Systems-of-Systems and Digital Twins: A Survey and Analysis of the Current Knowledge

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***Abstract*—Understanding the needs and constraints of systems in general and a system-of-systems in particular can be challenging, yet crucial. Relying only on upfront activities will not be sufficient. Important information can be gathered around the performance and behavior of the system as well as stakeholder needs in operation. A digital twin is a way to model and understand the operation of a system. To understand the challenges and enablers related to digital twins in a system-of-systems context, we performed a literature study. In total, only 10 papers were identified that explicitly address this topic, all from the last five years, indicating that this is an active field of research. The papers revealed that definitions and terminology are unclear and that similar challenges as for systems-of-systems also exist for systems-of-digital twins. The complexity and dynamic nature of systems-of-systems motivate further study of digital twins to understand needs and constraints. However, key challenges such as concepts and principles of digital twins for systems-of-systems, cost and benefits, and evolution needs to be better understood.**

***Index Terms*—System-of-systems, digital twins, literature review**

I. Introduction

It is challenging to understand the real-world goals and constraints for contemporary systems. Systems are becoming ever more complex and more often than not operate in complex contexts, collaborating in systems-of-systems [1]. Understanding real-world goals and constraints is a core part of requirements engineering [2]. However, understanding the needs of a system-of-systems is not a pure upfront activity but rather an evolution where it is important to capture the unique properties of the system-of-systems and how it behaves in the real-world during operation. This blurs the line between development and operations, extending requirements engineering with a data-driven activity [3]. The emergent characteristics of systems-of-systems, which often are more prominent than in other situations, pose additional challenges in understanding needs and constraints [4].

We have previously reasoned about the needs and concepts around data sharing in relation to quality requirements [5], [6]. In this paper, we explore the concept of digital twins [7] as a way to support the understanding of a system-of-systems' operation and evolution to enable data-driven requirements engineering principles.

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A. Digital Twins

A digital twin is a concept in which a (cyber-physical) system is modeled digitally and data from operation, including system characteristics, are used to monitor, predict, and prescribe the behavior of the system [7], [8]. The purpose of the digital twin, and which aspects of the system are relevant, drive the appearance of the digital twin. A digital twin has a conceptual overlap with models, test execution environments, simulations, analytics, and configuration of a system, to name a few. We will focus on the monitoring and representation aspects of digital twins as a means to understand the operations of a system-of-systems.

Interesting questions arise when wanting to create a digital twin for a system-of-systems. There are both different, more or less independent, developing organizations (perhaps in a joint software ecosystem [9]) and different, more or less independently, operating organizations of the constituent systems. Furthermore, different organizations might have different business goals or even competing ones. This is sometimes referred to as co-opetition [10] where different organizations cooperate but at the same time compete. Hence, there are several potential stakeholders who want to understand the operational behavior of the resulting system-of-systems perhaps to have a competitive advantage. To understand the operational aspects of a constituent system, aspects of the other constituent systems might have to be modeled. Furthermore, data from the operation of the other constituent systems might also be needed.

B. Research Question

Given the complex nature of systems-of-systems, and their continuous evolution, the organizations involved need to gather an understanding of how the system-of-systems and its constituents behave in operation. However, as mentioned, this is far from a trivial problem. Therefore, we study challenges and enablers for digital twins in a system-of-systems context. We focus on concepts for how to design and enable digital twins rather than specific modeling or simulation aspects. The first step is to establish the current knowledge to create a foundation for such research, which is the contribution of this paper.

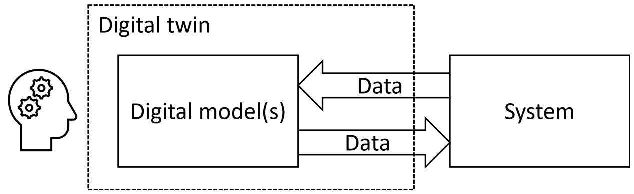

Fig. 1. A digital twin is the combination of data to and from the system, digital models of the relevant aspects, and the surrounding software needed for the operation.

Our overarching research question is: *What is the state of the art for digital twins in the context of systems-of-systems?* We study this question through the means of a structured literature review and analysis.

C. Overview of Paper

The remainder of the paper is structured as follows: In Section II, we give some background on different uses of digital twins and how they compare to other kinds of models. In Section III, we give an overview of related work, followed by a summary of our research method in Section IV. Section V presents the results, and these are further discussed in Section VI. The threats to validity are discussed in Section VII. Finally, the conclusions are summarized in Section VIII.

