with the standards, the basic technical requirements were identified, systematized, hierarchically ordered. To visualize the presentation of requirements (RBS) according to the developed method, a graph in the form of a "tree" is used (**Figure 7**).

Depending on the conditions of the operation and the requirements of the GDS, the composition of the GDS components may vary. An example of a fragment of the GDS physical components model representation (CBS) in the form of a graph "tree" is shown in **Figure 8**.

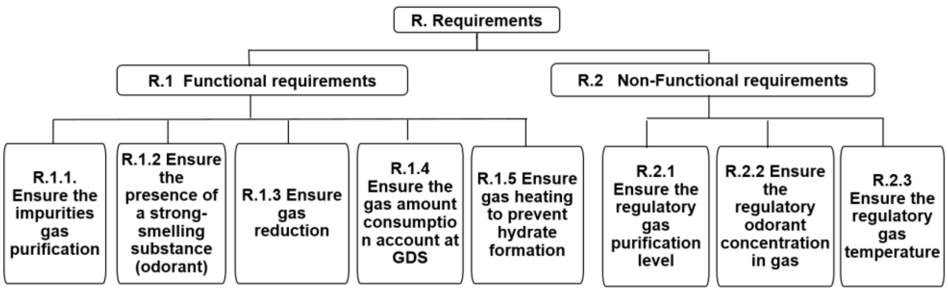

Figure 7. GDS requirements breakdown structure (RBS).

Figure 9 shows a matrix of requirements interconnections among themselves (RBS to RBS). **Figure 10** shows a matrix of physical components interconnections (CBS to CBS). **Figure 11** shows a matrix of interconnections of requirements and physical components (RBS to CBS). In these matrices, 1 indicates the presence of interconnections, and 0 indicates the absence of interconnections The indexes in **Figures 9–11** correspond to the indexes in **Figures 7** and **8**. At this level of hierarchies, only the most important relationships were highlighted. This allows the system engineer to create a description of the GDS system architecture quickly. With further modeling and complication of the physical architecture, at the next hierarchy levels of the object description, the interrelationships of requirements and components begin to manifest more clearly.

In the GDS requirements interconnections matrix (**Figure 9**) the connectivity by functionality is indicated. For example, it is indicated that the requirement R.1.3 "Ensure gas reduction" has a relationship with the requirements R.1.1 "Ensure the impurities gas purification", R.1.5 "Ensure gas heating to prevent hydrate formation" and R.2.3 "Ensure the regulatory gas temperature".

