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Evolutive Digital Twin Applied to Nuclear Industry

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Abstract

The Digital Twin (DT) is the most advanced paradigm to create a virtual representation of a real world multi-physical system for the sake of designing, monitoring, and supporting the decision making throughout its whole lifecycle. Therefore, DT requires a flexible ecosystem made of a variety of engineering tools and services that need to be highly interoperable and enable knowledge management and traceability. However, the major challenges that slows down the emergence of DT environment are the inherent incompatibility of engineering tools with the absence of a unified standard for interoperability, and the human change aversion to new technologies, tools and paradigms. For this purpose, we have developed an evolutive environment that answers the main requirements of Interoperability, Traceability, Flexibility, and Knowledge management. In this paper, we introduce a general overview of DT ecosystem with the limitation of some state-of-art existing implementations with respect to four metrics. Then we will introduce our solution applied to a nuclear case study to demonstrate a highly evolutive implementation of a DT ecosystem.
Keywords: Digital Twin, Interoperability, Traceability, Flexibility, Knowledge Management

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1 Introduction

The Digital Twin (DT) concept, having its roots in decades-old paradigms [3], has become an increasingly significant technology for generating virtual copies of real-world multi-physical systems. Such a virtual representation is not just an imitation; it paves the way for effective designing, real-time monitoring, and decision-making throughout the system's entire lifecycle [5,6]. Yet, for a DT to be genuinely effective, it necessitates a robust ecosystem supported by a myriad of engineering tools and services. This ecosystem, ideally, should champion the cause of interoperability, knowledge management, and traceability [4].

However, the path to realizing a universal DT ecosystem isn't devoid of challenges. One primary hurdle lies in the inherent incompatibility of engineering tools. The absence of a singular, unified standard has made interoperability a daunting task [3]. Simultaneously, the human element cannot be overlooked; there's a natural resistance to adopting novel technologies, tools, and paradigms, further decelerating the widespread acceptance and integration of the DT environment [5].

In light of these challenges, our work seeks to bridge the current gaps. Through our research, we aim to furnish an environment that is evolutionary by nature, addressing the core requisites of Interoperability, Traceability, Flexibility, and Knowledge Management. By juxtaposing the existing state-of-the-art DT implementations against our newly developed ecosystem, we offer insights into the limitations and the potential improvements that can reshape the future of DTs. Furthermore, to underscore the efficacy of our approach, we delve into its practical application in the context of a nuclear case study, hoping to shed light on a path toward a more adaptable DT ecosystem.

To set the context for our contributions, we will first provide a comprehensive review of the existing literature, citing the seminal and contemporary works that have shaped the current landscape of Digital Twin (DT) technologies. This exploration of related works will delineate the prevailing trends, identified challenges, and notable solutions proposed by the research community. Understanding these foundational works will aid in discerning the unique value proposition of our approach.

Following our survey of the related works, we will expound upon our research methodology in detail. The methodology section will articulate the design principles, approaches, and processes underpinning our DT ecosystem's development. By delving into the very heart of our methodology, we aspire to offer a transparent, replicable, and adaptable framework for future researchers and practitioners in the DT domain.

In the culmination of our study, we undertake a rigorous comparative analysis of prevailing DT technologies. For an empirical and objective assessment, we employ four pivotal metrics: Interoperability, Traceability, Flexibility, and Knowledge Management. This evaluation will underscore the strengths and potential areas of improvement for our proposed system in comparison to its contemporaries.

In the subsequent sections, we venture into each of these aspects in depth, providing readers with a holistic understanding of our approach and its significance in the DT domain.

2 Related Works

The Digital Twin (DT) paradigm, although relatively recent in terminology, is anchored in a rich tapestry of research and literature spanning various dimensions. Numerous researchers and scholars have elucidated the different facets of this burgeoning technology.

The very inception and evolution of DTs can be traced back to the formative attempts to virtually represent and simulate physical systems [3]. A holistic overview provided by Rosen et al. [3] charts the trajectory of the DT, transitioning from a nascent concept to a revolutionary technological paradigm.

Central to the discourse on DT is the recurring challenge of interoperability. The work of Tao [2] underscores the intricate challenges posed by the fusion of diverse engineering tools. This complexity is further echoed in the work of Rosen et al. [3], accentuating the imperative need for unified standards to champion seamless integrations.

Equally significant is the DT ecosystem's ability to ensure knowledge management and traceability. These foundational aspects have been the focus of seminal work by Soderberg et al [9], setting the benchmark for subsequent explorations to conceive methodologies that amplify these components within the DT milieu.

The innate demand for adaptability in the DT paradigm is meticulously explored by Lu et al [8], who unpacks the intricacies of ensuring flexibility in DT frameworks, thereby laying the groundwork for inventive solutions adaptable across a spectrum of applications.