II. Background

There exist several definitions of and purposes for digital twins. For example [11]:

- Virtual representation
- Computable virtual abstraction
- Virtual projection
- Digital model of the real network environment
- Virtual representation based on AR-technology
- Integrated virtual model of a real-world system containing all of its physical information
- Complete digital representation

The basis for a digital twin is a model of the system and its relevant aspects, see Figure 1. However, without a connection (neither any operational data from nor any control data to) to the actual system, it is typically called *a digital model* [8]. If data from actual system operations are collected and represented, but data are not sent to the system, this is often referred to as *a digital shadow*. The digital shadow reflects what happens in the operation of the system, but cannot influence it. Lastly, if there is the possibility of sending data to the system to influence and control the behavior in operation from the model, without a redeployment of the system, this is generally called *a digital twin*. A digital twin, in addition to reflecting the operational status, can influence the system, e.g., changing parameters or configuration. Therefore, a digital twin is the combination of data, models, and surrounding software needed for the implementation.

All models, and therefore also all digital twins, represent relevant aspects of a system but never the complete system.

A user of the digital twin utilizes the digital twin as a tool for decision support. The users of the digital twin have different purposes [8]. For example, for the design, development, analysis, simulation, and operations of a system in order to understand, monitor, or optimize the actual system. However, there is always a human in the loop.

If there is an update to the system, e.g., through a new release or deployment in a new context, the digital twin might also need to be updated.

III. Related work

Before describing the details of our study, existing studies that address similar research questions are summarized. Since the research question is about assessing the state-of-the-art, related work consists of other systematic literature reviews and mappings.

The literature does not appear to have a clear definition of digital twins [11]–[13]. However, in line with Section II, studies from the literature arrive at a definition of digital twins as models, data, and software. This is also in line with other recent publications [8]. The challenges in definition and terminology also exist in the systems-of-systems domain. We aim to highlight some of these issues in this paper.

Somers et al. found 26 articles on twin-based digital testing in their systematic literature review [12]. A literature review of challenges and enablers for digital twins in the process industry resulted in 79 papers [13].

Dalibor et al. found 356 papers in their systematic mapping study on software engineering for digital twins [11]. 104 of those are related to digital twins for systems-of-systems, for example, digital twins of a factory or manufacturing processes [11]. However, the included papers typically do not use the term system-of-systems or a system-of-systems engineering approach. We complement the systematic mapping study with a knowledge review specifically and explicitly focused on systems-of-systems and digital twins to identify challenges and opportunities in that field.

Various types of combination and integration challenges are reported [11], [13]. For example, how can different digital twins of individual systems be combined to represent a larger (system-of-)systems [11]? Furthermore, how can new and old legacy systems be integrated to support a digital twin [13]? We complement the existing studies with a specific focus on systems-of-systems where the integration and combination of systems is core to the discipline.

Another interesting systematic review focuses on digital twin based testing and cyber-physical systems [12]. It does not explicitly talk about system-of-systems but brings up autonomous cyber-physical systems. They identify that digital twins are typically not just for active testing. Rather, in terms of testing, digital twins are commonly used for monitoring the system in operation, i.e. passive testing.

IV. Method

To address the research question stated in Section I-B, we used a snowball method for our literature review [14]. Our aim was to find literature specifically for digital twins and system-of-systems.

We performed the following steps:

1) Define start set:
   - First, we looked for literature reviews on digital twins. We did not find any specific literature reviews on digital twins and system-of-systems. However, we found several quite recent literature reviews on digital twins [11]–[13]. The literature reviews as such are included as related work, but not as results.
   - We scanned system-of-systems-specific conferences (System-of-Systems Engineering Conference and Workshop on Software Engineering for Systems-of-Systems and Software Ecosystems) for publications on digital twins. If the title or abstract were clearly on digital twins, we preliminary included the papers.
2) Snowballing: Based on the starting set, we reviewed the references in the papers. We also reviewed forward references (papers referring to our start set). However, since the publications are quite recent, there were not many forward references. Papers with a title or abstract clearly on digital twins and system-of-systems were preliminary included.
3) All papers were read. Papers within the scope of our research question were included.
4) We did another round of snowballing of the included papers, again reviewing title and abstract. For the preliminary included papers, we conducted a full read to determine whether to include them in the final set of papers. After two rounds of snowballing, we reached saturation and found no more papers.
5) The papers were coded according to the research question, research method, and whether systems-of-systems are explicitly mentioned.

