A Vision for a Platform-based Digital-Twin Ecosystem

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Abstract: The widespread adoption of digital technology tied with the 4th industrial revolution means the complete reinvention of how business is done. Digital Twin (DT) technologies are now a key technology trend that is already being developed and commercialized to optimize numerous manufacturing processes. In this paper, and from an Information Systems (IS) discipline viewpoint, we take stock of the different technological visions of the DT in manufacturing. We leverage this summary as a stepping stone for discussing the DT's sociotechnical design implications by pointing how this approach is essential for the design of DT software that is specific to its environment and users and co-evolves with it. Furthermore, we present our vision for a DT-based Digital Platform that can support product design and life-cycle management while generating value through an ecosystem of twin-driven product-service systems.
Lastly, we show how the Transformer 4.0 project will demonstrate the main principle of our vision by placing the DT of the power transformer with the dual role of virtual counterpart of the physical product and as the architectural framework for (i) managing and processing the historical data collected from the multiple working instances of DTs, and (ii) managing and integrating design information (models, specifications, design data, among others).

Keywords: Digital Twin, Digital Platform, PLM Systems

1. INTRODUCTION

Digital Twin (DT) technologies are rapidly becoming a centerpiece of product development and manufacturing in Industry 4.0. The DT concept was initially proposed in 2002 as a conceptual model of product lifecycle management (PLM) that includes a physical system and a virtual system that contains information related to it, and this idea has been developed in subsequent work in the DT field. As such, current DT definitions vary around a common notion of the linking of a physical object or machine, with a virtual entity that represents it, through a data connection. Building on this core idea, works such as Glaessgen and Stargel (2012), Boschert et al. (2018), Gabor et al. (2016) and Weyer et al. (2016), introduce simulation as the primary technological means through which the physical world is twinned to the virtual space, and real world sensor data as a crucial enabler for this twinning. Furthermore, other literature, specifically Tao et al. (2018), place the emphasis not only on simulation enabled by operational sensor data, which can be seen as the virtualization of physical entities, but also on the materialization of the virtual space. This is accomplished through the interaction of the virtual twin with its physical counterpart, through, e.g., the exchange of commands and the generation of valuable services involving the physical product. The DT's applicability during the product life cycle has been increasingly researched and implemented, with most works focusing on product design, testing and manufacturing. In product design, academic literature attributes data capture and analysis capabilities to the DT (product DT), which uses design and operational data previously captured in existing products, to provide features such as the recommendation of design specifications, the identification of design contradictions, and the verification of conformity between design specifications and project requirements. Works, including Tao et al. (2018), Schleich et al. (2017), and Xie et al. (2020), propose DT's centered around these core functionalities. Further capabilities, especially the DT as a simulation tool Tao et al. (2018), are proposed to accurately predict a product's performance and identify design faults. This permits reduction in costs and lead time, as costly prototyping and laboratory testing become obsolete. In manufacturing, shop floor DT's (process DT) are envisioned to encompass production planning capabilities, as well as undertake in the management of maintenance activities through predictive maintenance services. These aspects have been a staple of research on the DT field, with a number of works, including Wu et al. (2015); Santos et al. (2019), proposing that the DT captures sensor data embedded in the production line, to accomplish goals such as optimizing production and maintenance, and monitor manufacturing activities in real time. In this paper, we detail our vision for the Digital Twin as the centerpiece of a digital platform that provides data-driven services in the intra-organization and inter-organization level. This is accomplished by defining the DT platform goals, and also the layers that compose its architecture. Finally, we provide an overview of how this

