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AI-MBSE-Assisted Requirements Writing and Management – Towards a Knowledge-Based Framework

Ali Asghar Bataleblu[1], Erik Felix Tinsel[2], Benjamin Schneider[3], Erwin Rauch[1], Armin Lechler[2], Oliver Riedel[2]

[1] Faculty of Engineering, Free University of Bozen-Bolzano, Bolzano, Italy
(Tel: +39-3885749413; e-mail: aliasghar.bataleblu@unibz.it, erwin.rauch@unibz.it).
[2] Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW), University of Stuttgart, Stuttgart, Germany (e-mail: erik-felix.tinsel@isw.uni-stuttgart.de, armin.lechler@isw.uni-stuttgart.de, oliver.riedel@isw.uni-stuttgart.de)
[3] Fraunhofer Institute for Industrial Engineering IAO, Stuttgart, Germany
(e-mail: benjamin.schneider@iao.fraunhofer.de)

Abstract: In transitioning to digital twins (DTs), the variety in requirements and their interactions impedes the effectiveness and efficiency of the developed DTs. The experts' information exchange and multi-domain dependency extraction are crucial in creating a practical DT. Interpreting a physical system's requirements through a knowledge-based approach into a new set of requirements in the digital domain, and connecting and tracing them concurrently, can significantly narrow the gap between digital twins and practical needs. This paper proposes an artificial Intelligence (AI) assisted tech-driven requirements writing and management framework based on the axiomatic design (AD) theory and a model-based systems engineering (MBSE) cloud. An outline of the envisioned framework is sketched on a W-model, one V is physical system and the other corresponds to digital model. The intersection of both V is where the interface will be managed to close the gap. Finally, the challenges in developing such a framework are discussed.

Keywords: Requirements Management, Digital Twins, Model-based Systems Engineering, Artificial Intelligence, Axiomatic Design

1 Introduction

Since the complexity of systems has changed dramatically throughout the years, organizations and industries have recognized the imperative to adapt and embrace innovative technologies, fostering a continuous evolution in software engineering, artificial intelligence (AI), and machine learning to not only cope with the heightened intricacies but also leverage them for enhanced efficiency, improved decision-making, and unprecedented levels of automation (Masior et al. 2020). The synergy between software engineering, model-based engineering, and systems engineering and moving toward digitalization and Digital Twins (DTs) has contributed to the creation of intelligent systems that can autonomously analyze vast amounts of data, resulting in a reduction of complexity through automated decision-making processes (Bataleblu et al. 2023a). At the same time, this continuous progress in software engineering has been a driving force in reshaping the nature of system complexity and bringing new challenges for writing and managing requirements of this new era (Jantunen et al. 2019). Therefore, the landscape within which Requirements Engineering (RE) is applied has undergone a profound transformation, marked by escalating system complexities, heightened information interdependencies, and an amplified level of intricacy in interface control (Jarke et al. 2015, Schön et al. 2017).

Many challenges in Requirements Writing and Management (RW&M) have been attributed to the research community's difficulty in synchronizing with the dynamic nature of contemporary complex problems, specifically in discerning needs, extracting correct requirements, and finally tracing them through the product lifecycle (Ahmad et al. 2023, Dick et al. 2017). In mitigating these challenges, there has been a transition in RE from document-centric approaches to web-based solutions and subsequently to model-based requirements management. Two research streams are active in this transition: Requirements Writing (RW) on one side and Requirements Management (RM) on the other side. In the first category, studies focused on automating the RW process through extraction and classification of different types of requirements by text mining based on natural language processing (Kostova et al. 2020, Akay et al. 2021a). Whereas RM research is inclined to software engineering and Model-based Systems Engineering (MBSE) tools to alleviate difficulties arising from verification, validation, and traceability of requirements. Meanwhile, some other literature has looked at the development of system design decomposition methods based on the Axiomatic Design (AD) theory to decrease the complexity of the systems by defining functional requirements (FRs) and related physical solutions (PSs) starting from stakeholders' needs to different levels of the system (Bataleblu et al. 2024a and 2024b, Cochran et al. 2022). These activity streams are based on separate tools and require specific expertise. This issue becomes worrisome when the people assigned to this work do not have enough knowledge of the studied system and subsystems. For instance, data scientists will work on RW, software engineers will do the RM, and finally, system designers must work with this set of requirements. This may lead to ambiguous situations, significant rework, irreparable mistakes, and ultimately the failure of the product or mission.