V. RESULTS

We ended up including 10 papers that are explicitly on digital twins and system-of-systems, see Table I. The papers are from 2019-2022, hence this does not seem like a topic that has been studied a lot. Related concepts such as federated digital twins [15] or cognitive twins [16] are sometimes used or simply integrating digital twins [17], [18].

A. Challenges

There are different challenges reported in literature:

- *Lifecycle*—as the constituent systems change, so does the system-of-systems. This means that the digital twin(s) also must be updated [19]. That is, the system and the corresponding digital twin are tightly coupled, whether the digital twin is built for a specific constituent system or for the system-of-systems. Furthermore, traditional cyberphysical systems tend to have a long lifecycle whereas understanding the operations of a system-of-systems might have a shorter one [17]. Hence, even though the constituent system might not need change for the sake of operation, there might be a need to change to facilitate a digital twin implementation.
- *Access to data*—the digital twin might require different data than the constellations for their operation [19]. Hence, more data might need to be collected and exchanged for the digital twin to have the required fidelity. Access and availability of data can also be a challenge [17].
- *Data sharing*—even though the constituent systems might have agreed to share data within the constellations for its operation, building a digital twin might require different data than normal operation [19]. Due to the managerial independence, more agreement with potentially different stakeholders is needed which can make sharing of data for digital twins even harder than for a system-of-systems [15]. Data ownership and privacy are also highlighted as aspects to consider.
- *Technical*—computing power and data storage can be a limiting factor for distributed digital twins [15], as well as communication bandwidth, especially for near real-time updates [21].
- *Forming and disbanding constellations*—the digital twin(s) must form and disband along the constellations [15].
- *Integration*—if there are multiple digital twins each twinning different constituent systems, then the digital twins as such also need to be integrated or forming constellations [18], [21], [25]. The challenges of integrating different,perhaps independently developed and independently operated, digital twins overlap a lot with challenges for system-of-systems. This is also reported as interoperability of digital twins [23].
- *Modeling*—achieving a suitable level of fidelity of a digital twin is a modeling challenge [21]. Even though developing the digital twin is a system-specific activity, it often does not begin until the development of the system it is twinning has ended [25].

B. Mitigation Strategies

There are several ideas on how to address the above challenges. Bonorden et al. reason about how to make design decisions for when you have federated digital twins [15]. They use the term “federated digital twins” when a digital twin is divided into several cooperating digital twins. This is mainly driven by technical design decisions regarding computing power and data sharing.

Jia, Wang and Zhang propose a 4C modeling architecture, dividing a complex digital twin into several simpler [23]. Individual twins are united through an ontology and knowledge graph, enabling the individual twins to interact, thereby creating a whole.

Similarly, one paper discusses the term cognitive digital twins [16]. They propose to add some processing of data for the digital twin at the edge nodes of the network, and a cognitive layer for complex decision making. The cognitive

TABLE I
IDENTIFIED PAPERS ADDRESSING THE USE OF DIGITAL TWINS IN THE CONTEXT OF SYSTEMS-OF-SYSTEMS.

Authors	Title	Year	Forum	Ref
L. Bonorden, et al.	Decision-Making About Federated Digital Twins – How to Distribute Information Storage and Computing	2022	Modellierung conference	[15]
M. Borth, J. Verriet, and G. Muller	Digital Twin Strategies for SoS 4 Challenges and 4 Architecture Setups for Digital Twins of SoS	2019	System-of-System Engineering conference	[19]
J. Ahlgren et al.	Facebook's Cyber–Cyber and Cyber–Physical Digital Twins	2021	Conference on Evaluation and Assessment in Software Engineering	[20]
M. I. Ali, P. Patel, J. G. Breslin, R. Harik, and A. Sheth	Cognitive Digital Twins for Smart Manufacturing	2021	Journal of IEEE Intelligent systems	[16]
L. Zhang, L. Zhou, and B. K. Horn	Building a right digital twin with model engineering	2021	Journal of manufacturing systems	[21]
J. Michael, J. Pfeiffer, B. Rumpe, and A. Wortmann,	Integration challenges for digital twin systems-of-systems	2022	Workshop on Software Engineering for Systems-of-Systems and Software Ecosystems	[18]
A. Rasheed, O. San, and T. Kvamsdal	Digital Twin: Values, Challenges and Enablers From a Modeling Perspective	2020	IEEE Access	[22]
W. Jia, W. Wang, and Z. Zhang	From simple digital twin to complex digital twin part i: A novel modeling method for multi-scale and multi-scenario digital twin	2022	Journal of Advanced Engineering Informatics	[23]
M. Tisi, H. Bruneliere, J. de Lara, D. Di Ruscio, and D. Kolovos	Towards Twin-Driven Engineering: Overview of the State-of-the-Art and Research Directions	2021	IFIP International Conference on Advances in Production Management Systems	[24]
D. Hallmans, K. Sandström, S. Larsson, and T. Nolte	Challenges in providing sustainable analytic of system of systems with long life time	2021	System-of-System Engineering conference	[17]

