Product Lifecycle Information Management with Digital Twin: A Case Study

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***Abstract*—The use of new-generation information technologies in industry and manufacturing is increasing rapidly. However, although information about products is generated and consumed during their entire lifecycle, current research on Product Lifecycle Management (PLM) tends to focus mainly on the physical products themselves rather than on the related information. The Digital Twin (DT) concept aims to connect the physical world with the virtual one by making all the information about physical objects accessible from a single place, even though that information might be distributed over many information systems. This paper presents and analyses new Product Lifecycle Information Management (PLIM) with DT for managing the lifecycle of smart products in the IoT environment. A real-world use case that is a recently finished main building of the Aalto University campus is presented to demonstrate the proposed approach.**

***Index Terms*—digital twin, product lifecycle, IoT, information system, PLIM**

I. INTRODUCTION

Internet of Things (IoT) concept refers to the idea that product information should be easily available everywhere. This underlying principle allows it to behave as a fundamental information system which can be used to access the information of smart products [1]. This capability of IoT can be extended by employing IoT technology in the entire product lifecycle (PLC), consisting of Beginning of Life (BoL), Middle of Life (MoL), and End of Life (EoL). In other words, all information generated by the smart product from manufacturing until the time of disposal, required to be monitored during the lifecycle while handling such a huge volume of information is impossible without defining a virtual product replica or counterpart, which includes all the information in one place.

Digital Twin (DT) as a virtual replica of a physical entity has been proposed for handling the information in the virtual enterprise [2]. With DT, all information requests for a given physical product are available at a single address on the Internet. Such a new mechanism assists in managing IoT devices and IoT systems-of-systems throughout the lifecycle, specifically during the design and service phase of lifecycle [3]. These two phases have received less attention in IoT analysis. In general, DT is constructed through three main components: the physical model, the virtual model, and the connection between physical and virtual models [4].

It is impossible to determine when the DT concept emerged. The simulation and production model for petrochemical plants developed in 1990 [5] is obviously a DT, as well as the related earlier work cited. The *holon* concept proposed by the agent community for production management also has numerous DT properties. Combining physical objects with a virtual counterpart in an IoT and Product Lifecycle Management (PLM) setting was presumably first presented by Kary Främling in 2002 [2] under the name *Product Agent*. Michael Grieves has presented a similar idea in 2002 under the name *Doubleganger* [6]. The term DT was eventually coined by John Vickers of NASA in a 2010 Roadmap Report, based on the work of Michael Grieves. Although the terms and approaches are different, all the definitions integrate the idea of using a DT for managing the lifecycle of physical objects, which can be considered groundbreaking for PLM [7].

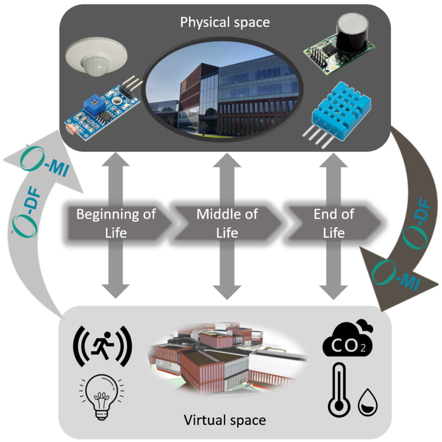


Figure 1. DT for Smart building

A subcategory of PLM incorporating the management of data associated with physical objects during their lifecycle is known as Product Lifecycle Information Management (PLIM) [1, 14]. PLIM mostly enables accessing the existing information; however, it processes poorly any new information generated about the products [1]. Hence such a strategic approach can be developed by accompanying the concept of DT, which signifies the importance of updated data. Given this concern, this paper proposes a PLIM system based on DT, which provides DT for all the lifecycle phases in an IoT ecosystem. Creating an information system applying the data combined from these phases in this heterogeneous ecosystem where

