Towards a Cyber-Physical PLM Environment: The Role of Digital Product Models, Intelligent Products, Digital Twins, Product Avatars and Digital Shadows

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Abstract. Over the last year, there was rarely a day without industry announcing a new project involving Digital Twins or a scholarly publication with Digital Twin in the title. However, given the novelty of the concept and the pace of these developments, there are several fundamental open questions yet to be answered. In this paper, we take a step back and holistically discuss the Digital Twin and its related concepts. We aim to explore the "engineering requirements" for developing a Cyber-Physical Product Lifecycle Management (PLM) Environment to support the cyber-physical product lifecycle – the foundation of functional and effective Digital Twins. Furthermore, we provide definitions for a digital product model, an intelligent product, a cyber-physical product, a product avatar, a digital shadow, and a digital thread, and discuss their interrelations as the main building blocks for developing a Cyber-Physical PLM Environment.

Keywords: Product Lifecycle Management, Digital Product Models, Intelligent Products, Cyber-Physical Products, Digital Twins, Product Avatars, Digital Shadow, Industry 4.0, Industrial Internet of Things.

1. INTRODUCTION

The *Digital Twin* – has emerged as one of the core concepts associated with Cyber-Physical Production Systems (CPPSs), the Industrial Internet of Things, and Industry 4.0 (Kiritsis, 2011; Negri et al., 2017; Mittal et al., 2019). The term was originally coined by Dr. Michael Grieves in (2003) as a conceptual model describing how virtual, digital equivalent representations of actual, physical products, and potential products-to-be, could drive innovative and lean product developments through their entire lifecycles (Grieves, 2011). Almost a decade later of its original conception, and in light of the Industry 4.0 technological advances, the *Digital Twin* has matured from a potentially useful concept that aids in understanding the relations between a specific (item-level) physical product and its underlying information across its whole lifecycle (Grieves, 2011) to become the foundation for realising Cyber-Physical Systems (CPSs) for new Industry 4.0 business and operating models (Negri et al., 2017; Uhlemann et al., 2017).

Nowadays, a *Digital Twin* is defined as a virtual representation of a physical product, asset, process, or system in a CPS/CPPS, and across its lifecycle, capable of mirroring in real-time its static and dynamic characteristics as a result of a seamless data transmission between its digital replica and physical entity (Saddik, 2018; Ashtari et al., 2019). Moreover, a *Digital Twin* is divided into three main components: (i) a physical product in the real-world embedded with sensors, actuators, processors, software and connectivity, also known as a "smart connected product", (ii) a virtual product in the cyber-world represented by a 3D virtual model designed for advanced simulations and data analytics which synchronizes the cyber- and the real-world systems, and (iii) the bi-directional connection of data flows between the physical- and cyber-worlds that unifies the virtual and real products – also referred as the "digital thread".

Digital Twins promise significant benefits for their different stakeholders when used to support the design, manufacturing management, monitoring and control as well as optimisation of manufactured products, and production equipment and systems in manufacturing. Furthermore, *Digital Twins* support the development of industrial Product-Service Systems (PSSs) business models enabling new possibilities for the provision of value-added services and physical upgrades in all phases of a product, asset, process, or system lifecycle (e.g. certification, maintenance, monitoring, updating, predictions) (Khan et al., 2019).

In this paper, we take a step back and carefully look at the *Digital Twin* and its related concepts holistically to explore the "engineering requirements" for developing a *Cyber-Physical Product Lifecycle Management (PLM) Environment* aimed at supporting a cyber-physical product lifecycle – the foundation of functional and effective digital twins.

2. TOWARDS A CYBER-PHYSICAL PRODUCT LIFECYCLE MANAGEMENT ENVIRONMENT

In the following subsections, we provide definitions for base concepts and discuss their interrelations as the main building blocks for developing a *Cyber-Physical PLM Environment.* Furthermore, from each of the building blocks, different engineering requirements will be identified, extracted, and documented in this research work.

2.1 Base Concepts

A *Digital/Virtual Product Model,* or digital mockup, is defined as a Computer-Aided Design (CAD) 3D model, which provides a complete 3D geometrical composition of a physical product for enabling the computation of the accurate limits of each of its parts or subassemblies as well as of its "virtual behaviour" (i.e. as a collection of signals and parameters representing its physical nature) as a finished product (Clark, 2012).