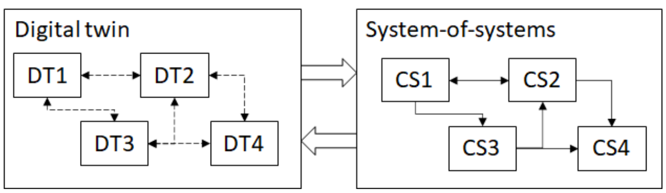

Fig. 2. A monolithic digital twin.

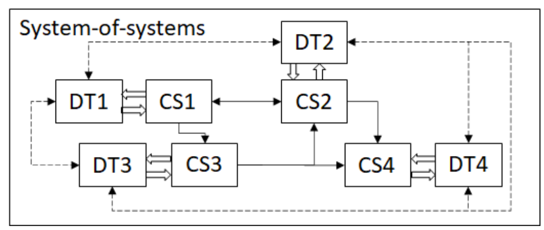

Fig. 3. A system-of-digital twins or distributed digital twins.

digital twins can then be networked into an ecosystem and feed into a knowledge graph.

VI. DISCUSSION

The findings from literature points at several challenges related to the use of digital twins in the context of systems-of-systems. In this section, some of those challenges related to the perspectives of architecture, lifecycle, and business value will be discussed.

A. Architecture Perspective

One way of designing a digital twin of a system-of-systems is to have one digital twin for the entire system-of-system, see Figure 2. This might be appropriate for certain system-of-systems such as directed ones [26]. However, the monolithic nature requires someone to understand and manage the entire system-of-digital-twins.

The other extreme is to have a digital twin for each constituent in a distributed manner, see Figure 3. Each constituent digital twin needs to agree with other relevant digital twins on exchange of relevant data. The challenges for the system-of-digital-twins are similar to the challenges of any system-of-systems.

There are obviously many different variations of the two principal cases, and the precise border between a monolithic and a distributed digital twin architecture is difficult to draw. Finding an appropriate architecture for distributed digital twins appears to be a key, and central in this is the interoperability between the different digital twins. The solution ideas recognize that it is challenging to have a monolithic digital twin for an entire system-of-systems.

Different ideas are presented to divide a larger, more complicated digital twin into smaller and simpler digital twins which are then interacting. However, most solution focus on creating a digital twin for the entire system-of-systems. Just as it is at times difficult to talk about a system-of-systems as a whole, e.g., due to forming and disbanding of constellations of constituent systems, also the digital twins can exhibit properties meaning that representing the whole system-of-systems is not possible. Therefore, it can be interesting to think of a digital twin for a constituent system as a constituent digital twin with its goals and value even without the other digital twins for other constituents.

At the same time, there is a system-of-digital-twins with similar challenges, e.g., independent development, independent operation, evolutionary development, etc., as a system-of-systems. We believe, though, that concepts and principles addressing how to organize and reason around system-of-digital-twins for system-of-systems need to be elaborated and clarified.

The constituent system digital twins will be developed by different organizations that have their own interests and vocabulary. Therefore, the digital twin will reflect that organization's world model [27], which may not be fully compatible with that of another organization involved in the same system-of-systems. Therefore, the interoperability between different digital twins is an important architectural concern. Due to the rich data that may need to be exchanged, powerful concepts such as linked data and ontologies are likely to be needed to resolve this [28].

B. Lifecycle Perspective

As pointed out by, e.g., [19], [24], [25], the digital twins become systems of their own. If they are cooperating, they form constellations, i.e., are part of a system-of-systems. Therefore, even digital twins, which can be complex and large systems on their own, need to be properly handled in terms of the development process with requirements, etc. [11].

Depending on the usage of the digital twins, they can be seen as either part of what is being delivered through the engineering efforts (e.g. the digital twins are used to monitor and control operation) or as a tool for delivering results (e.g. the digital twins are used as a test and visualization environment during development)—or both!