Lots of researchers addressed these topics separately; automated RW (Kim et al. 2019, Akay et al. 2021a, b, Rauch et al. 2021), automated RM (Beatty et al. 2016, Tinsel et al. 2022, Bataleblu et al. 2023b), and AD (Akay et al. 2021c, Rauch et al. 2020, Cochran et al. 2022). Despite recent progress in AI and MBSE tools, guidelines for RW (INCOSE 2023), and movement from traditional to automated RW&M, still there are many open issues and challenges in the RE era. Some of these challenges namely are: time consumption, lack of expert knowledge, unclear objectives, scope creep, incomplete requirements, changing requirements, lack of consistency, multiple vendors contracted for different revisions, managing multiple or conflicting requirements, inconsistent formatting across documentation, lack of prioritization, and limited user involvement. (Mike 2015). Linking MBSE and AI allows for mutually beneficial synergies to be expected that have not yet been fully exploited (Chami et al. 2019 and 2022). Looking at RW&M from a systematic perspective, it can be seen that eliciting stakeholder expectations, translating needs into functional requirements, exploring physical solutions and physical solutions alternatives (PS-ALT) for each FR and decomposing to the next levels, reviewing and revising FRs-PS sets using expert knowledge, and finally verification and validation along with online traceability are its key steps. (see Figure 1).

Figure 4. Systematic requirements writing and management.

As proposed in Figure 1, although there are different solutions for those steps, all processes are being automated in today's modern and competitive world and try to enhance the system's resilience by developing a DT that mirrors the real system. Since RW&M is a vital part of systems development, interpreting a physical system's requirements through a knowledge-based approach into a new set of requirements in the digital domain, and connecting and tracing them concurrently, can significantly narrow the gap between DTs and practical needs. This can only be accomplished through a synergy between practical and abstract understanding of real systems both in digital and physical domains. As for physical systems, where a set of FRs is defined and PSs and PS-ALTs are proposed to satisfy them (taking into account the level of technology and manufacturing readiness) the same conditions apply to the digital model or to the creation of a DT. For developing a digital model, a series of FRs must be determined and the related solutions must be found based on the technology available in the digital domain. In order to guarantee that the digital model is an accurate representation of the physical model, it is essential to establish a connection between the requirements of the physical system and the digital model, ensuring that the digital model encompasses the physical domain FRs and constraints. In this context, the knowledge-based approach can play a pivotal role, with the exchange of information between experts from disparate fields and the extraction of multi-domain dependencies being of paramount importance. The objective of this paper is to present a framework that enables experts from the physical domain to review and trace the requirements and related solutions of the digital domain online. This framework employs an MBSE cloud, which facilitates the creation of a final DT that aligns closely with the practical expectations of the end user. Furthermore, following AD theory for system design decomposition and going from higher-level FRs and PSs to the lower desired levels allows to remarkably alleviate the level of system complexity and enhance the feasibility of the final results. In this respect, AI tools could help collect the general and higher level FRs and solutions in both domains while knowledge-based revision of questions will accelerate achieving correct and feasible responses. Therefore, the proposed AI-MBSE-Assisted framework could be a systematic way to automate all these procedures given in Figure 1 and especially close the gap between Solutions C and E considering experts' knowledge. To differentiate among various terminologies mentioned in the framework proposal and clarify the concept in the continuation of this article. A brief description of each is provided below:

- **Functional Requirements (FRs):** a minimum set of independent requirements that completely characterize the functional needs of the system in the functional domain (What needs to happen?).
- **Physical Solutions (PSs):** the key physical variables in the physical domain that characterize the design that satisfies the specified FRs (How to satisfy an FR?).
- **Physical/Real Model:** refers to a physical representation of an object or system which can be a scaled model, prototype, or any tangible object similar to what exists in the physical world.
- **Digital Model:** a digital representation of an existing or planned physical object that does not use any form of automated data exchange between the physical object and the digital object.
- **Digital Shadow:** a model that includes an automated one-way data flow between the state of an existing physical object and a digital object.
- **Digital Twins:** here, the data flows between an existing physical object and the digital one are fully integrated in both directions.

To address different aspects of the AI-MBSE-Assisted framework, the rest of the article is structured as follows: First, the main idea of the proposed framework encompasses RW, AD, AI, and MBSE is introduced. Then, the challenges and some research initiatives are discussed. Finally, the paper concludes with an outlook on future directions.

