Towards Engineering Product Digital Twins for Industry 5.0: Definition and Modeling Approach

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***Abstract*—The vision of Industry 5.0 builds upon the advanced technologies of Industry 4.0, aligning its emerging concepts with three key pillars: human-centricity, sustainability, and resilience. In this context, the idea of the Product Digital Twin (PDT), first introduced in 2002, which has further matured (and refined) by the Asset Administration Shell (AAS) standard, must continue evolving to integrate the vision of Digital Product Passport (DPP) as promoted via several initiatives from the European Commission. Moreover, positioning PDT correctly within this broader context of Industry 5.0 is crucial, as it involves the modeling and implementation of PDT instances, which then significantly influence manufacturing applications. To address this need, this paper first harmonizes different PDT definitions and then proposes a modeling and deployment approach appropriate to the new concept of PDT information models.**

***Index Terms*—Manufacturing, Digital Passport Product, CSS, PPR, Asset Administration Shell**

I. Introduction

Unlike the first four industrial revolutions that radically transformed production technologies, Industry 5.0 reflects an evolution towards a vision with greater responsability that will impact both society and production. Indeed, while Industry 1.0 to Industry 4.0 are marked by flagship technologies such as steam power, electricity, computers, and the Internet of Things, Industry 5.0 focuses on guiding technological advancements in human-centric, sustainable, and resilient directions [1]. This policy change not only supports better relevant existing application fields, such as the human-robot interaction for human-centricity, but also opens the way for new domains, such as the Digital Passport Product (DPP[1]) for sustainability. DPP can be defined as *"a digital representation of a product's information through its lifecycle, from creation to disposal"* [2]. Technically speaking, DPP is *"structured with a collection of product-related data with a pre-defined scope and agreed data management and access rights conveyed through a unique identifier"* [3]. Moreover, the DPP concept shares many common characteristics with Product Digital Twin (PDT) and, from one perspective, can be considered another variant of the PDT that adds value from several perspectives for sustainable product fabrication, management, and consumption.

The original idea of Digital Twin (DT) in product lifecycle management was first coined by Michael Grieves in 2002 to describe one or multiple digital model instances in a virtual space representing a physical product in the physical space [4]. In the era of Industry 4.0, the concept of DT has evolved with refinements and contributions from credible organizations. In 2017, Plattform Industrie 4.0[2] proposed the Asset Administration Shell (AAS[3]) standard as an official guide to making standardized DTs. For semantic clarity, it is worth noting that such DTs, also known as AAS DTs, are digital representations of assets, i.e., they are not limited to be DTs of products only but can also be DTs of processes and DTs of resources [5]. In 2020, the Industrial Digital Twin Association (IDTA[4]) was founded and took the role of managing and developing the AAS standard. In the same year, the Digital Twin Consortium (DTC[5]) was founded and released its first definition of a digital twin: *"A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity"* [6]. In 2023, the International Electrotechnical Commission (ISO/IEC) had a common vision with DTC and officially defined a DT as: *"a digital representation of target entity with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization"* [7]. Likewise, the French Alliance Industrie du Futur[6] refers a DT as: *"a set of digital models representing a real-world entity and is equipped with advanced operations tools, including the ability to understand, analyze, predict, and optimize the operation management of the real entity"* [8]. These two latter definitions are solid and complement each other, thus effectively covering several types of DTs for resources, processes, and even complex systems such as a holistic factory. However, they may be too ambitious for PDTs, which may lack connections to their physical products. Figure 1 summarizes the evolution of the DT concepts against the three latest industrial revolutions.

The differences in defining the DT concepts reflect the differences in applicative concerns of the industrial community at different points in time. This paper aims to harmonize such definitions by clarifying their related industrial applications, then to present our perspective on the PDT. The motivation behind this study is to have a unified PDT understanding

[1]https://cirpassproject.eu/dpp-in-a-nutshell/

[2]https://www.plattform-i40.de
[3]https://github.com/admin-shell-io
[4]https://industrialdigitaltwin.org/en/
[5]https://www.digitaltwinconsortium.org
[6]http://www.industrie-dufutur.org