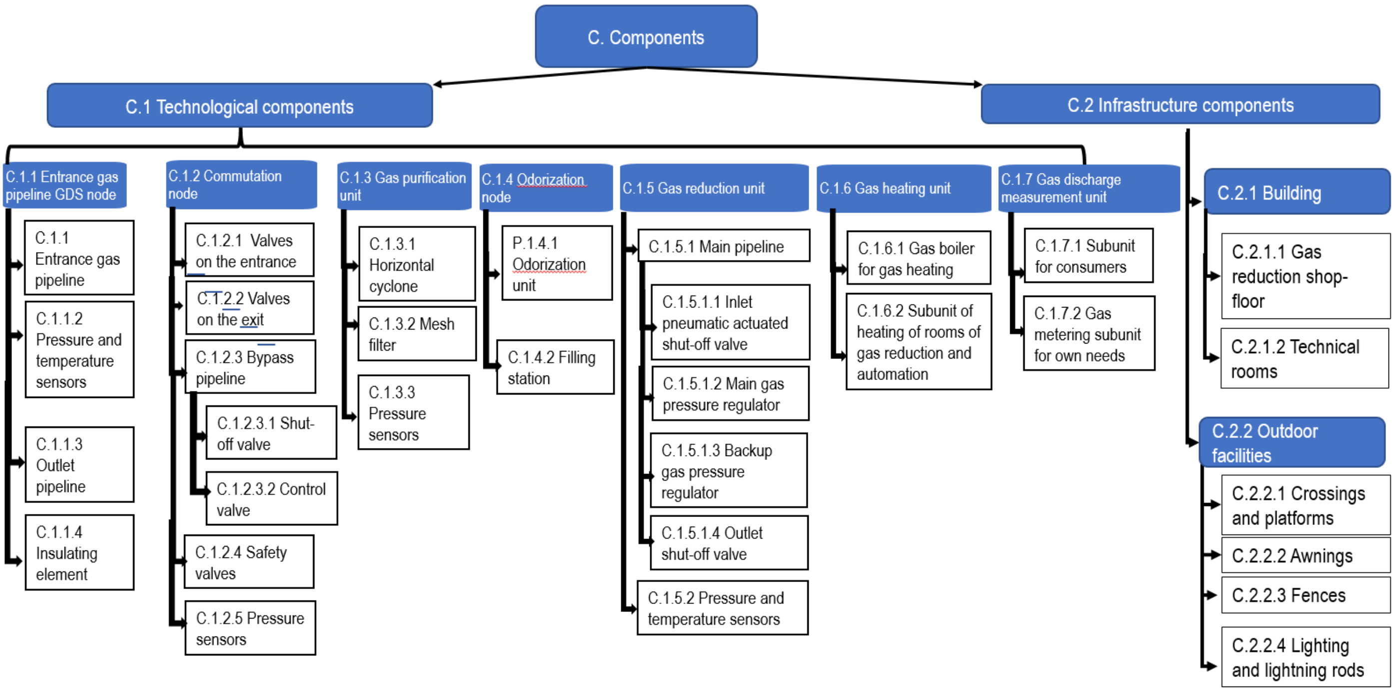

Figure 8. Fragment of the GDS physical components representation model (CBS).

	R.1.1	R.1.2	R.1.3	R.1.4	R.1.5	R.2.1	R.2.2	R.2.3
R.1.1		0	1	0	0	1	0	0
R.1.2	0		0	0	0	0	1	0
R.1.3	1	0		0	1	0	0	1
R.1.4	0	0	0		1	0	0	1
R.1.5	0	0	1	1		0	0	1
R.2.1	1	0	0	0	0		0	0
R.2.2	0	1	0	0	0	0		0
R.2.3	0	0	1	1	1	0	0	

Figure 9. Fragment of a matrix of requirements interconnections.

The interconnectedness of the components (CBS to CBS) is formed to indicate the physical interaction and the order of arrangement in the technological process (**Figure 10**). For example, C.1.5 "Gas reduction unit" is interconnected (located immediately behind it) to C.1.3 "Gas purification unit", functionally interconnected to C1.6 "Gas heating unit", located in C.2.1 "Building", and is located ahead of C.1.4 "Odorization node".

	C.1.1	C.1.2	C.1.3	C.1.4	C.1.5	C.1.6	C.1.7	C.2.1	C.2.2
C.1.1		1	0	0	0	0	0	0	1
C.1.2	1		1	0	1	1	0	0	1
C.1.3	0	1		0	1	1	0	0	1
C.1.4	0	0	0		1	1	0	0	1
C.1.5	0	0	1	1		1	0	1	0
C.1.6	0	1	1	1	1		1	1	1
C.1.7	0	0	0	0	0	1		1	0
C.2.1	0	0	0	0	1	1	1		0
C.2.2	1	1	1	1	0	1	0	0	

Figure 10. Fragment of a matrix of physical components interconnections.

	C.1.1	C.1.2	C.1.3	C.1.4	C.1.5	C.1.6	C.1.7	C.2.1	C.2.2
R.1.1	0	0	1	0	1	1	0	0	1
R.1.2	0	0	0	1	0	0	1	0	1
R.1.3	0	1	1	0	1	1	0	1	0
R.1.4	0	0	0	0	0	1	1	0	0
R.1.5	0	0	0	0	1	1	0	1	0
R.2.1	0	0	1	0	1	1	0	0	1
R.2.2	0	0	0	1	0	0	1	0	1
R.2.3	0	0	0	0	1	1	0	1	0

Figure 11. Fragment of a matrix interconnections of requirements and physical components (RBS to CBS).