2 Intelligent Requirements Writing

In the current era, the ability to ideate rapidly is crucial for organizations to survive in a competitive environment where unexpected regulations are becoming increasingly common. These regulations are driving the development of cost-effective, sustainable products with high reliability. Consequently, organizations must identify resilient and feasible solutions as quickly as possible to ensure their technology and manufacturing operations are fully prepared for the future.. Furthermore, careful consideration and planning are crucial for adapting to technological progress.

Although digitalization and DTs have become a vital way of dealing with nowadays demands, skipping the systematic view has created challenges like bidirectional non-synchronization and consistency between physical and digital models (Wagg et al. 2020, Sharma et al. 2022). It is rooted in the difference between functions that are considered in real and virtual space and the information gap between the two sides of experts, especially in large-scale industries. To resolve this kind of problem from a system of systems viewpoint, an intelligent RW&M framework is introduced in this section to bring the digital model (DM) as close as possible to the physical model (PM) considering the knowledge of experts and accelerate organizations DTs adaptation in this swiftly evolving design terrain.

Figure 2 illustrates the schematic representation of a W-model as a basis for the AI-MBSE-Assisted framework consisting of two V for PM and DM. Starting at the top-left with stakeholder expectations from the physical model, the RW continues going down the left-hand part of the V (indicated by 1 in Figure 2) to PM's requirements and physical solutions. In contrast and starting at the top-right with stakeholder expectations from the digital model, the RW proceeds by going down the right-hand part of the V (indicated by 2 in Figure 2) to DM's requirements and physical solutions. During each V, AI and MBSE experts communicate with each other through a cloud space to extract and collect FRs and related PSs correctly and according to the stakeholders' needs and system objectives. In this process, AI and data mining tools can be utilized to identify, categorize, and analyze extracted data. Then, this information will be exchanged, synchronized, and sent to the MBSE tools for requirements management. The FRs-PSs for both PM and DM are then verified and validated as the process continues up in the Vs until the analysis is complete. In this step, interface management will be performed to ensure consistency between PM and DM. After consistency confirmation, decomposition will be integrated and different scenarios will be analyzed based on the alternative solutions for FRs to enhance the performance of the system. having such an integrated framework and considering different criteria like cost, time, productivity, reliability, TRLs, and sustainability enhance the resilience of organizations' roadmaps and will play a crucial role in closing the gap between research and what is required in practice.

2.1 Requirements Writing

Translating stakeholders' needs to the right set of functional requirements is the foundation of any problem definition. Functional requirements decomposition (FRD) bridges the gap between stakeholders, managers, developers, and manufacturers, i.e., between people with and without expertise. Therefore, a comprehensive and precise requirements decomposition would significantly decrease the reworks as well as development time arising due to interaction or feasibility overlooking. The transition towards digital twinning markedly elevates the significance of meticulous attention to FRD, as it is imperative for the digital model to align and exhibit consistency with the actual model to the greatest extent feasible. Sometimes, satisfying one functional requirement of the physical model in practice requires deriving a set of requirements in DT which is due to the differences in physical and digital considerations. It will underscore the necessity for controlling the consistency and similarity between PM and DM, analogous to the interface management evident among disparate elements within physical models.

Since the solutions that will be found for satisfying functional requirements play a key role in determining the level of complexity of the problem, these requirements must be derived systematically through a system of systems perspective considering interconnections to be as much as possible independent of each other. Axiomatic design is a helpful theory for decreasing the complexity of systems through a systematic FRD with application in various fields of research (Rauch et al. 2016). Furthermore, to avoid different interpretations of the requirements and decrease the ambiguities, certain predetermined rules and frameworks like INCOSE guidelines for RW (INCOSE 2023) must be followed.

Although with progress in machine learning and AI, recently a few researchers have started to automate FRD using deep learning and natural language processing through textual mining (Akay et al. 2021c), still there are many open issues in this field in dealing with real-world problems. The main aim of the RW step in the proposed AI-MBSE-Assisted framework is to train OpenAI for extracting FRs-PSs relying on a cloud environment to bring experts' knowledge in the training loop and derive a practical set of FRs-PSs consistent with company/organization technology maturity, available equipment, and machinery.