An *Intelligent Product,* or smart connected product, is defined as a physical product that possesses a unique identification code, continuously monitors its status and environment, stores data about itself, deploys a language to display its features and production requirements, and is capable of participating in or making decisions relevant to its own destiny, generally by interacting with other information systems and users (Kiritsis, 2011; Wuest et al., 2018).

A *Cyber-Physical Product* represents a product that seamlessly integrates computation, communication, control and physical processes into a single entity, where physical processes affect computations and vice-versa. A *cyber-physical product* has two main parts: (i) a mechanical part, which is the physical system that is manufactured to perform a function in the real world, and (ii) the virtual part, which is the "digital twin" that collects the dynamic status of the product across its lifecycle in order to enable different digital services and applications along with the mechanical part lifespan (Uhlemann et al., 2017; Al-Ali et al., 2018).

A *Product Avatar* is defined as a stakeholder specific graphical representation and visualization of product-related information along its lifecycle in the virtual world, establishing suitable interfaces accommodating different stakeholder requirements. Moreover, a *product avatar* is characterised by its capabilities to process a unique identity; communicate effectively with its environment; create, access, transfer and operate upon information about itself; deploy a language to display its features and requirements; and of participating in or making decisions relevant to its own destiny (Wong et al., 2002; Hribernik et al., 2006).

A *Digital Shadow,* or a digital footprint, is a metaphor for all the digital information that a product, asset, process, or system creates during its entire lifecycle and it is traceable for data analytics (Riesener et al., 2019). Two types of *digital shadows*[*] can exist in the Internet of Everything: (i) active digital shadows created intentionally by – e.g. logging and registration systems, and (ii) passive digital shadows created unintentionally as a result of – e.g. web-browsing and stored cookies.

A *Digital Thread* is an integrated data-flow from multiple data sources that dynamically produces a coherent product data model in order to support various product lifecycle activities (e.g. design, engineering, manufacturing, quality control, and servitization) without requiring a "one-to-one" data mapping (Hedberg Jr. et al., 2016; Helu et al., 2017).

2.2 Interrelations of Base Concepts

The so-called *Intelligent Products,* and later on *Cyber-Physical Products,* have emerged to be utilized within the frameworks of the Industrial Internet, Industry 4.0, CPSs/CPPSs, and closed-loop PLM systems in order to actively participate in the decisional processes that concern themselves along with all their lifecycle phases for which these decisions may apply (Kiritsis, 2011; Barbosa et al., 2016).

As defined before, a *Cyber-Physical Product* is composed of its digital product model, (physical) intelligent product and digital thread. At the beginning of its life, a *Digital Product Model* is created as part of the cyber-physical product design and engineering activities by means of a CAD/CAE system, which also brings into existence the first records of its *Digital Shadow.* This initial digital shadow is represented by different CAD model versions and engineering simulations data (e.g. stress analysis data of components and assemblies). In parallel, the *Digital Product Model* will enable the creation of a *Digital Twin* and a *Product Avatar* for the cyber-physical product (see Fig. 1).

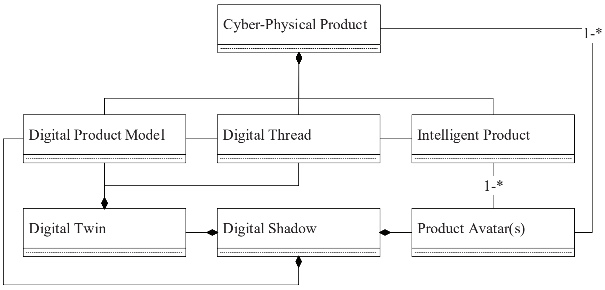

Fig. 1. Interrelations of Base Concepts

For designing and engineering a *Digital Twin,* Tao et al. (2018) have suggested six steps. The first step is to enrich its *Digital Product Model* with additional data to geometric elements so as to include behaviours and rules for evaluation, optimization and forecasting computer models. The second step focuses on the first part of the creation of its *Digital Thread* by defining and implementing a data collection and integration strategy, from multiple sources into an integrated product data model, to address all the data requirements from the various product lifecycle activities of a cyber-physical product. The third step concentrates on the implementation of different data analytics and simulation technologies, incl. virtual reality, to simulate the key functions and behaviours of the physical part of a cyber-physical product in the virtual world (e.g. from virtual prototyping to virtual engineering to virtual commissioning). The fourth step takes advantage of the sensors and actuators embedded in a cyber-physical product to create cyber-physical feedback-loops to monitor and command its physical part to perform recommended behaviours according to rules and to enrich its digital part with new data for supporting data-driven decision-making. The fifth step focusses on the second part of the *Digital Thread* creation by establishing real-time, two-way and secure connections between the physical and virtual worlds of the cyber-physical product along its lifecycle using feasible communication technologies. The last, and sixth step, creates and makes use of a *Product Avatar* in order to generate several instances of it with the aim of establishing suitable interfaces for each of the product lifecycle stakeholders with the cyber-physical product-related data of their interest in an interactive manner.