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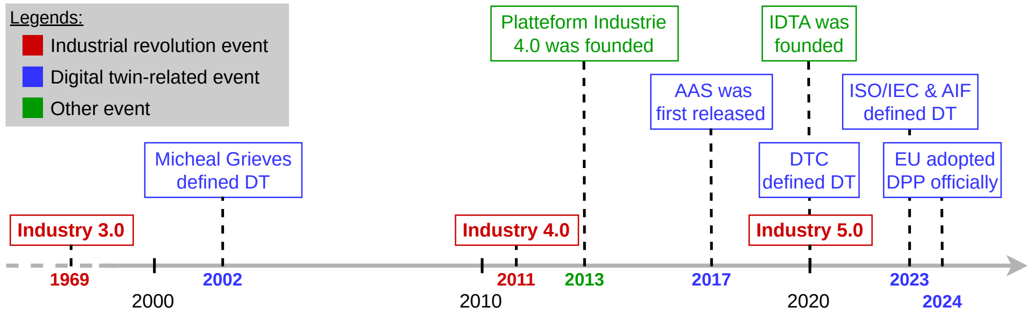

Figure 1. Timeline of industrial revolutions and the evolution of DT concepts

that can be accepted in different manufacturing applications and contexts. To support this vision, we also propose a PDT modeling and deployment approach for collective production.

The rest of this paper is organized as follows. Section II presents the background information leading to the PDT concept adopted in this paper. Section III describes an approach for modeling and deploying PDT information models. Finally, a conclusion sums up this paper and outlines future works.

II. Perspective on Product Digital Twins

Product-Process-Resource (PPR) is a widely adopted paradigm in manufacturing domain. It emerged during the Industry 3.0 and remains a core principle in every production environment. The main idea of PPR is to classify all the manufacturing assets into three categories: product, process, and resource [9]. Logically, a PDT is the data representation of a product, and its information model should be able to present the physical product's characteristics enough for applications such as product design optimization and performance testing. A limitation of Industry 3.0 is the lack of agreement within the industrial community on a standard for modeling and implementing PDT, leading each factory to develop its independent strategies and advancements.

Industry 4.0 introduces a new vision of adaptable factories and flexible manufacturing. In this sense, the Capability-Skill-Service (CSS) paradigm allows the industrial community to form a network of partner factories for collective production, in which a customer request can be divided into production orders fulfilled by services shared within the network [10]. Each factory adopts the capability-skill concept to manage production flexibly and independently to a fixed configuration of resources and processes. Consequently, the DT domain has evolved to align with this new vision. First, the AAS standard emerged as a standardized tool for modeling and implementing DTs, enhancing interoperability between partner factories. It not only provides sufficient vocabulary and mechanisms to represent different aspects of products, processes, and resources, but also includes elements supporting the CSS paradigm, such as the capability element type. Second, new applications arising from CSS, such as capability matchmaking and service negotiation, require PDT, along with the DTs of resources and processes, to evolve by containing and providing new types of information needed for these applications.

The early stage of Industry 5.0 highlights Digital Product Passport (DPP) as the pioneer application domain in its sustainable direction. DPP is relevant not only during the production phase but also throughout the entire product lifecycle, including product consumption and usage by end users. For instance, a user can scan the barcode of a product with a handheld device to download and retrieve data from its digital representation. Unlike the traditional product authentication where all product instances share the same data, each product instance in DPP contains a unique DPP instance with information specific to that particular product[7]. In a sense, DPP is a type of PDT with an information model that aggregates data about vital properties related to sustainability and usage, such as carbon footprint and product recycling.

PDT should be applicable and support all applications within the above contexts. Therefore, it should adhere to the three following principles.

- Different from DTs for processes and resources, the data synchronization between a PDT instance and its product may not be real-time. Even more, there may be no communication between them at all. This remark relies on the fact that many everyday products lack connection capabilities. For example, a trivial toy car may have no medium for a connection, but it can still have a digital version available on the user account of its owner.
- The PDT concept should be general and abstract enough to be accepted by a wide range of applications, users, and developers. In this sense, we decided to choose one of the Digital Data Chain Consortium (DDCC[8]), which describes a PDT as *"the collection of all information of a product including the ones of the DPP"*, and a DPP as *"the collection of all product information relevant for circularity and authorities"* [11].
- The viewpoint of Micheal Grieves in distinguishing a PDT prototype and its instance [4] should be adopted to clarify the concepts of a blueprint of PDT and PDT instances. Each PDT instance should be unique and contain particular information according to its product

[7]Except for DPPs in batches, where all product instances in the same batch share the same batch/group/lot information and the information for different batches differs.