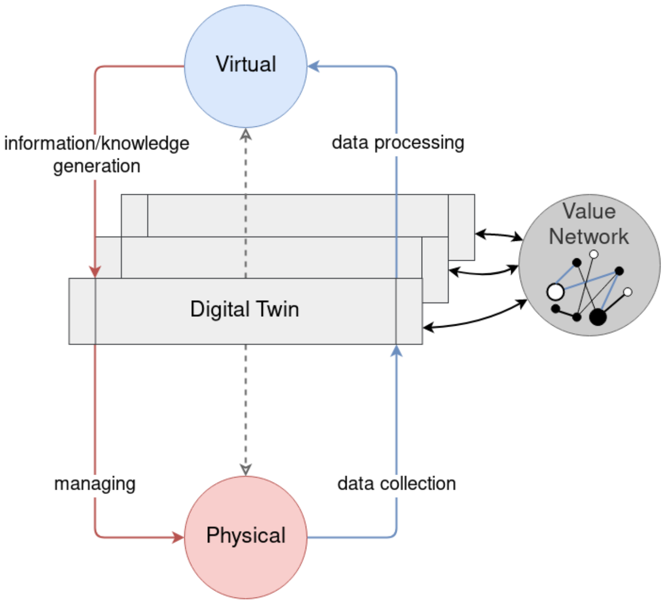

Fig. 1. Digital twin concept

platform will be developed in a use case addressing the development of power transformers.

2. A NEXT-GENERATION DIGITAL TWIN

Firstly introduced more than 20 years ago as part of a university course on Product Lifecycle Management (PLM) (Grieves, 2014), the concept of DT has recently emerged as our society becomes more interconnected (Batty, 2018). At its core, and from a holistic point-of-view, a DT system is composed of three main components as depicted in Figure 1: (i) physical components; (ii) virtual models; and (iii) the data connects them. Grieves (2014) describe how the data functions as the main connector between physical and virtual components. In Grieves's approach, data that flows from the physical components to the virtual models is raw, in need of processing, while data created in the virtual components gets processed and stored as knowledge across the digital models. We can then conceptualize DT systems as loops where the physical components become responsible for collecting real-world data that is subsequently transmitted to the virtual models. In turn, these systems are encharged with transforming data into information and knowledge that is then leveraged to manage the physical components (Boje et al., 2020).

Different authors have tried to map the evolution path of DT systems. Evans et al. (2019) outline a five-stage maturity spectrum that focuses on the purpose and added-value benefit of each stage while Boje et al. (2020) propose a 3-tier generation evolution that, despite focusing on a digital twin for the construction sector, end up with a model that is effective in an industry-agnostic setting. These two models stand on the gradual advancement in technical sophistication, supply-chain integration, and data/information semantics, leading to complete coverage of a product or service lifecycle on a different verbosity level.

Boje et al. (2020) define the first as mere monitoring platforms. The core functionality of these is to enable sensing of the physical and, to some capacity, analyze and report. This generation fits with the first level of Evans et al. (2019) maturity level where models are purely object-based with no metadata or information attached.

A second generation by Boje et al. (2020) introduces semantic capabilities into the DT system. This generation broadly fits with the second and third levels of maturity by integrating different sources, enriched with real-time data, and enhanced with semantic capabilities. A single reference point from which all data can be viewed and interrogated is created and can be leveraged to reduce errors, uncertainties, and costs. A semantic data model of this maturity further enables integrating multi-physics, multi-scale, probabilistic models for enabling simulations and predictions. On the other hand, at this level of development, both authors point to the optimization of the system as a still manual process that is primarily carried out by humans. The last generation, that Boje et al. (2020) entitle as Agent Driven Socio-technical Platforms encompass level 4 and five of Evans et al. (2019) maturity level. At this stage of development, not only can the physical assets be developed and modified via the twin, with output and results fed back and updated back into the twin, but the fully semantic DT can leverage machine learning, deep learning, data mining, and artificial intelligence capabilities to construct a self-reliant, self-updatable and self-learning DT. While Evans et al. (2019) focus its two last maturity levels on the engineering systems and applications and how they allow for these full autonomous operations of the system, Boje et al. (2020) see the social aspects as also playing a fundamental role. At this stage, the DT can adapt to social requirements and engage with end-users to support holistic decision-making Boje et al. (2020).

Parallel to this work, authors such as Rosen et al. (2019), have focused on how DT technologies can be arranged in value networks to generate ecosystems. These ecosystems and the realization of the interconnectedness of multiple instances of a DT or even different DTs can enable and accelerate product and service development processes and lead to new development approaches of product-service systems (PSS). We consider that the evolution of the DT concept encompasses not only the self-configuration and autonomy for ever more complex environments that more sophisticated technologies will bring but also the adoption of socio-technical constructs that allow for users to engage with the systems to fully integrate them in organizational processes that range from product development processes to decision making processes. Furthermore, by aligning both technical and socio-technical components in a multi-sided ecosystem (Figure 1) able to generate externalities to further fuel this self-learning loop, we become able to leverage the abundance of data, information, and the generated knowledge into an environment that would deliver improved product-service lifecycle efficiency and costs. In the next section, we will detail how a DT can emerge to give form to this vision.