For designing and engineering a *Product Avatar,* Hribernik et al. (2002) and Wuest et al. (2014) have provided the following recommendations. First, the product avatar requirements need to be elicited from the cyber-physical product stakeholders (e.g. designers, engineers, manufacturers, sellers, service providers, and of course the customer, and other "intelligent things") and

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[*] https://en.wikipedia.org/wiki/digital_footprint

analyzed, since each may have different requirements towards the selection, presentation and use of the product lifecycle data. Second, based on the stakeholders' data requirements, proper interfaces and delivery channels should be custom designed for each stakeholder. For example, desktop-applications or mobile-apps for human stakeholders, and web services or software agents for non-human stakeholders.

For designing and engineering a *Cyber-Physical Product,* two models have emerged as references in the CPSs literature. For the "physical part" of a cyber-physical product, the (physical) *Intelligent Product,* the "V-model" for mechatronic systems design (VDI, 2004) has become the most popular model due to its synergic point of view, facilitating the integration of heterogeneous mechanical, electrical, electronic and informatic components, and subsystems needed to create a cyber-physical product. When it comes to the "cyber part" of a cyber-physical product, the "5C Architecture" proposed by Lee et al. (2015a), provides a solid guideline for creating (i) smart Connections for acquiring accurate and reliable data (viz. by an effective sensors selection for condition-based monitoring), (ii) data-to-information Conversion by different data analytic techniques (viz. using specialized algorithms for prognosis and health management), (iii) Cyber as the product information hub (i.e. the digital thread of the CPS), (iv) Cognition as the interface for humans and other systems with the product information hub (e.g. by means of a digital product model, a digital twin or a product avatar supporting decision-making), and (v) Configuration as the feedback from the cyber to the physical word for supervisory control and adaptation (viz. a resilience control system).

For designing and engineering a *Digital Shadow,* a long-term archiving and retrieval strategy for a cyber-physical product data is essential in order to support all data requirements along its lifecycle. This because of the short lifecycle nature of software and hardware in comparison to a product lifecycle, putting companies at risk of losing access to their data while their products are still in operation (Brunsmann et al., 2012). Hence, a *Digital Shadow* should create the conditions for the accumulation of diverse data and establish the bases for its further analysis in a software and hardware "agnostic" way. Some international projects developing recommendations for the practical introduction of long-term archiving and retrieval solutions for relevant product lifecycle data are LOTAR, KIM, VDA, MOSLA, DEA, SEI, and SHAMAN (Brunsmann et al., 2012). These projects focus on different solutions based on semantic annotations of product data; annotated product data models, metadata threated for semantic obsolescence and knowledge representation and reuse, integration of long-term archives into PLM processes, etc.

For manufacturing a *Cyber-Physical Product,* its (physical) *Intelligent Product* part can facilitate its mass-customization or even personalization (lot-size-one) by supporting the shift in its production control from standard programmable logic controllers (PLCs) to a service-oriented and decentralized control system enabled by its digital memory together with highly flexible manufacturing systems, such as additive manufacturing. This feature can enable to control its own production process in a "smart manufacturing system" and to communicate its unique identity to machinery and their associated manufacturing and assembly processes across the production line in order to be produced according to its specifications (Kärkkäinen & Holmström, 2002; McFarlane et al., 2003; Meyer et al., 2011; Gorecky et al., 2016). Moreover, its digital memory can contribute to a Computer-to-Computer-to-Machine communication (i.e. from the CAM system to the product digital memory to the CNC or Additive Manufacturing machine), eliminating in this way the "human error" in input parameters, and also to the enrichment and use of its *Digital Shadow* for example as a "digital quality certificate" of its full production process by storing all its real production parameters in its memory or the cloud (Lyly-Yrjänäinen et al., 2016).