Table I
STATE-OF-THE-ART COMPARISON

Ref	Year	Concept	Methodology	Application	Lifecycle phase
[7]	2016	New generation of data management for smart products	prototyping a SDM integration platform	Cyber Physical systems	Entire lifecycle
[8]	2018	To support decision-making in asset lifecycle management	Assess management	Industrial AM research projects	1 BOL & 5 MOL
[9]	2016	A comprehensive reference model as a DT in design and manufacturing	Based on skin model shape	Design & Production Engineering	BOL
[10]	2016	Experimentable DTs by combining Virtual Testbeds and DTs	VSD,an object-oriented real-time database holding a description of simulation model	on-orbit servicing, Localization of Forest Machines, Driver Assistance Systems, Industrial Automation	Entire lifecycle
[11]	2016	To model physical components at a high level to exchange information	Automation ML to model attributes related to DT	Industrial valve modelling case study	Entire lifecycle
[4]	2019	Product design based on DT	DT-driven product design (DTPD) framework	Bicycle design	BOL
[12]	2019	waste electrical and electronic equipment recycling, recovery and remanufacturing in the background of Industry 4.0	Conducting a cloud-based CPS in the laboratory environment	WEEE remanufacturing industry	EOL
[13]	2019	Application framework of DT for PLM	consists of three parts, physical space, virtual space and information-processing layer	Welding production line	Entire lifecycle

various devices with different data are connected around the world, is an immense challenge. A system with such features should fulfil the specific requirements and follow the steps investigated in this paper through a real-world use case. The selected use case is a smart building constructed inside a smart campus. Fig. 1 shows the general DT mode for such buildings, considering not only the PLC according to physical products but also according to the virtual counterparts of the physical products. The connection between two spaces over the entire lifecycle is managed by open messaging standards called Open Messaging Interface (O-MI) and Open Data Format (O-DF). O-MI provides a real-time communication framework between products and distributed information systems. O-DF is defined as a simple ontology, specified as an extensible XML Schema, to represent the payload in IoT applications [15].

The paper is structured as follows. Section I provides a brief introduction to DT and PLC, and Section II reviews the related literature on DT considering the PLC. The PLIM based on DT is proposed in Section III, explained in more detail with a Väre building proof of concept in Section IV. Finally, Section V concludes the paper with outlines of future work.

II. RELATED WORK

In this section, the state-of-the-art and applications of DT are elaborated along with its characteristics. TABLE I presents a summary of the applications. Many DT-based methods have been proposed thus far but only few take the context of all the stages of PLC into consideration. Among them, a comprehensive DT reference model is proposed for the physical product only in design and production industry by Schleich et al. [9]. Additionally, the reference model supports some of the PLC operations including composing, converting, decomposing, and evaluating but does not focus on all of the lifecycle operations. The reference model is evaluated by applying it to the application of geometrical variations management to test the conceptualization, implementation, and representation of the model. Another study presents the DT framework for product design to apply the information provided in product design for manufacturers [4]. To target the end phase of PLC, DT can be extended and integrated with Industry 4.0, which opens up many opportunities to interoperability, connectivity, and transparency. For this purpose, Wang and Wang [12] propose a DT-based approach to support WEEE recovery by focusing on recycling of materials and remanufacteuring of components. Furthermore, Zheng et al. [13] design an application framework based on PLC with three main functional modules- data storage, processing, and mapping in the information processing layer.

DT can also be combined with other technologies to present more benefits. For instance, Schluse and Rossmann [10] employ a combination of Virtual Testbeds and DT to develop Experimentable DTs. Using detailed system-level simulations, this approach assists complex technical systems in streamlining the development of intelligent systems. The simulations in different situations and multiple use of models reduce the need for simulation technology in the entire lifecycle of complex technical systems. DT also has been combined with Service Provider (SP) components using cross-enterprise the Semantic Data Management (SDM) integration platform in development and SP configuration [7]. This overall engineering information model offers the advantage that they can abide by the freedom of partner-specific SP-components as well as their engineering systems. It facilitates the interdisciplinary cooperation among companies as well as engages in the independent development of internal SP components. The benefits provided by DT functionalities have also been converged with the assess management and its requirements for decision support through research projects use cases [8]. The multitude of decisions by the use cases in practice are supported by DTs at disparate asset control levels in company. The modelling of DT has also been achieved from a completely different perspective by using AutomationML at a high level to offer services for different applications [11]. The model acts as a communication methodology for the exchange of data among DT and other systems.