3. A DIGITAL TWIN ENABLED PLATFORM

3.1 Digital Platforms as Infrastructure

”Digital platform” is a broad term that is used in many fields of research. Sun et al. (2015) and de Reuver et al. (2017) present an extensive list of definitions from the management and information systems areas: from a technical point of view, a DP could be considered as an extensible codebase to which complementary third-party modules can be added; while a sociotechnical perspective defines platforms as a set of technical elements (software and hardware) along with its associated organizational processes and standards. DPs for the enterprise sector represent a technological trend that is impacting how companies shape their businesses. Scholars such as Parker et al. (2016) point to how the rapid rise of the DP model has already transformed many significant industries, starting with information-intensive ones, and will transform many others in the near future.

Tiwana (2013) summarizes the characteristics that differentiate platforms into four properties: (i) compressed evolution, the capacity of platforms to shorten the period required to observe different market dynamics; (ii) evolution that predicts survival. In the same way that a product or service needs to go further than to meet users' needs to be successful, platforms can and must be built to evolve to survive; (iii) the capacity to harness external disruptions. Platforms allow disruptions to be harnessed by industry insiders to invert the trend of major disruptive innovations coming from outsiders; and (iv) the ability of architecture and governance to shape evolution. As architecture and governance are intrinsically tied in platform environments, shaping the two elements can be leveraged to mold a platform ecosystem's evolution. The flexibility these four properties embed DPs with has positioned them as the preferred infrastructure for developing a new paradigm of business models centered around customers, suppliers, and developers' aggregation. The resulting ecosystem is then able to generate externalities and synergies where the joint value creation is greater than the sum of the value created by individual businesses (Yablonsky, 2018).

Hunter and Coleman (2016) argue that a platform is an architecturally innovative means of sharing assets such as algorithms, data, and functions with ecosystems of people, businesses, and things. Our vision (Figure 2) brings together the paradigm of DPs as the supporting infrastructure, with the next generation DT as the core architectural element for (i) managing and processing the historical data collected from the multiple working instances of DTs, and (ii) managing and integrating design information (models, specifications, design data, among others). From an intra-organizational perspective, this results in a platform that provides DT-based tools to support the entire PLM. In contrast, from the inter-organizational perspective, it generates a multi-sided market of products and services that, by its data-rich nature, can be leveraged to fuel the development of new business models centered around product-service systems.

We formulate several properties this novel DT based platform fulfills in order to accomplish its intra and inter-organizational goals:

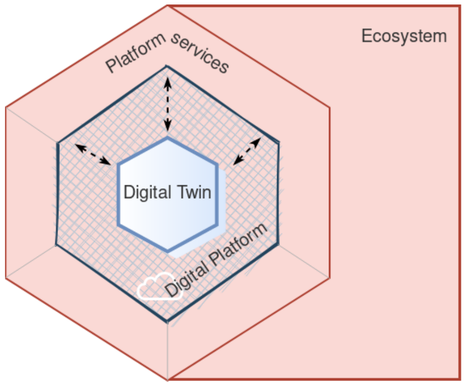

Fig. 2. Digital twin enabled platform concept

- Leverage semantic technologies to answer the complex challenge of integrating data sources of multiple DTs characterized by their heterogeneity in terms of (i) data and content types, (ii) time properties, and (iii) structure;
- Provide tools to enable the management and orchestration of multiple instances of a DT;
- Aggregates, structures, and provisions historical data from the multiple product lifecycle stages of various working instances of DTs;
- Contains simulation models to serve as the virtual counterpart to the physical products or services;
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- Implement tools for the development of intra organizational platform-based services;
- Provide tools and interfaces to facilitate the generation of new product-service systems based on twins integrated into the platform;
- Support and facilitate the development of an ecosystem of users (customers and suppliers) of product-service systems; and
- Integrate tools and mechanisms to ensure the data sovereignty among the entire ecosystem;