Yet, amid the technical rigors, it is crucial not to sideline the human dimension in the discourse on DT adoption. The profound exploration by Davis et al [11] demystifies the psychological and socio-cultural impediments to new technology assimilation, offering a nuanced understanding of the dynamics that govern DT's integration into conventional workflows.

While this survey of related works is by no means exhaustive, it furnishes a foundational understanding of the existing DT landscape. The insights gleaned from these pioneering works help situate our research, delineating the context for our novel contributions.

3 Methodology

The development and integration of Digital Twins (DTs) into modern systems are increasingly gaining attention across industries. Central to this growth are four pivotal concepts that define the effectiveness, accuracy, and usability of DTs: Interoperability, Traceability, Flexibility, and Knowledge Management. Interoperability, at its essence, is about ensuring seamless communication. It defines the capacity of different systems, tools, or applications to communicate, share, and exchange data without hindrance. In the Digital Twin landscape, this seamless exchange is paramount. The virtual components must synchronize harmoniously with an array of real-world systems, regardless of their origin or platform. Where a multitude of engineering tools are involved in DT creation and management, the role of interoperability becomes fundamental, ensuring real-time responsiveness and overall DT efficacy.

Traceability, on the other hand, anchors the principle of accountability and evolution tracking within DTs. It pertains to the meticulous recording and tracking of changes, adaptations, and the overarching developmental trajectory of the digital twin. For high-stakes industries such as nuclear energy or aerospace, traceability ensures that any adjustments are carefully logged and, if required, can be revisited or even reversed. Furthermore, traceability offers an invaluable historical dataset that can be pivotal for subsequent system analyses and improvements. Flexibility, in this context, encapsulates the adaptability factor. Given that real-world systems are in perpetual evolution, their virtual counterpart, the DT, should mirror this dynamism. This demands that DTs be designed to easily assimilate new data, integrate with emergent tools, or adjust to changing operational parameters, ensuring its longevity.

Knowledge Management (KM), while last in the list, is arguably the linchpin of this quartet. In the DT realm, KM is all about converting the vast data streams generated into actionable insights. It centers on capturing, organizing, and deploying this knowledge optimally, making it instrumental for predictive analytics, preventive maintenance, and informed decision-making. Building on these foundational concepts, our research methodology will employ them as yardsticks for comparison. We aim to probe the offerings of leading Digital Twin solution providers, namely Siemens, Dassault, Nvidia, evaluating each against the tenets of Interoperability, Traceability, Flexibility, and Knowledge Management. Furthermore, our own developed solution will be critically assessed under these metrics, allowing for a comprehensive comparison. This rigorous assessment seeks to spotlight strengths, uncover potential gaps, and furnish insights into their alignment with the broad requirements of a holistic DT ecosystem.

4 Review and comparison of DT solutions

In the realm of digital twin technologies, various industry leaders such as Siemens, Dassault, and Nvidia have provided notable solutions. This section delineates a comparison of these solutions based on four pivotal metrics: Interoperability, Traceability, Flexibility, and Knowledge

Management.

4.1 Comparison

Siemens: Siemens Digital Industries Software is renowned for its expansive digital twin suite that spans an entity's entire lifecycle. In terms of *Interoperability*, Siemens' Xcelerator boasts tools capable of integrating with a myriad of third-party systems and IoT functionalities. With its Mindsphere platform, *Traceability* is enhanced, allowing real-time monitoring and predictive analytics. The suite's modularity affords significant *Flexibility*, allowing it to cater to varied industry needs. Lastly, in the realm of *Knowledge Management*, Siemens leverages its consistent data management tools, ensuring optimal data utilization across different stages.

Dassault: Dassault's 3DEXPERIENCE platform is grounded in providing an integrated environment for digital twin development. Their strength in *Interoperability* is marked by a seamless integration across diverse domains. The platform's concept of a 'single source of truth' emphasizes *Traceability*, allowing stakeholders to access consistent data. For *Flexibility*, Dassault's approach to replicating entire factories in a virtual environment stands out, allowing for risk-free modifications and optimization. Their robust data management tools further accentuate their capabilities in *Knowledge Management*.

Nvidia: Predominantly known for GPU technologies, Nvidia's approach to digital twins focuses on AI and deep learning. Nvidia Omniverse's architecture ensures high *Interoperability*, integrating AI-driven insights with high-fidelity simulations. This platform's real-time collaborative environment underscores its *Traceability*. In terms of *Flexibility*, the AI-driven nature of their digital twins allows them to be dynamic and adaptable. Lastly, with respect to *Knowledge Management*, Nvidia integrates learning capabilities, ensuring the twin evolves alongside its physical counterpart.

In the following table we have summarized the comparison of the solutions provided with respect to the aforementioned metrics.