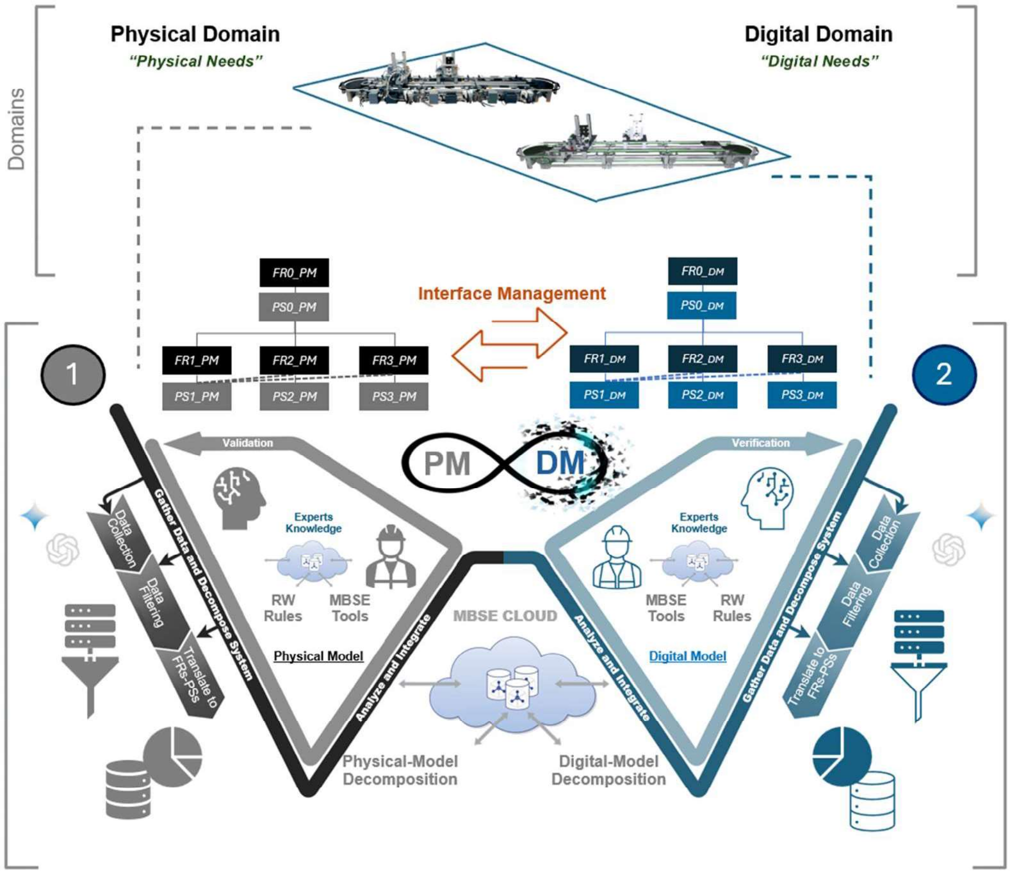

Figure 2. AI-MBSE-Assisted framework

2.2 MBSE for Requirements Management

In the extension of the quote "A problem well-stated is a problem half-solved" by John Dewey (Murphy et al. 2016) to the system development it is obvious that if functional requirements are well and comprehensively defined, further solutions to satisfy them guarantee 50% of system success. In this regard, the majority of critical system design decisions and project complications originate from the requirements development phase. By integrating DTs within MBSE and employing them throughout the entire system lifecycle, it is possible to enhance the capacity for performance optimization and financial success even before the physical system has been constructed (Madni et al. 2022). However, although managing requirements throughout the product lifecycle has always been challenging, MBSE tools could alleviate this difficulty by involving the whole expert team to define and/or capture requirements and provide a link between them and related parts of the system to facilitate their traceability (see Figure 3). In other words, relying on a visualized and automated environment, MBSE can help system developers overcome the primary issues encountered during requirements management including online traceability, inefficient validation, change management, and interface control. Furthermore, it can play a vital role in bridging the gap between digital models and what we need in practice by interlinking all functions required to be visualized or checked in DT. Therefore, MBSE can provide a digital integration environment before physical integration and consistency from requirements to models and performance analysis. By creating this closed loop, any update in requirements and their impact on the whole product lifecycle could be immediately warned. Using these features, it would be easier to identify, predict, and prevent any failures through a comprehensive uncertainty analysis, and finally, the number of expected real-model tests will be decreased.