3.2 Digital Twin-based Digital Platform Architecture

Figure 3 presents an initial architecture that realizes our vision of the DT as the platform's central component and illustrates the essential components that articulate the previously defined properties. For the platform's architecture design, we considered three main principles: (i) simplicity - at this high level of abstraction, we opt for decomposing the platform into its primary subsystems to present core functionalities and interactions. Later iterations should go more in-depth into technologies plus data and information flows; (ii) resilience - the platform's ability to ensure basic functionality with a minimal set of tools and without relying on external dependencies. Although we design the platform to sit at the center of an emerging set of platform services, the platform itself needs to provide a stable set of tools and functionalities to ensure ecosystem stability; (iii) evolvability - the capacity for the platform to, in the future, develop capabilities and functionalities not considered initially. To endure over time, DPs, particularly its interfaces, need to evolve and adapt to emerging market needs and trends. This architecture is then kept versatile from its modular set of tools to its decoupled

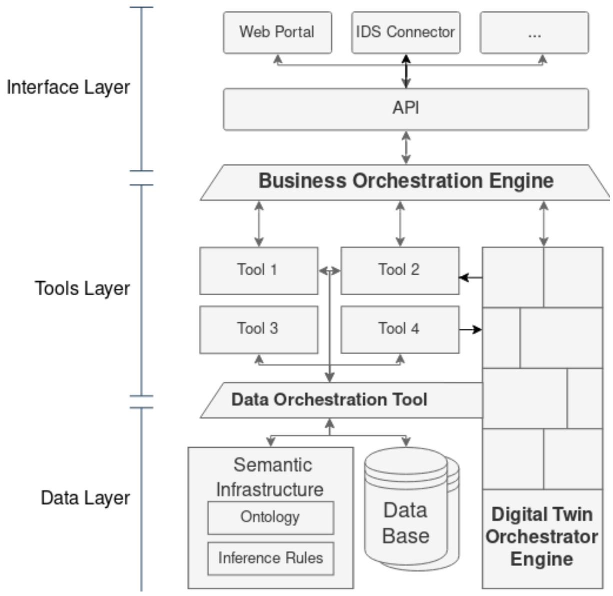

Fig. 3. Twin at the core platform architecture concept

interface layer to allow for this plasticity. In this sense, our envisioned architecture comprises three main layers, connected by abstraction tools: a data layer, a tools layer, and an interface layer.

Data Layer and Data Orchestration Tool The data layer, responsible for the persistence and structuring of data, integrates traditional forms of storage and the semantic infrastructure. This semantic infrastructure, composed of the specific domain ontology and a set of inference rules, is crucial for integrating the data recovered from the multiple instances of DTs and fully realizing the interoperability between different twin systems. These components directly interface with the Digital Twin Orchestrator tool in order to retrieve data as well as ensure the validity of the semantic constructs. The data layer interfaces with the remaining components of the platform through a data orchestration tool. This tool's primary goal is to abstract the complexity of managing the heterogeneous data sources into an interface that provides data and information structured in the most useful form for the different platform's tools and services.

Digital Twin Orchestrator Engine Placed at the core of our architecture, the Digital Twin Orchestrator Engine (DTOE) extends past the data layer to the tools layer. While the interface with the data layer is crucial for realizing the semantic interoperability, a direct link between platform services and the DTOE allows for a shorter latency between platform services and the virtual and physical realities of products/services. This direct link benefits the management of the existing products while facilitating the development and prototyping of new products and services based on the twin. In sum, the DTOE is responsible for the dual role of: (i) centralizing the management of the DT components by providing the platform with structured interfaces for direct control, and thus influence both virtual and physical components of multiple instances of a product or service; and (ii) interface with the remaining data layer components in order to structure and integrate design and operational data and information.