III. AN INFORMATION MANAGEMENT BY DT

Currently IoT data are collected by several vendors such as google and apple with different infrastructures spreading around the world. Hence, users have no knowledge how their personal information is managed and whether the related technology is secure. Such distributed structure triggers unsafety and insecurity in users about the IoT systems. DT solves the problem by building an information system which collects information locally and provides a facility management which would have access to the data collected in one place, regardless of its source. In other words, DT uniquely organizes the information supplied by various sources during their entire lifecycle collectively in one place. Therefore, security techniques can exclusively be adopted on the DT server which has access to all the information.

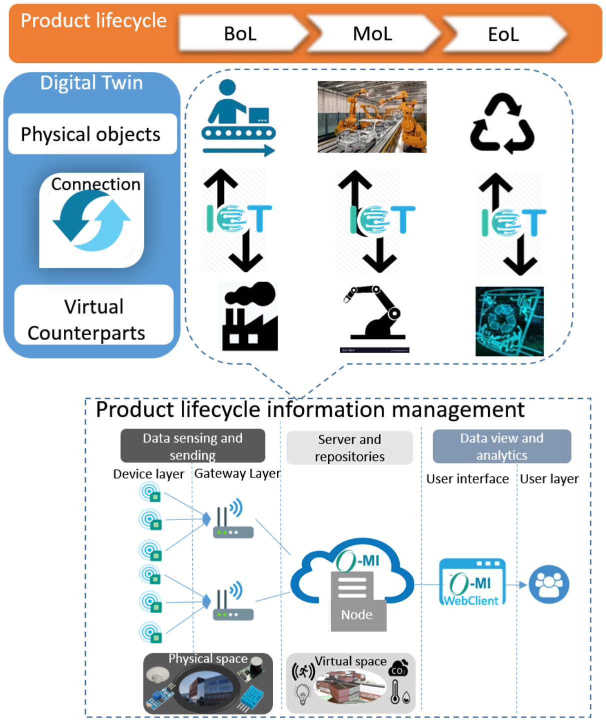


Figure 2. PLIM using DT

Such DT-based features can be applied to implement an information system which contributes mainly to lifecycle information. Product information over the lifecycle is managed via PLIM, and as DT is known as a solution for enabling PLIM [1], the combination of these two concepts can enhance various aspects of both. Fig. 2 shows how information about the physical and digital product is managed by PLIM in DT across the entire lifecycle. The lifecycle is divided into three phases: BoL, MoL, and EoL [16]. DT consists of three main components: physical objects, their virtual counterparts, and the connection between these two components. The connection can be created by IoT technology and the information processing through this connection will be handled by PLIM. By means of a PLIM system, physical objects send their data to the server (e.g. O-MI server) as a single access point. In the same vein, the system users operating in each phase can obtain the product information by connecting to the same server.

SmartCampus is one example of a DT-driven PLIM system which aims to coordinate publishing and consumption of data through a standardized Web-API. It provides information about energy consumption, occupancy, and user comfort by integrating Building Information Models (BIMs) and IoT devices via open standards (O-MI/O-DF). To show its functionality as a DT employing PLIM, we concentrate on a real use case of such an information system. This use case relates to a smart building, named Väre as part of the smart campus located in the Aalto Otaniemi campus. Väre is considered a DT-driven system due to its adherence to the necessary requirements. The first two requirements are extracted from the DT definition presented in literature. First, in DT, IoT devices and systems are required to be managed throughout their lifecycle [3]. Second, a DT system contains three components including the physical product, the virtual product, and the connection between these two products, based on [4]. Finally, a set of requirements is defined by Tao et al. [4] as six essential steps for having a functional DT. Fig 3 displays the six steps around the circle along with the first two requirements in the middle where three components are presented in respect to lifecycle phases.