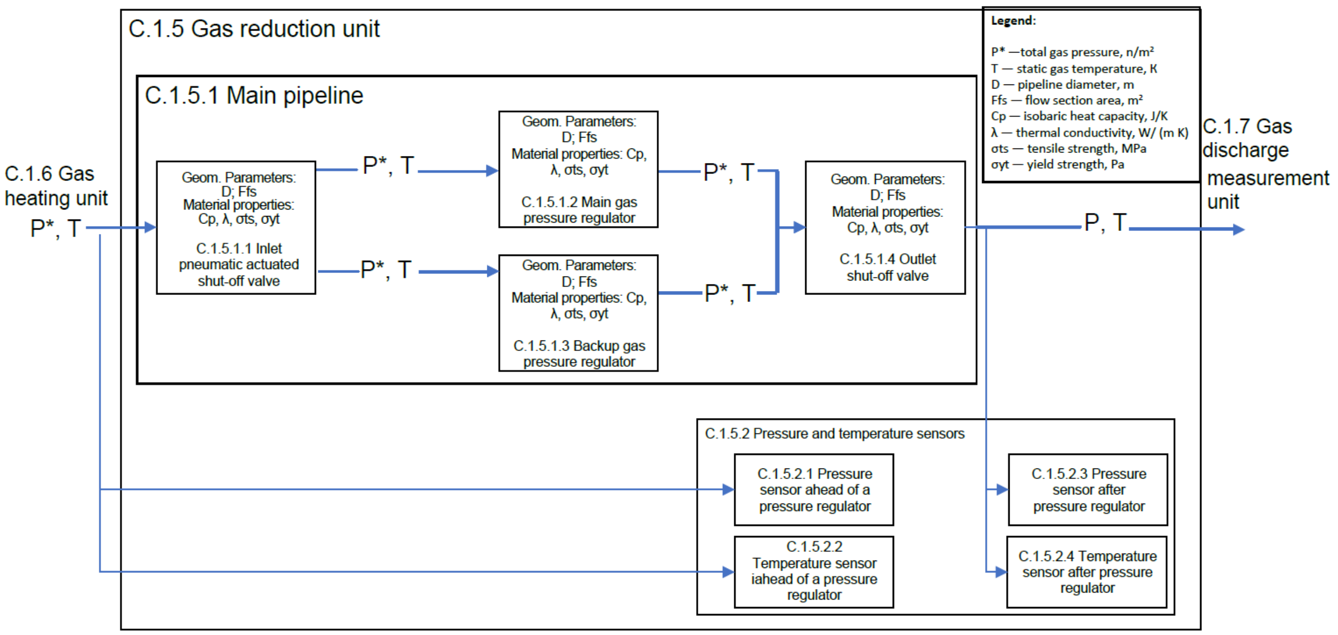

Figure 12. An example of parameters interconnectivity of the gas reduction unit of GDS.

The matrix of interconnections of requirements and physical components (RBS to CBS) defines the list of the components involved in implementation of the GDS specific requirements (**Figure11**). For example, in fulfilling the requirement R.1.1 “Ensure the impurities gas purification”, physical components take part: C.1.3 “Gas purification unit”, C.1.5 “Gas reduction unit”, and C.1.6 “Gas heating unit”, located in C.2.2 “Building”.

In the next step, the architectural models are supplemented with key attributes. **Figure 12** shows an example of the GDS gas reduction unit parameters interconnectivity.

To create a digital representation of the GDS, it is necessary to determine the typology of the applied mathematical models and their description. **Figure 13** shows an example of the description of such models for GDS and the attributes of these models. **Figure 13** shows only gas-dynamic and thermal mathematical models. In addition, in the process of a digital transformation of the GDS, energy, strength, ergonomic and resource mathematical models are used for physical components.

For the GDS according to the proposed methodology also an architecture of mathematical models is developed. An example of the GDS architecture of mathematical models is shown in **Figure 14**.

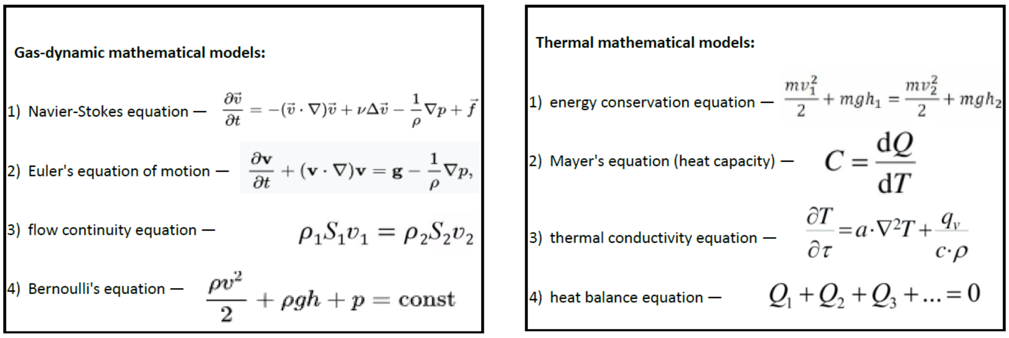

Figure 13. A fragment of a mathematical model for the GDS.