For transporting and delivering a *Cyber-Physical Product,* its (physical) *Intelligent Product* part can contribute to increasing the transaction and processing speed and accuracy of logistics data for developing "smart logistics" capabilities (e.g., item-level tracking and tracing along the supply chain with real-time data on its location and condition) (Uckelmann, 2008). Also, its *Digital Shadow* can contribute to "smart logistics" planning and optimization strategies. Access to all available and relevant information across various IT systems can fuel data-driven optimization models within digital supply networks. Furthermore, data on packaging and physical dimensions, for example, can inform routing models to reduce the amount of wasted space on containers and thus contribute to a reduction of traffic and resource waste.

During the middle of its lifecycle, the *Digital Twin, Product Avatar* and *Digital Shadow* of a cyber-physical product will contribute to the engineering of different value-added (digital) services and new business models such as product-service systems as well as enable continuous optimization of the next generation engineering design of a product and/or data-driven automated mass-customization/personalization (Lehmhus et al., 2015). Providing access and an interface to the product for a variety of stakeholders including the users themselves but also service providers and OEMs adds value to the physical product itself and also is a prerequisite for advanced services in the Shared Economy. In a B2B context, *Digital Twins* of machine tools enable the customers of the products being produced to receive real-time insights in the manufacturing process as well as lay the foundation for new concepts such as zero-defect and zero-downtime manufacturing operations and non-ownership business models.

Lastly, during the end of its lifecycle, also the *Digital Twin, Product Avatar* and *Digital Shadow* of a cyber-physical product will be used to support different Circular Economy activities such as smart reverse logistics and cyber-physical products remanufacturing and recycling. Comprehensive contextualized data, made available through a *Digital Twin, Digital Shadow* and *Product Avatar,* enables end-of-lifecycle stakeholders to better utilize the available resources in a sense of the reduce, reuse, remanufacture, and recycle pyramid. Concepts such as cascade use that split complex systems such as a car into various components that are still within their remaining useful life are dependent on accurate and available information and data throughout the life of the system. Upgrades of capital equipment as an alternative to its replacement also depend on the data provided by a *Digital Twin* and/or *Digital Shadow.*

2.3 Requirements for Developing a CP-PLM Environment

See Fig. 2, "Towards a Cyber-Physical PLM Environment".

2.3.1 Beginning-of-Lifecycle (BoL)

The main prerequisite for developing a *CP-PLM Environment* is the creation of CAD 3D models especially designed and engineered not only for manufacturing *Cyber-Physical Products* but also for generating *Digital Product Models* for a variety of applications such as advanced 3D modelling, simulation, and twinning. CAD is the first part of a digital product development activity within a PLM process, and as part of this vital activity, conventional CAD systems must be upgraded with advanced functionalities, and richer data models, in order to support emerging *CP-PLM services* such as product avatars, digital twins, virtual reality training settings, and augmented reality assisting systems. These new services on the basis of a holistic product lifecycle data model. Therefore, conventional CAD systems' data models and 3D modelling principles should be enriched and extended beyond simply recording and processing geometrical elements with fixed values to more sophisticated data management and modelling capabilities. Some examples of these modern CAD systems are those build on parametric, feature-based and knowledge-based capabilities, able to deal with several geometrical elements with variable parameters and behavioural rules (i.e. features) that can be understood as semantic information objects, and from which conclusions for a design situation can be drawn to find a solution for a design problem (VDI, 2009). Furthermore, CAD 3D models and its design data should be enhanced and enriched for easy-rendering of 3D objects and engineering analysis tasks for/by Computer-Aided Engineering (CAE) tools, virtual and augmented reality applications and other downstream services along the cyber-physical product lifecycle in a 3D continuity.

The next requirements for a *CP-PLM Environment* take place in the CAE activity of a *Cyber-Physical Product,* where choices of mechanical, electrical, fluid-power, electro-mechanic and informatic components within the product must be evaluated in order to produce the best possible "cyber-physical design". (Stensson & Kortüm, 2000). In order to validate the integration of all the mechatronic systems of a *Cyber-Physical Product* and get its overall behaviour, "co-simulation" solutions (Veitl et al., 1999; Thule et al., 2019) will be required in order to enable a global simulation via the composition of different simulators. For doing so, "co-simulation software" will need to comply with different requirements that can be found, for instance, in the "Maestro" framework aimed at supporting the co-simulation of cyber-physical systems (Thule et al., 2019). Two main recommendation offered for co-simulation software by the "Maestro co-simulation framework[†]" are: (i) the use of an orchestrator with an agnostic language and (ii) the creation of rapid feedback loops during the co-simulation itself.