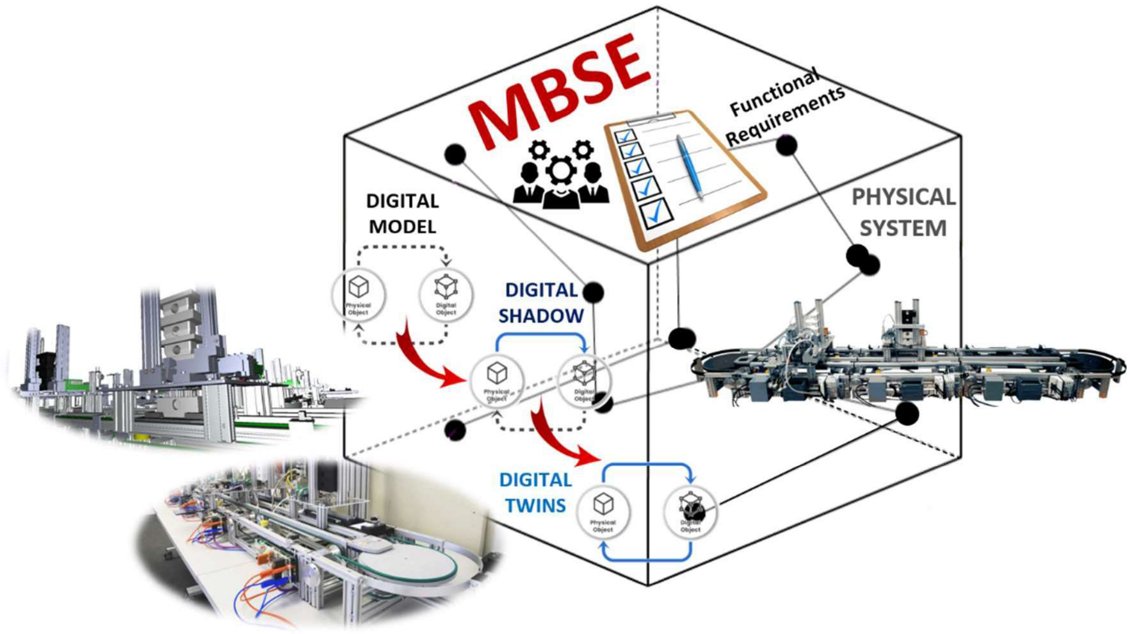

Figure 3. Unified DT-MBSE framework.

2.3 Digital Twins

Digital twins differ in design and structure depending on the application they serve and their development is a hierarchical process starting with the digital model (manual information exchange), then digital shadow (one-directional automatic data flow), and finally DTs (bidirectional automatic data flow). To minimize the development effort for their creation, models from the planning phase are increasingly being transferred to the DT. One way of transferring such a model is to use simulation models from Virtual Commissioning (VCOM) (see Figure 4).

These physics-based models are based on the real plant or machine using CAD data and allow X-in-the-loop control testing to ensure that the system operates correctly. An advantage of transferring the VCOM models to the operational phase is the ability to test subsequent adjustments or changes to the machine or system on the digital model first. The DT's FRs-PSs can then be verified and validated by running a VCOM first and checking their connection with the models. The interrelatedness between FRs-PSs of PM and DT can then be directly compared in the MBSE tools, if discrepancies are found, models and simulations can be iteratively adjusted.

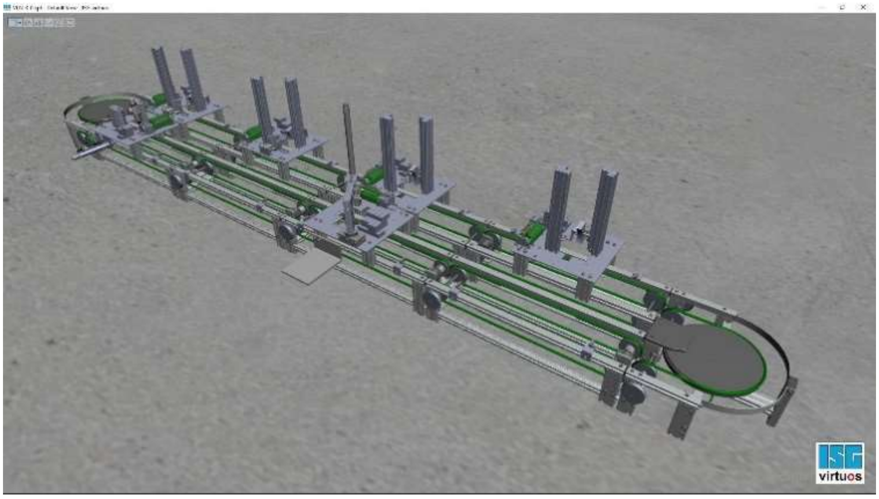

Figure 4. VCOM model of a Lucas-Nülle teaching system.