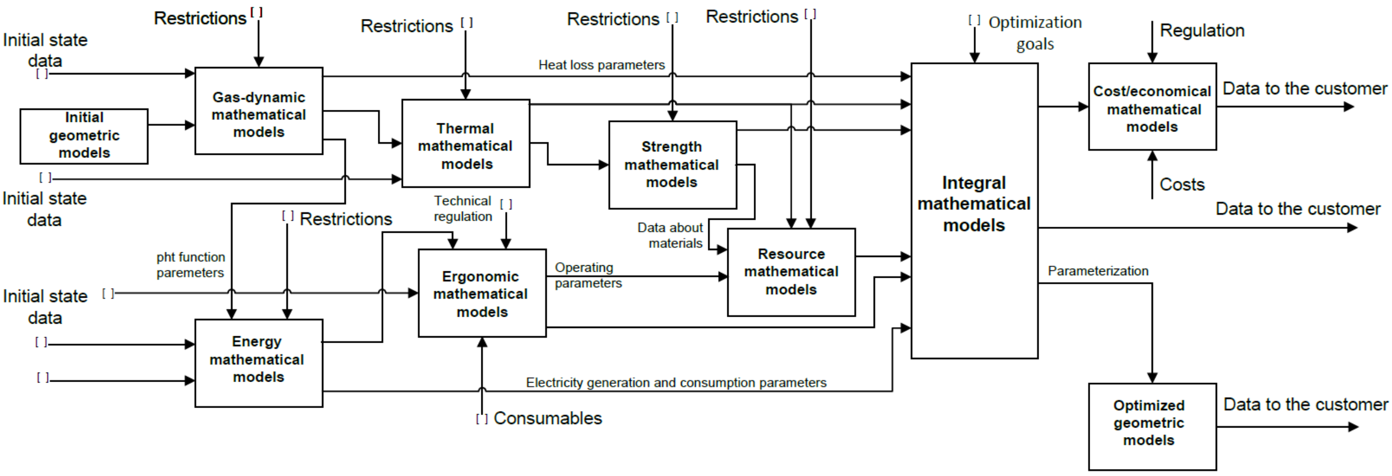

Figure 14. An example of the GDS architecture of mathematical models.

The next step is to describe the parameters and characteristics of mathematical models in the form of a multi-level matrix of requirements, connections and constraints, as a system of interconnected data structures containing formalized requirements. In this way, mathematical models and a multilevel matrix of requirements are formed. Further, computer and digital models are built based on mathematical models to create a digital representation of the GDS.

4. Discussion

The results of this research show that MBSE has serious prospects for the development of the EIE digital transformation methods. **Figures 7–11** demonstrate the GDS structure, which is understandable not only to specialists, but also to all stakeholders. Therefore, the proposed methodology really serves as an effective tool for justifying investments in the rather expensive EIE digital transformation process. Thus, in our opinion, a real tool for justifying decision-making on a digital transformation has been demonstrated. The proposed universal practical methodology is based on the methodological approaches of INCOSE systems engineering and can be applied to the design and reengineering of a wide range of technical objects.

The analysis and discussion of the practical results for GDS also allows us to formulate proposals for the development and application of the EIE architectural system models. The paper considers and organizes the approaches and tools of architectural modeling of technical objects as systems. The modeling is based on the formation and filling of unified reference books and matrices of interconnections of requirements and components of the object with text entries. The presented results show how in traditional engineering documentation unified architectural system models can be effectively applied. Already at the initial stages of the EIE digital transformation process, this methodological approach allows engineers to streamline a digital representation of target features and elements, quickly and uniformly form and evaluate the EIE structure, reduce development time and evaluate the quality of the development.

The proposed methodology is available for rapid learning and mastering by digital models developers, complies with the rules of system engineering and allows it for a wide application and development in applied projects of the EIE digital transformation. It is shown that the approach to system architecture modeling of technical objects can be expanded by taking into account other types of models—mathematical, cyber-physical, digital, and also intelligent models and algorithms. This approach makes it possible to overcome the known difficulties of a hybrid description of complex objects using many models, to form a modeling policy on systematized repositories of component descriptions and engineering processes, without wasting time on repeating existing developments, thereby increasing the quality and productivity of engineering activities.