The requirements for a *CP-PLM Environment* from the CAM perspective will require to support "hybrid manufacturing" due to the nature of *Cyber-Physical Products* embedded with e.g. sensors. Current CAM system interfaces and their internal tool path representations are designed for material removal processes. Hence, CAM systems should be extended to dually support subtractive and additive manufacturing process chains, a hybrid process chain. In particular, new hybrid CAM systems will need to be able to (i) provide a shorter and compacter tool-chain for the hybrid manufacturing process, (ii) facilitate information exchange between its "subtractive" and "additive" modules to avoid collisions after subsequent processing steps, (iii) print on pre-existing geometry, (iv) communicate a dual, subtractive and additive, view of functional requirements, (v) adapt to complex designs, (vi) iterate for design adaptation due to slicer information and between additive pre-processing and the manufacturing process itself, and (vii) manage optical or physical markers for part fixing and positioning (Hedrick et al., 2015; Elser et al., 2018).

In the context of Industry 4.0, and the vision of the "lot-size-one" paradigm, the requirements for a *CP-PLM Environment* from the MES perspective will entail supporting traditional production control approaches and emerging product-centric control approaches. A "product-centric control" makes use of *Intelligent Products* to simplify raw materials, components and subassemblies handling and control, customization, and information sharing in the production line. The basic principle is that the *Intelligent Product,* while it is in the process of being manufactured and delivered, it directs itself across the production line (Kärkkäinen & Holmström, 2002; McFarlane et al., 2003; Meyer et al., 2011; Gorecky et al., 2016).

2.3.2 Middle-of-Lifecycle (MoL)

In general, the requirements for supporting traditional services, digital services, smart services, and product-service systems during the whole lifecycle of a *Cyber-Physical Product* demand the development of an internal (i.e. inside the smart factory) and extended (i.e. outside the smart factory) Industrial Internet of Things (IIoT) Infrastructure. This IIoT Infrastructure will be responsible for enabling different connectivity solutions (e.g. 5G IIoT (Giri et al., 2017; Li et al., 2018)) for providing a cyber-secure bi-directional communication, a "cyber-secure" *Digital Thread,* between different information systems and entities (e.g. its *Digital Twin* and *Product Avatars*) and the *Cyber-Physical Product.*

In particular, the requirements for a *CP-PLM Environment* for supporting an "intelligent maintenance" service activity for a *Cyber-Physical Product* will involve making determinations for active and predictive maintenance strategies. Maintenance decisions need to (i) be performed actively as malfunction or failure arise while influencing and informing data to earlier product lifecycle stages/activities (e.g. CAE activities), and (ii) be anticipated predictively through appropriate prognosis models, profiting particularly from advancements in machine learning algorithms and data analytics techniques to anticipate failure (Lee et al., 2015b).

Furthermore, from the sustainment perspective, a *CP-PLM Environment* will require to support controlled modifications to its representative "digital models" as change is continuously occurring through servicing. Reliability elements and changes for model-based sustainment will induce variance for products initiated with identical *Cyber-Physical Products* and the *CP-PLM Environment* will need to be adaptive to such changes and variances (e.g. an updated part design for a certain product will create an instance of the *CP-PLM Environment* dedicated

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[†] https://github.com/INTO-CPS-Association/maestro

to the sustainment of this variance). Moreover, a *CP-PLM Environment* should enable the evaluation of non-destructive tests that are continuously performed on a *Cyber-Physical Product* as the product is in service and is subject to varying conditions that might accelerate or decelerate its expected performance. The communication of such evaluations in terms of "indices" through the product lifecycle will update and reflect performance indicators of the *Cyber-Physical Product* (Shi, 2018).

Additionally, a *CP-PLM Environment* should support Product-Service Systems (PSSs) by offering numerous opportunities to get an improved understanding of products behaviour (e.g. big data analytics) as well as to manage their related services (Gerhard, 2017; Wiesner & Thoben, 2017; Romero & Rossi, 2017). Furthermore, without connectivity and digital interfaces (e.g. its Product Avatars), a PSS cannot effectively provide advanced services, including "Service Lifecycle Management".