A major challenge is to automatically adjust the simulation for the modified or adapted machine or plant using only FRs and PSs as a database. While some errors can be detected more easily (e.g., overlapping machines in a plant with given positions and dimensions), other problems, such as collision testing, require additional (3D) models. To overcome this problem, more detailed constraints or simulation model variant generation can be used to transform FRs-PSs given a simulation component library (Tinsel et al. 2022). Initial Model-in-the-Loop results, such as performance and consumption data, can then be utilized for FRs' measure.

If PSs already exist but differ from the given simulation results, variants of the simulation model can be generated and retested. This process can be further accelerated by saving the simulation results at the end of each test for model reuse. PSs can then be compared directly to find a matching variant, rather than iteratively testing all variants for a simulation model composition.

3 Discussion and Needs

In the contemporary business environment, characterized by heightened competition, both small-scale enterprises and expansive corporations are striving to enhance their operational efficacy. This is being achieved by delivering heightened business value, minimizing the incidence of rework, and mitigating the frequent occurrences of budget overruns attributable to inadequate requirements management. In this respect, moving toward automation, digitalization, and DTs are essential steps. However, the complex nature of nowadays systems and hasty decisions on solutions at the lower levels of systems do not allow to fill the gap between DTs and real models in practice – especially in dealing with large-scale industrial problems. This issue is illustrated in Figure 5 focusing on the difference between "*Reality*" and "*Expectation*". Large industrial facilities and infrastructure projects are subject to the needs and requirements that originate from a multitude of stakeholder networks, complementary regulations, suppliers, technical considerations, and other sources that influence final product realization and success directly or indirectly. Therefore, considering all of these requirements in DT development is approximately impossible without involving experts' knowledge from various fields. The complexity of this issue is doubled when developing DT before the physical system has been created which requires a system of systems teamwork.

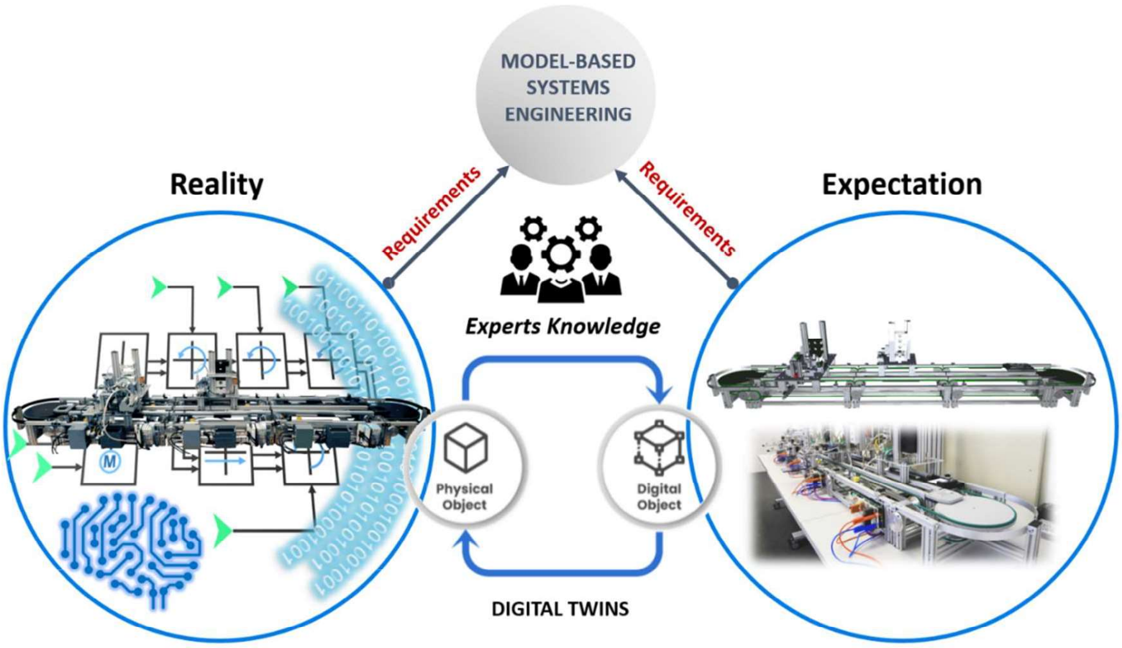

Figure 5. Real model versus digital twins.