5. Conclusion

To implement the EIE digital transformation strategy using the MBSE approach, relevant practical methodology based on common INCOSE pricipals are presented. The proposed methodological approach is available for rapid development by system engineers and can be widely used in a digital representation creation of existing complex technical objects in the process of digital transformation of enterprises. The methodology to modeling physical architectures of objects can be expanded by taking into account other models of target objects including mathematical, cyber-physical, digital, and intelligent models and algorithms.

Currently, system engineering in general and MBSE in particular are increasingly penetrating the processes of digital transformation of existing industrial enterprises. The development of the MBSE approaches and the expansion of the use of unified techniques will make it possible to transfer the experience of system engineering between industries with greater efficiency.

The authors recognize that the main barrier to a widespread adoption of MBSE in different EIE digital transformation practices is the lack of useful systems engineering automation tools. Another problem is the lack of qualified staff who are familiar with the principles and have an experience in the practical application of system engineering and MBSE. At the same time, a special attention should undoubtedly be paid to the creation of adequate language models of an industry orientation. Therefore, the authors see the directions of a further research in the development of technologies for automating the construction of an attributed system architecture of an enterprise, including using language models of artificial intelligence.

Author contributions: Conceptualization, VB and VY; methodology, VB, VY and ET; software, GB; validation, VB, VY and LA; formal analysis, VB and VY; investigation, ET; resources, GB; data curation, LA and VB; writing—original draft preparation, VB and VY; writing—review and editing, ET and VB; visualization, GB, VB; supervision, VB; project administration, VY; funding acquisition, VY. All authors have read and agreed to the published version of the manuscript.

Funding: The research is partially funded by the Ministry of Science and Higher Education of the Russian Federation as part of the World-class Research Center program: Advanced Digital Technologies (contract No. 075-15-2022-311 dated 20 April 2022).

Conflict of interest: The authors declare no conflict of interest.

References

Badenko, V. L., Bolshakov, N. S., Tishchenko, E. B., et al. (2021). Integration of digital twin and BIM technologies within factories of the future. Magazine of Civil Engineering, (1 (101)), 10114. https://doi.org/10.34910/MCE.101.14

Bai, C., Dallasega, P., Orzes, G., et al. (2020). Industry 4.0 technologies assessment: A sustainability perspective. International journal of production economics, 229, 107776. https://doi.org/10.1016/j.ijpe.2020.107776

Bemmami, K. E., & David, P. (2021). State-of-practice survey in industry on the deployment of simulation in systems engineering. IFAC-PapersOnLine, 54(1), 1132-1137. https://doi.org/10.1016/j.ifacol.2021.08.133

Bolshakov, N., Rakova, X., Celani, A., et al. (2023a). Operation Principles of the Industrial Facility Infrastructures Using Building Information Modeling (BIM) Technology in Conjunction with Model-Based System Engineering (MBSE). Applied Sciences, 13(21), 11804. https://doi.org/10.3390/app132111804

Bolshakov, N., Badenko, V., Yadykin, V., et al. (2023b). Cross-Industry Principles for Digital Representations of Complex Technical Systems in the Context of the MBSE Approach: A Review. Applied Sciences, 13(10), 6225. https://doi.org/10.3390/app13106225

Boehm, B., Koolmanojwong, S., Lane, J. A., et al. (2012). Principles for successful systems engineering. Procedia Computer Science, 8, 297-302. https://doi.org/10.1016/j.procs.2012.01.063

Bone, M. A., Blackburn, M. R., Rhodes, D. H., et al. (2019). Transforming systems engineering through digital engineering. The Journal of Defense Modeling and Simulation, 16(4), 339-355. https://doi.org/10.1177/1548512917751873

Bretz, L., Kaiser, L., & Dumitrescu, R. (2019). An analysis of barriers for the introduction of Systems Engineering. Procedia CIRP, 84, 783-789. https://doi.org/10.1016/j.procir.2019.04.178

Browning, T. R. (2015). Design structure matrix extensions and innovations: a survey and new opportunities. IEEE Transactions on engineering management, 63(1), 27-52. https://doi.org/10.1109/TEM.2015.2491283

Buschhaus, C., Gerasimov, A., Kirchhof, J. C., et al. (2024). Lessons learned from applying model-driven engineering in 5 domains: The success story of the MontiGem generator framework. Science of Computer Programming, 232, 103033. https://doi.org/10.1016/j.scico.2023.103033