[8]https://digitaldatachain.com

instance; however, all PDT instances should share the same PDT prototype. This clarification is also helpful for CSS, where production applications are more interested in PDT prototypes than the specific data of any individual PDT instance. For example, when a system generates a production quotation for a client, it should retrieve information from the PDT prototype of a product to include in the quotation, rather than from a specific PDT instance that may not yet be produced.

III. Modeling and Deployment Approach

Modeling a PDT information model that satisfies multiple applications is a complex task. First, it requires designers to analyze the requirements of each application derived from the target PDT. For example, the PDT information model of a toy car used for two applications: quotation generation and additive manufacturing, includes the toy's unit price for the former application and a download link to its 3D model file for the latter. Second, an application may require a PDT information model to include multiple types of information related to different aspects of the product. For example, the product lifecycle management application may require a toy car's information model to contain data on its location and carbon footprint, corresponding respectively to the two aspects of the product: traceability and sustainability. The mentioned challenges highlight the need to model PDT information models in a collective and standardized manner to maximize the potential to cover all applications.

The target vocabulary to model PDTs comes from the AAS standard. AAS structures an information model as a collection of submodels, each representing an aspect of the PDT to be modeled. A submodel consists of submodel elements that can be various types, including properties, operations, and capabilities. The AAS standard has two advantages over other modeling vocabularies. First, its concept is easy to understand and can be represented by the well-known UML class diagram. Second, IDTA encourages industrial partners and other experts to develop and contribute submodel templates, leveraging their deep knowledge in manufacturing. A submodel template is a pre-designed submodel that helps users import and customize a submodel instance, rather than designing it from scratch. These templates are available online at the IDTA submodel hub[9]. Moreover, Deliverable 5.1 of the CIRPASS 1 project identifies several vocabularies for product modeling in their study [3]. These vocabularies include ontologies (e.g. GoodRelations), Web of Things (WoT) (e.g. Thing Descriptions and Capability Schemas), and dataset attributes from GS1 GDM. They can enhance the semantics of PDT submodels by using AAS reference elements to link to other vocabularies. Otherwise, they can serve as a reference for AAS model designers to create custom submodels. The United Nations Transparency Protocol (UNTP[10]) also supports vocabularies dedicated to DPP, which can be helpful to model DPP-related requirements.

[9]https://industrialdigitaltwin.org/en/content-hub/submodels
[10]https://uncefact.github.io/spec-untp/docs/specification/

Such rich resources for modeling enable our research team to propose a modeling approach that extends the submodel development instructions suggested by IDTA [12]. The aim of this approach is to develop submodel templates and instances for PDTs based on the applications that require them. Figure 2 illustrates the workflows of developing submodel templates and instances. Before going into detail, it is worth noting two remarks. First, a submodel instance can be part of a PDT prototype or a PDT instance. Second, this approach involves two roles: submodel instance designers and template designers. The submodel instance designer can be an individual entity, such as a factory, vendor, or user, who uses submodel instances to form PDT information models tailored to their target applications. The template designer is a group of individuals who collaborate to analyze applications beforehand and provide derived submodel templates for collective use.

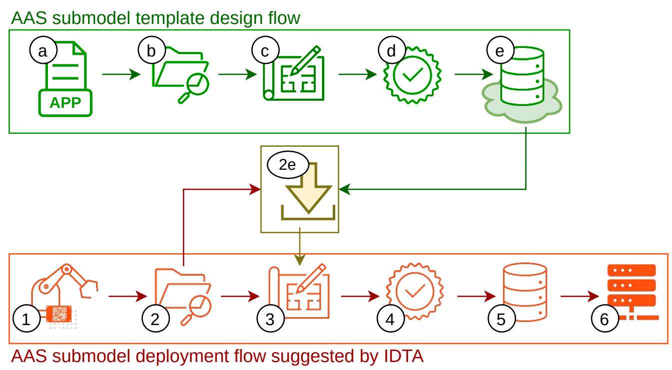

Figure 2. Workflows to develop submodel templates and instances

The workflow to develop a submodel instance proposed by IDTA includes six steps: (1) determining a target asset, (2) finding a submodel template from the IDTA submodel hub, (3) using a modeling tool to model a submodel, (4) validating the submodel model, (5) deploy the submodel on an AAS server, and (6) register the AAS with its endpoint into an AAS registry. The extension proposed in this paper presents a five-steps workflow to develop a submodel template:

(a) From the specification of an application, template designers derive the requirements of PDT to be modeled.
(b) Template designers search for modeling components. As a priority, they should consult the IDTA submodel hub to check whether there are submodel templates appropriate to model the requirements of PDT. Note that an application may require different aspects from a PDT; thus, template designers may need to search for several submodel templates. When a requirement is not covered, they should study vocabulary from other sources, such as ontologies, for self-customized design.
(c) Template designers use a tool to design their submodel templates and encode them in a format accepted by the community, such as AASX or UML.
(d) Template designers should use a tool to validate the new-designed submodel templates.

(e) The submodel templates are uploaded to a model lake, a cloud-based infrastructure that hosts and registers submodel templates. The model lake should offer two services: (1) application-driven search for submodel templates, and (2) conversion of a template from one format to another.

With the model lake, submodel instance developers can use step (2e), that is, downloading submodel templates from the model lake, to support step (2) for the design in step (3).

The following provides an example of a PDT prototype and PDT instances in a factory applying the CSS paradigm. The PDT instances are used for product lifecycle management and are referred to as DPPs. Figure 3 presents a reference architecture to depicts the production steps of the factory. The architecture is composed of three basic components:

1) A cloud-based storage, known as DPP Repository (DPPR), stores and shares data of DPP instances. This storage integrates with and operates within a dataspace.
2) An AAS development service offers a web-based design environment and can download submodel templates from a model lake. Assuming that all the required submodel templates for this application are already stored in the model lake. This service enables the generation of DPPs along with their associated data carriers (e.g. QR code and barcode). The DPPs data are uploaded to the DPPR for secured and sovereign data exchange.
3) A factory adopts the CSS paradigm and integrates DPP into its production. It is in a network of partner factories and provides its available services to the network.

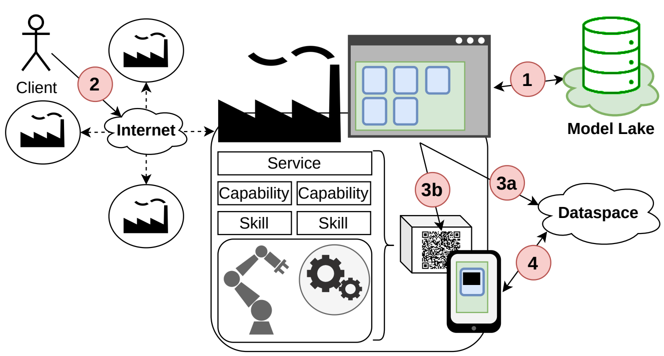

Figure 3. Architecture to implement PDT prototypes and DPPs

In Step 1, factory operators use a web browser to access the AAS development online service, select and download AAS submodel templates for PDT from the model lake, and design the PDT prototype for their products. In Step 2, the factory operators make their production service available on the network of partner factories. This service contains information about the PDT prototype, allowing clients and other factories to verify whether the factory can manufacture the product they need. When the service is invoked, an automated process selects the appropriate resources and executes the necessary tasks based on the capability-skill relationship. The creation of a new product triggers the generation of a DPP on the DPPR in Step 3a, and a QR code that embeds the endpoint of the DPP in Step 3b. In Step 4, the factory operators use a device to scan the QR code to validate whether the DPP information can be retrieved from the DPPR.

IV. Conclusion and Future Works

This paper presents a viewpoint on PDT, harmonizing different definitions of the PDT concept from Industry 3.0, 4.0, and 5.0. This combination enables a unified vision across various manufacturing applications and contexts. The approach to modeling PDT information models and deploying PDT prototypes and instances, as presented in this paper, is planned to be developed during the RAASCEMAN[11] project, addressing the sustainable and resilient directions in Industry 5.0.

As future work, we will provide a solution based on a concrete use case from the RAASCEMAN project for the development of PDT using CEA List's Papyrus4Manufacturing[12] framework. This framework is well-known in the Model-Driven Engineering community for modeling AAS through its AAS UML profile. Its upcoming version(s) will have a user-friendly web-based design environment along with integration of new features, such as an AI agent for design automation.

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