4.2 Digital Twin in the context of the Nulcear Industry

The utilization of the Digital Twin (DT) paradigm within the nuclear industry presents a set of distinct challenges. Firstly, the safety-critical nature of nuclear operations mandates exceptionally high levels of accuracy and reliability from any technological solution, and even minor inaccuracies in a DT can result in catastrophic consequences. Secondly, the long lifespan of nuclear facilities, often spanning several decades, makes them susceptible to technological obsolescence, complicating the continuous integration of evolving DT solutions. Thirdly, nuclear operations involve complex multi-physics processes, which are challenging to model and simulate accurately. Fourthly, the sheer scale and complexity of nuclear facilities require DT solutions with unprecedented computational capabilities. Fifthly, there's the challenge of data sensitivity and security, given the strategic importance and potential risks associated with nuclear data. Lastly, there's a significant concern related to the integration of legacy systems, which might not be readily compatible with modern DT technologies. In light of these unique challenges and the comparison we have presented above, off-the-shelf DT solutions developed by Siemens, Dassault, and Nvidia, while advanced in their own domains, are not easily adapted for the nuclear industry. Their architectures, primarily designed for more conventional industrial applications, might not address the nuanced requirements and constraints that nuclear operations entail, demanding more tailored solutions.

4.3 Our Digital Twin solution

In addressing the unique challenges associated with deploying a digital twin in the nuclear industry, we have developed an innovative ap-

	Provider	Inter.	Trace.	Flex.	KM
	Siemens	-	++	++	++
	Dassault	-	+++	+	++
	Nvidia	+	++	++	+

Table 1: Comparison of Digital Twin Solutions across four metrics. Inter. = Interoperability, Trace. = Traceability, Flex. = Flexibility, KM = Knowledge Management

proach that stands distinct from conventional offerings. Central to our solution is a versatile digital twin that is not confined to a specific type of model. Instead, it can be centered around a 3D model, a logical model, or even a behavioral model, catering to a variety of application scenarios within the nuclear domain. This inherent flexibility ensures that our solution remains adaptable to evolving requirements.

Unlike other commercial solutions that might be tied to proprietary platforms or software licenses, our digital twin allows for the use of open-source software for its creation and definition. This ensures not only affordability and accessibility but also paves the way for extensive community-driven enhancements in the future. Furthermore, the absence of any stringent dependency on platforms like 3Dexpreience implies that our model can be deployed directly in the cloud.

Recognizing the immense benefits of cloud-based solutions in terms of scalability and accessibility, we have established a dedicated open-source cloud environment to host our digital twin. From this environment, authorized users can access, modify, monitor, and inspect the digital twin using the Identity and Access Management (IAM) protocol. This ensures that while the twin remains universally accessible, its integrity and security are never compromised.

Importantly, the entire definition and implementation of our digital twin remain independent of any licensed software. This not only makes it free from the constraints and costs of proprietary platforms but also enhances its interoperability, as it can seamlessly integrate with a variety of tools and systems. The cloud-based approach further underscores its flexibility; the resources necessary for computations or other operations are dynamically allocated on demand, guaranteeing optimal performance and scalability.

Last but not least, our solution boasts an integrated Knowledge Management platform, also hosted on the cloud. This platform forms the crux of our commitment to knowledge management and is designed to be a repository of invaluable insights and data. Access to this platform is meticulously regulated using the IAM protocol, ensuring that while collaborative inputs are facilitated, the sanctity and confidentiality of information remain uncompromised.

Collectively, these features position our digital twin solution as superior in terms of interoperability, traceability, flexibility, and knowledge management. We believe that this holistic approach not only addresses the immediate challenges of the nuclear industry but also provides a scalable and adaptable framework for future advancements.

5 Conclusion

The digital twin paradigm has emerged as a transformative solution, redefining how industries model, monitor, and manage their operational assets and systems. The challenges of implementing digital twin solutions in the nuclear industry are manifold, given the sector's unique demands for safety, accuracy, and reliability. Traditional solutions offered by major players like Siemens, Dassault, and Nvidia, while commendable in general contexts, often fail to address the intricacies and bespoke requirements of the nuclear domain.

In this study, we delved deep into the

core metrics that determine an effective digital twin: interoperability, traceability, flexibility, and knowledge management. Our analysis of leading solutions against these metrics highlighted areas of improvements and gaps. Guided by these insights, we presented our cloud-based digital twin solution that stands apart in its adaptability, independence from licensed software, and comprehensive knowledge management platform. Our approach, underpinned by open-source principles and centered around a versatile modeling capability, promises a scalable and cost-effective digital twin platform tailored for the nuclear industry.

While the journey of perfecting and refining digital twins for nuclear applications is ongoing, our solution marks a significant step forward. It not only addresses the immediate challenges faced by the industry but sets the foundation for an adaptable and resilient framework that can accommodate future technological advancements and industry needs. The nuclear industry, with its high stakes and stringent standards, deserves a digital twin solution that's robust, flexible, and forward-looking. We believe our solution is poised to meet and exceed these expectations.

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