Cameron, B., & Adsit, D. M. (2018). Model-based systems engineering uptake in engineering practice. IEEE Transactions on Engineering Management, 67(1), 152-162. https://doi.org/10.1109/TEM.2018.2863041

Campo, K. X., Teper, T., Eaton, C. E., et al. (2022). Model-based systems engineering: evaluating perceived value, metrics, and evidence through literature. Systems Engineering, 26(1), 104-129. https://doi.org/10.1002/sys.21644

Chen, X., Zhang, X. E., Cai, Z., et al. (2024). The Non-Linear Impact of Digitalization on the Performance of SMEs: A Hypothesis Test Based on the Digitalization Paradox. Systems, 12(4), 139. https://doi.org/10.3390/systems12040139

Cimino, A., Gnoni, M. G., Longo, F., et al. (2023). Integrating multiple industry 4.0 approaches and tools in an interoperable platform for manufacturing SMEs. Computers & Industrial Engineering, 186, 109732. https://doi.org/10.1016/j.cie.2023.109732

Elhabbash, A., Elkhatib, Y., Nundloll, V., et al. (2024). Principled and automated system of systems composition using an ontological architecture. Future Generation Computer Systems, 157, 499-515. https://doi.org/10.1016/j.future.2024.03.034

Fang, M., Nie, H., & Shen, X. (2023). Can enterprise digitization improve ESG performance?. Economic Modelling, 118, 106101. https://doi.org/10.1016/j.econmod.2022.106101

Fett, M., Wilking, F., Goetz, S., et al. (2023). A Literature Review on the Development and Creation of Digital Twins, Cyber-Physical Systems, and Product-Service Systems. Sensors, 23(24), 9786. https://doi.org/10.3390/s23249786

Gajo, A. H., & Akyuz, G. A. (2023). Digital Transformation Implementation Challenges in Turkish Industrial Enterprises. International Journal of Innovation and Technology Management, 20(06), 2350037. https://doi.org/10.1142/S0219877023500372

Ghobakhloo, M., & Fathi, M. (2019). Corporate survival in Industry 4.0 era: the enabling role of lean-digitized manufacturing. Journal of Manufacturing Technology Management, 31(1), 1-30. https://doi.org/10.1108/JMTM-11-2018-0417

Guide to the Systems Engineering Body of Knowledge (SEBoK), version 2.10 (2024). Available online: https://sebokwiki.org/w/images/sebokwiki-farm!w/d/db/Guide_to_the_Systems_Engineering_Body_of_Knowledge_v2.10.pdf (accessed on 14.08.2024)

Henderson, K., & Salado, A. (2021). Value and benefits of model-based systems engineering (MBSE): Evidence from the literature. Systems Engineering, 24(1), 51-66. https://doi.org/10.1002/sys.21566

Henderson, K., McDermott, T., Van Aken, E., et al. (2023). Towards developing metrics to evaluate digital engineering. Systems Engineering, 26(1), 3-31. https://doi.org/10.1002/sys.21640

Henderson, K., & Salado, A. (2024). The effects of organizational structure on MBSE adoption in industry: Insights from practitioners. Engineering Management Journal, 36(1), 117-143. https://doi.org/10.1080/10429247.2023.2210494

Henderson, K., McDermott, T., & Salado, A. (2024). MBSE adoption experiences in organizations: Lessons learned. Systems Engineering, 27(1), 214-239. https://doi.org/10.1002/sys.21717

Hennig, A., & Szajnfarber, Z. (2023). The impact of system representation choices on architecting insights. Systems Engineering, 26(5), 531-547. https://doi.org/10.1002/sys.21673

Huang, J., Gheorghe, A., Handley, H., et al. (2020). Towards digital engineering: the advent of digital systems engineering. International Journal of System of Systems Engineering, 10(3), 234-261. https://doi.org/10.1504/IJSSE.2020.10031364

Huldt, T., & Stenius, I. (2019). State-of-practice survey of model-based systems engineering. Systems engineering, 22(2), 134-145. https://doi.org/10.1002/sys.21466

INCOSE (2023). Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, version 5.0. Hoboken, NJ, USA: John Wiley and Sons, Inc, ISBN: 978-1-119-81429-0.