2.3.3 End-of-Lifecycle (EoL)

The requirements for a *CP-PLM Environment* to support re-use, re-manufacturing and recycling activities in the Circular Economy involve (i) closing information gaps, and (ii) feeding information about in-use and end-of-use of products to different stakeholders. Furthermore, the development of a closed-loop PLM system for Circular Economy will require considering the management of "multiple product lifecycles" in which products are changed or reconfigured in a sustainable way (Kiritsis, 2011; Freitas de Oliveira & Soares, 2017). Novel EoL concepts such as "cascade use" depend on the availability and comprehensive management of detailed product lifecycle information, especially during the use phase, to optimally allocate resources across the different cascades of possible use (Kalverkamp et al., 2017). Without access to reliable, item-level product usage information, the promising cascade use concept cannot be adapted at large due to the uncertainty and risk for the providers.

3. DISCUSSION

As described in Section 2, the emergence of *Cyber-Physical Products* has forced us to "re-think" several PLM phases and Computer-Aided (CAx) systems functionalities as a result of their higher level of autonomy and intelligence (Kiritsis, 2011; Barbosa et al., 2016). Thus, we must rethink also the classical "PLM system" definitions in the light of the emerging cyber-physical products capabilities. In this paper, we propose the following **working definition** for a *CP-PLM Environment, or system – is a product-centric and data-driven system that is composed of different integrated and/or interoperable cyber-physical systems, supporting the entire lifecycle of a cyber-physical product. The lifecycle covers the whole range from design and engineering, through manufacturing, transportation and servitization, to circularity into a new lifecycle.* Moreover, *a CP-PLM Environment provides (i) a universal product data model for access and use by different stakeholders with various viewpoints and requirements, (ii) maintains the integrity of the product's definition and its related information throughout its entire lifecycle, (iii) offers different data-driven value-added services for augmenting the product itself for its stakeholders, and (iv) enables the cyber-physical product to influence design variations and enhancements (personalization) and to conduct self-assessment, self-monitoring and self-healing as well as to independently adapt to changes in operating conditions.*

4. CONCLUSIONS

In order to face the challenges of shorter product development times and mass-customization as well as to respond to the trend of servitization, *CP-PLM Environments* will require to offer powerful virtual engineering tools, AI-powered and data-driven decision support services, and information loops along the whole cyber-physical product lifecycle. These tools will need to enable data sharing between multiple products as well as between multiple trades for the same product (i.e. design, engineering, manufac-turing). The fundamental approach is that *CP-PLM cycles* are organic and they get influenced by a third dimension of a somewhat similar *Cyber-Physical Product* at a different stage in their respective *CP-PLM cycle.* A product undergoing "recycling" in one *CP-PLM cycle* can influence "maintenance decisions" in another *product's CP-PLM cycle.* To sum it up, we believe that a *CP-PLM Environment* is three dimensional: product, trades and world, each of them capable of sharing and influencing.

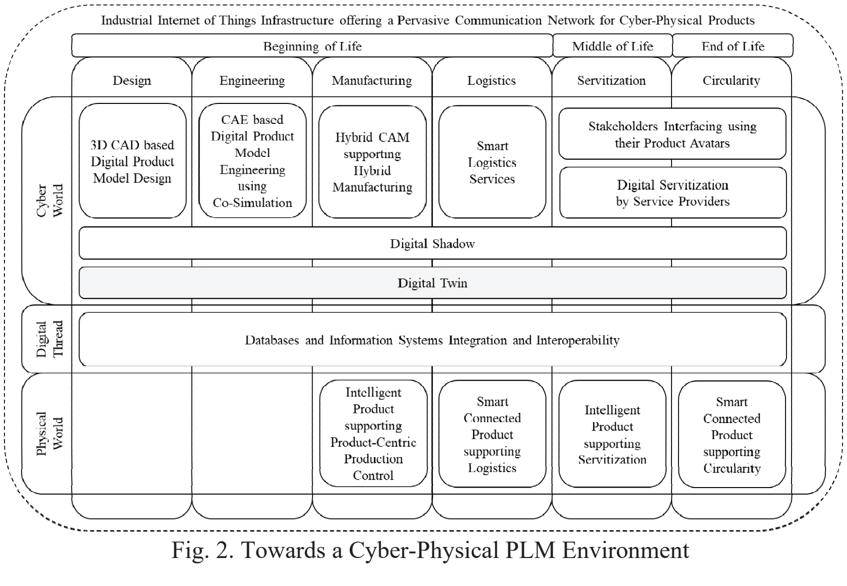

Fig. 2. Towards a Cyber-Physical PLM Environment

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