Although the AI-MBSE-Assisted framework proposed in this paper can close the gap between DT and PM somewhat and accelerate achieving feasible innovative solutions to create cutting-edge products and systems, implementation of this framework has challenges in practice:

- Training AI for data collection is a time-consuming process and defining the right questions for gathering the right answers is not straightforward. New training and tuning are required from one question to another one.
- The extraction of FRs and PSs from the collected data based on AD rules and distinguishing between FRs and PSs is a major challenge (Akay et al. 2021a, b). It is a recursive process to define correct independent FRs to be sure that the FR could not be a PS or vice versa. The differentiation procedure is question-sensitive and the experts' knowledge and confirmation are required to avoid misleading the decomposition into further levels.
- To prevent further consequences arising from non-singular, incomplete, inconsistent, infeasible, and incomprehensible requirements, applying a requirement writing guideline like “INCOSE Guide to Writing Requirements” (INCOSE 2023) in the proposed framework is crucial.
- Prioritization of FRs in the decomposition is an iterative and recursive process that requires clear higher-level decision criteria.
- -Translating one FR from the physical system sometimes needs a set of FRs, assumptions, and constraints in the digital model. In other words, to visualize the satisfaction of one of the FRs in the physical environment, the integration of different software and tools is required in the digital model. This leads to defining a new set of requirements and constraints in the digital environment to cover all concepts hidden in the related requirement of the physical model.
- Best PS is not a unique solution between alternatives and can depend on lots of factors and could differ from case to case.
- Despite progress in MBSE tools, having an online collaboration with experts and models through immersive simulation is still required to be developed.
- Different analysis needs specific tools or software and it is required to have all of them in one place by creating a user-friendly interface environment.
- Comprehensive platforms relying on data Ocean are required for data-driven work and data optimization.

- To automatically transfer changes from the machine or system to the simulation environment and vice versa, a component library including the modified elements or information is necessary to create a closed-loop system like DTs. However, this poses a problem for non-modular projects in particular, as the digital models are missing and have to be developed first. To carry out initial tests despite the lack of models, placeholders could be inserted that simulate the behavior of the component (Tinsel et. al 2022).

- The multi-functionality of some solutions and their interconnections with other parts required an online update on models' dependencies to prevent misalignments (Kreimeyer et. al 2007). Multiple Domain Matrices (MDMs) (Danilovic et. al 2008) with multi-domain dependency extraction from several parts of the system simultaneously could be helpful but required to be adapted within the proposed framework to create not only MDMs for each physical system and digital model separately, but also provide the MDMs for the dependency between a physical and digital model. Therefore, what is required would be developing new meta-MDMs to cover interdependencies between both sides from a practical perspective.

4 Conclusion and Outlook

As breakthroughs in digital technology continue to reshape the landscape of future systems relying on virtual reality, augmented reality, and DTs, the arrival of autonomous requirements writing and management accelerators as an initiative and a major part of the systems engineering engine appears imminent. With the emergence of next-generation AI architectures like Large Language Models besides advanced systems engineering software like SysML 2 and MBSE tools and the power of natural language processing, emergent and potent methodologies for information processing are poised to redefine the landscape of systems development, ushering in a revolutionary era. Nevertheless, the variety in requirements and solutions' interactions following technology and manufacturing readiness levels hinders bridging the gap between DTs and real systems in the transitioning phase to have practical DTs. To alleviate this issue, the automation of the information exchange between experts from various fields, multi-domain dependency extraction, and tracing requirements concurrently during the systems development lifecycle is crucial.

In this respect, this paper has presented a new AI-MBSE-Assisted framework for requirements writing and management to create an intelligent tool for DT-enabled MBSE and close the gap between the physical system and its DT from the beginning of FRs' definition. This framework encompasses an automated requirements extraction based on AI, deep learning, and natural language processing; FRs-PSs decomposition based on AD and requirements writing rules; and requirements management using MBSE tools. Furthermore, the interfaces between the physical model and DT will be managed by creating an interlink between the FRs and the PSs of both physical and digital sides. To bring the digital model as close as possible to the real system and achieve practical solutions, experts' knowledge will address the consistency of extracted information throughout the whole process.

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