Kaiser, J., McFarlane, D., Hawkridge, G., et al. (2023). A review of reference architectures for digital manufacturing: Classification, applicability and open issues. Computers in Industry, 149, 103923. https://doi.org/10.1016/j.compind.2023.103923

Khandoker, A., Sint, S., Gessl, G., et al. (2022). Towards a logical framework for ideal MBSE tool selection based on discipline specific requirements. Journal of Systems and Software, 189, 111306. https://doi.org/10.1016/j.jss.2022.111306

Kukushkin, K., Ryabov, Y., & Borovkov, A. (2022). Digital twins: a systematic literature review based on data analysis and topic modeling. Data, 7(12), 173. https://doi.org/10.3390/data7120173

Laing, C., David, P., Blanco, E., et al. (2020). Questioning integration of verification in model-based systems engineering: an industrial perspective. Computers in Industry, 114, 103163. https://doi.org/10.1016/j.compind.2019.103163

Liu, S., Zheng, P., & Bao, J. (2024) Digital Twin-based manufacturing system: A survey based on a novel reference model. Journal of Intelligent Manufacturing, 35, 2517–2546. https://doi.org/10.1007/s10845-023-02172-7

Lu, J., Ma, J., Zheng, X., et al. (2021). Design ontology supporting model-based systems engineering formalisms. IEEE Systems Journal, 16(4), 5465-5476. https://doi.org/10.1109/JSYST.2021.3106195

Madni, A. M., & Sievers, M. (2018). Model-based systems engineering: Motivation, current status, and research opportunities. Systems Engineering, 21(3), 172-190. https://doi.org/10.1002/sys.21438

Madni, A. M., & Purohit, S. (2019). Economic analysis of model-based systems engineering. Systems, 7(1), 12. https://doi.org/10.3390/systems7010012

Madni, A. M., Madni, C. C., & Lucero, S. D. (2019). Leveraging digital twin technology in model-based systems engineering. Systems, 7(1), 7. https://doi.org/10.3390/systems7010007

Maier, M. W. (1998). Architecting principles for systems-of-systems. Systems Engineering: The Journal of the International Council on Systems Engineering, 1(4), 267-284. https://doi.org/10.1002/(SICI)1520-6858(1998)1:4%3C267::AID-SYS3%3E3.0.CO;2-D

Matarazzo, M., Penco, L., Profumo, G., et al. (2021). Digital transformation and customer value creation in Made in Italy SMEs: A dynamic capabilities perspective. Journal of Business Research, 123, 642-656. https://doi.org/10.1016/j.jbusres.2020.10.033

Meißner, M., Jacobs, G., Jagla, P., et al., (2021). Model based systems engineering as enabler for rapid engineering change management. Procedia CIRP, 100, 61-66. https://doi.org/10.1016/j.procir.2021.05.010

Mitola III, J., & Prys, M. (2023). Cyber oriented digital engineering. Systems Engineering, 27(1), 109-119. https://doi.org/10.1002/sys.21710

Papavasiliou, S., Gorod, A., & Reaiche, C. (2024). System of systems engineering governance framework for digital transformation: A case study of an Australian large government agency. Systems Engineering, 27(2), 267-283. https://doi.org/10.1002/sys.21719

Psarommatis, F., & May, G. (2023). A literature review and design methodology for digital twins in the era of zero defect manufacturing. International Journal of Production Research, 61(16), 5723-5743. https://doi.org/10.1080/00207543.2022.2101960

Purohit, S., & Madni, A. M. (2021). A model-based systems architecting and integration approach using interlevel and intralevel dependency matrix. IEEE Systems Journal, 16(1), 747-754. https://doi.org/10.1109/JSYST.2021.3077351

Rehberg, L., & Brem, A. (2024). Industrial prototyping in the German automotive industry: bridging the gap between physical and virtual prototypes. Journal of Engineering and Technology Management, 71, 101798.

San Cristóbal, J. R., Carral, L., Diaz, E., et al. (2018). Complexity and project management: A general overview. Complexity, 2018. 4891286. https://doi.org/10.1155/2018/4891286

Sanfilippo, E., Kitamura, Y., & Young, R. I. (2019). Formal ontologies in manufacturing. Applied Ontology, 14(2), 119-125. https://doi.org/10.3233/AO-190209

Schlemitz, A., & Mezhuyev, V. (2024). Approaches for data collection and process standardization in smart manufacturing: systematic literature review. Journal of Industrial Information Integration, 38, 100578. https://doi.org/10.1016/j.jii.2024.100578