The digital twin is an engineering artifact of considerable complexity. It needs to be treated as such, with appropriate lifecycle processes, and a foundation for that is to find a suitable architecture. This architecture needs to be distributed, and the digital twin of one organization will to some extent rely on data from other organizations involved. This includes not only engineering data, but also exchanging models on appropriate levels of abstraction. The interoperability aspects thus become a key, and appropriate data formats need to be specified. In essence, the architecture of the system-of-systems' digital twin will be a system-of-systems itself, with all the difficulties this involves along with unique challenges for digital twins.

One of the reasons why digital twins are becoming increasingly attractive is the introduction of model-based systems engineering practices. During the development of a physical system, it is common practice to create a digital model of that system that allows simulation to evaluate different design alternatives. This model can then be reused as a starting point for a digital twin, thus reducing the effort to create the twin. However, for the system-of-systems, such digital models may not exist during development. Also, the sharing of detailed constituent system models is not attractive since they contain a lot of intellectual property about the physical product.

C. Business Perspective

It is today difficult to systematically reason about the value of digital twins, especially from a lifecycle perspective where the digital twin will have to evolve along with the system. Furthermore, the cost associated with digital twins is also unclear. Costs will occur both on the development side as well as on the operation of digital twins. We therefore posit that value of digital twins as well as the cost needs to be better understood for digital twins usage to be picked up.

Additionally, incentives and rules for data sharing will need to be put in place. This can be especially tricky in a co-opetitive context where the participating organizations are cooperating but also competing. There needs to be a strategy for what data to share. As we reasoned in our previous paper [6], there might also be a need for a mediator or concepts such as open data ecosystems [29].

VII. Threats to Validity

There are two main threats to the validity of our literature study: 1) Inappropriate start set and 2) incorrect exclusion of papers.

We used literature reviews on digital twins as part of our starting set. Their scope is not exactly the same as ours; hence, there is a risk that they did not include references which might be relevant for us. The other part of our start set are publications in the "System-of-Systems Engineering Conference" and the "Workshop on Software Engineering for Systems-of-Systems and Software Ecosystem". These fora are relevant for the system-of-systems part of our scope but might not include an appropriate start set for digital twins for system-of-systems. However, the two parts of the starting set complement each other, mitigating the threats to validity of not finding relevant references. In conclusion, we believe there is a risk that the start set is a limiting factor. It is not likely to be a threat to the results we found, but we might not have found all challenges and mitigation strategies.

We screened the papers based on title and abstract for the terms system-of-systems and digital twins. There is a risk that papers might not have used the term system-of-systems even though this was a topic in the paper. Hence, we might have excluded some papers inadvertently, especially when considering the literature review of Dalibor et al. [11]. They report finding 104 papers on system-of-systems. However, when looking at the titles in their reference list, it is not obvious which these 104 papers are. Therefore, there is a risk that we overlooked relevant papers. This is a threat to the validity similar to the start set. At the same time, we want to be more specific on the system-of-systems topic, hence this threat should not be exaggerated.

VIII. Conclusion

The complexity and dynamic nature of systems-of-systems make it challenging to understand needs and constraints. It is not sufficient to rely on an upfront process to understand the requirements. The systems in operation need to be analyzed and utilized as a means to understand needs and constraints—and also when constraints are not met [6]. Digital twins are one possible means for this. However, ironically, the needs and constraints of digital twins for systems-of-systems are not well understood, nor the process to implement digital twins.

The terminology and definition of the digital twin concept is maturing and converging. Similar for system-of-systems where the unique properties and characteristics are now better understood. However, the terminology and definitions of the combination of digital twins and system-of-systems is very much evolving. There are several attempts to model and implement digital twins in system-of-systems contexts, but it is difficult to grasp the field as the terminology is varying to a large extent. Nevertheless, it is quite clear that the use of digital twins in a system-of-systems context has several particular challenges, and more research is needed to fully address them.

An aspect is the fact that the digital twin becomes an additional engineering artifact of high complexity, for which appropriate engineering methods and tools must be provided. Although the digital twin can support the system-of-systems specific challenges related to the continuous evolution, this also creates a need for continuous evolution of the digital twin that adds to the system development and maintenance efforts.

We see a need to better understand the return on investment for digital twins for system-of-systems. Our results indicate that it is not clear how to design distributed digital twins. We also need methods to estimate the effort. The benefits of having a distributed digital twin need to be coupled with this. We see a need for research on scoping and requirements for distributed digital twins in parallel to the architecting of them.

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