Tools Layer and the Business Orchestration Engine The tools layer consists of a modular set of tools that, built upon the DTOE, and leveraging the data and information available from the data layer, deliver the platform's core functionalities. This set of tools range from the standard platform services to power the ecosystem, such as user and transaction management, to sets of data-driven tools that fuel the PLM from product development to after-sales servicing. This layer's modularity is meant to embed our architecture with a plasticity that allows the platform to grow into different products and services. The connection between the tools layer and the interface layer is facilitated by the Business Orchestration Engine (BOE). The BOE is responsible for the abstraction and orchestration between the platform's different tools into a coherent set of platform-services. Through the BOE, platform users can leverage and arrange the different modular platform tools and the DTOE itself into different configurations to test and develop new and innovative product-services. This tool is another component of our architecture that gives the platform the plasticity we find so critical for the platform ecosystem's long-term expansion and extension.

Interface Layer The interface layer encompasses all the tools through which end-users and even other systems interact with the platform services. We comprehend this layer as mainly composed of a web API responsible for interfacing the BOE with the platform's different types of interfaces. In parallel with the web portal interface depicted in Figure 3, we likewise envision this API as being responsible for: (i) integrating with first and third-party applications that interface with the platform, such as enterprise resource planning systems, internet of things systems, among others; and (ii) serving as the gateway for the integration of the platform with data interoperability and sovereignty tools such as the International Data Spaces.

4. THE TRANSFORMER 4.0 CASE

Current power transformer development processes are still traditional in nature, relying on document-based information exchange and a set of PLM and simulation tools that are not interconnected. As such, an opportunity presents itself to implement a DT- based Digital platform as described in previous chapters, which will enable the integration of information and data originating in various sources and offer services that streamline PT development and add value to the machine beyond its operation and maintenance. Our vision for the Digital Twin and the DT Enabled Digital Platform will be applied to the Power Transformer lifecycle in a Portuguese enterprise of the energy field, effectively shaping its technologies and processes to Industry 4.0 standards. This platform will be employed across the organization, presenting development stakeholders with a set of tools, such as the detection of design non-conformities based on operational insights, requirements, and rules, simulation of critical operating conditions, and an ever-evolving centralized knowledge-base that captures and makes available knowledge created during the PT lifecycle. Furthermore, the DT platform will offer customers increased value to the power transformer product, including real-time monitoring using sensor data, predictive maintenance, and Remaining Useful Life predictions based on operational parameters. As such, the power transformer will enter the Industry 4.0 paradigm by employing emerging technologies such as machine learning and big data to become a product-service system that can respond to the customer's needs. A research & development methodology will be employed to develop the DT-based platform, model the PT Digital Twin, and shape organizational processes to conform to newly developed DT-based services. Furthermore, from an inter-organizational perspective, new value propositions will be leveraged from the DT platform, enabling the development of a new business model supported by it. Supported by this DT platform, the enterprise will be able to streamline PT development, resulting in reductions in cost and lead time, improve design by certifying that it meets requirements and expectations, improve knowledge capture and sharing, and finally, add additional value to the product which will result in a better offering altogether.

5. SUMMARY AND OUTLOOK

The current research landscape presented in section 3 sees the DT paradigm evolving from plug-and-play technologies, relevant only for the capturing of existing physical assets, more analogs to monitoring platforms, to autonomous systems able to self-configure and optimize for the most complex of environments. In this article, we argue that along this path, and for the DT to become the central artifact in the management of data and information along a product-service lifecycle, two factors play an influential role: (i) the socio-technical aspects that enable a user-driven experience; and (ii) the development of a DP-centered ecosystem of value-added services. To drive the evolution of this paradigm, we present in section 2 our vision for a DP that takes the DT system as a principal technical component and leverages it as the core building block for a set of platform services to support the product-service lifecycle and incentivize the development of new and innovative PSS. We present several properties that a DT-centered platform must fulfill from an inter and intra-organizational perspective and follow up by describing a high-level architecture to support all these. Finally, in section 4, we present the Transformer 4.0 case, where the concepts and conceptualization previously present will be implemented to develop a next-generation power transformer.

The full realization of this vision also requires further research into different areas. The development of the semantic components necessary for: (i) the enriching of the various data streams the DT creates and manages; (ii) the managing and orchestration of multiple instances of a DT; and (iii) the integrated management and interoperability between different DTs. The definition and testing of socio-technical constructs that will make up the interface points between the different typologies of users and the platform, along the various stages of the product-service lifecycle. On the business development front, the development of platform-based business models that can leverage an ecosystem of PSS into generating value for all the stakeholders is still an open point.

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