Schummer, F., & Hyba, M. (2022). An approach for system analysis with model-based systems engineering and graph data engineering. Data-Centric Engineering, 3, e33. https://doi.org/10.1017/dce.2022.33

Sharon, A., de Weck, O. L., & Dori, D. (2013). Improving project–product lifecycle management with model–based design structure matrix: a joint project management and systems engineering approach. Systems Engineering, 16(4), 413-426. https://doi.org/10.1002/sys.21240

Shoshany-Tavory, S., Peleg, E., Zonnenshain, A., et al. (2023). Model-based-systems-engineering for conceptual design: An integrative approach. Systems Engineering, 26(6), 783-799. https://doi.org/10.1002/sys.21688

Skare, M., de Obesso, M. D. L. M., & Ribeiro-Navarrete, S. (2023). Digital transformation and European small and medium enterprises (SMEs): A comparative study using digital economy and society index data. International journal of information management, 68, 102594. https://doi.org/10.1016/j.ijinfomgt.2022.102594

Swickline, C., Mazzuchi, T. A., & Sarkani, S. (2024). A methodology for developing SoS architectures using SysML model federation. Systems Engineering, 27(2), 368-385. https://doi.org/10.1002/sys.21727

Tikayat Ray, A., Cole, B. F., Pinon Fischer, O. J., et al. (2023). Agile Methodology for the Standardization of Engineering Requirements Using Large Language Models. Systems, 11(7), 352. https://doi.org/10.3390/systems11070352

Titus, L. M. (2024). Does ChatGPT have semantic understanding? A problem with the statistics-of-occurrence strategy. Cognitive Systems Research, 83, 101174. https://doi.org/10.1016/j.cogsys.2023.101174

Tong, X., Bao, J., & Tao, F. (2024). Co-evolutionary digital twins: A multidimensional dynamic approach to digital engineering. Advanced Engineering Informatics, 61, 102554. https://doi.org/10.1016/j.aei.2024.102554

Varriale, V., Cammarano, A., Michelino, F., et al. (2024). The role of digital technologies in production systems for achieving sustainable development goals. Sustainable Production and Consumption. 47, 87 – 104. https://doi.org/10.1016/j.spc.2024.03.035

Veile, J. W., Kiel, D., Müller, J. M., et al. (2020). Lessons learned from Industry 4.0 implementation in the German manufacturing industry. Journal of Manufacturing Technology Management, 31(5), 977-997. https://doi.org/10.1108/JMTM-08-2018-0270

Verbruggen, C., & Snoeck, M. (2023). Practitioners' experiences with model-driven engineering: a meta-review. Software and Systems Modeling, 22(1), 111-129. https://doi.org/10.1007/s10270-022-01020-1

Vernadat, F. (2014). Enterprise Modeling in the context of Enterprise Engineering: State of the art and outlook. International Journal of Production Management and Engineering, 2(2), 57-73. https://doi.org/10.4995/ijpme.2014.2326

Voth, J. M., & Sturtevant, G. H. (2022). Digital engineering: expanding the advantage. Journal of Marine Engineering & Technology, 21(6), 355-363. https://doi.org/10.1080/20464177.2021.2024382

Weerakkody, V., Janssen, M., & El-Haddadeh, R. (2021). The resurgence of business process re-engineering in public sector transformation efforts: exploring the systemic challenges and unintended consequences. Information Systems and e-Business Management, 19(3), 993-1014. https://doi.org/10.1007/s10257-021-00527-2

Yadykin, V., Barykin, S., Badenko, V., et al. (2021). Global challenges of digital transformation of markets: Collaboration and digital assets. Sustainability, 13(19), 10619. https://doi.org/10.3390/su131910619

Yang, X., Liu, X., Zhang, H., et al. (2023). Meta-model-based shop-floor digital twin architecture, modeling and application. Robotics and Computer-Integrated Manufacturing, 84, 102595. https://doi.org/10.1016/j.rcim.2023.102595

Younse, P., Cameron, J., & Bradley, T. H. (2022). Comparative analysis of model-based and traditional systems engineering approaches for simulating a robotic space system architecture through automatic knowledge processing. Systems Engineering, 25(4), 360-386. https://doi.org/10.1002/sys.21619

Zhang, J., & Yang, S. (2024). Recommendations for the Model-Based Systems Engineering Modeling Process Based on the SysML Model and Domain Knowledge. Applied Sciences, 14(10), 4010. https://doi.org/10.3390/app14104010