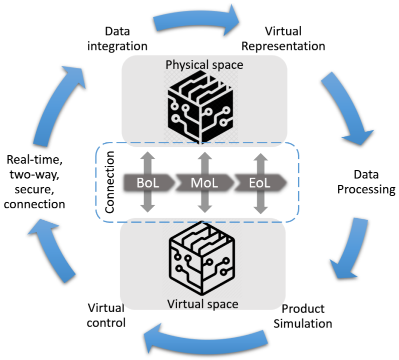


Figure 3. Functional DT by 6 steps and 2 requirements [4]

IV. VÄRE BUILDING: PROOF OF CONCEPT

The proof of concept is accomplished for Väre, which is comprised of 24 blocks in the entire building with three floors with a total property area of 34000 m^2. Energy efficiency is considered in building design by deploying renewable energy sources like solar and geothermal energy. As mentioned in previous section, in the case of an existing physical product, Väre generally poses two main requirements (req.1 and req.2) and six steps in creating a completely functional DT, demonstrated as follows.

Req.1: Managing throughout the entire lifecycle

Three main phases for the lifecycle of the Väre building are recognized: architectural design, construction, and use-time

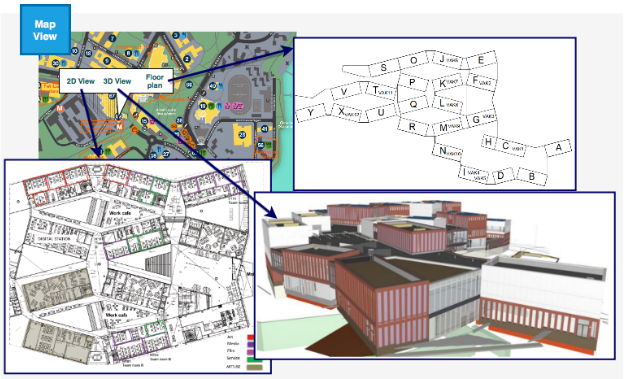
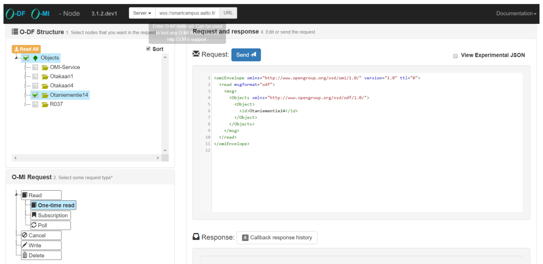


Figure 4. Geometrical representation of Väre building



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    <msg>
      <Objects xmlns="http://www.opengroup.org/xsd/odf/1.0/">
        <Object>
          <id>Otaniementie14</id>
        </Object>
      </Objects>
    </msg>
  </read>
</omiEnvelope>
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Figure 5. Väre data visualization

maintenance, which are equivalent to BoL, MoL, and EoL, respectively. The architectural design phase is very detailed. All items, nooks, and corners have loads of data about the construction. The architect places equipment minutely into the model that naturally grows to be a big one. Then, this model is printed out and given to the construction team. Previously, the construction site used paper prints and made necessary changes with a red pencil on the paper, after which the original data model started to deviate from the actual situation. Recently, in many cases, the changes are directly recorded in the virtual model. In the last phase, the virtual data and models are adapted by the maintenance team. Formerly, the data models were not portable amongst different systems but software such as Autodesk Forge have made it possible in our current use case.

Req.2: Combining 3 parts i.e. virtual, physical, and connection

The Väre building as a DT, has three components in general. The *physical entities* available in the physical space of the building such as electrical sensors are real products manufactured from raw material. The *virtual models* in virtual space map the physical entities including the entire lifecycle. As shown in Fig. 1, the *connection* between these two spaces is managed with O-MI and O-DF standards.

Step 1: Virtual representation of the product

Fig. 4 illustrates the main interactive views of the dimensional representation of the geometric data of the system. The core components are the building floor plan, detailed cross-sectional 2D view of the building, and detailed 3D models of the building. The 2D view helps in tapping into the innate human cognitive abilities in interpreting and understanding the building spaces as well as visual information. One of the main enabling technologies of this step is 3D modelling, a commonly used technology in product design.

Step 2: Data processing for decision making

To support decision making, the data should be visualized, integrated, and analysed. As shown in Fig. 5, data can be visualized through O-MI webclient [1] where the sensor value can be revealed based on user requests. Data of the Väre building is collected from room facilities including heating and cooling valve, presence and temperature sensors together with sensor data assembled from five electrical systems installed throughout the building. Information such as CO2 concentration, inlet pressure, and amount of exhaust air is provided by sensors in the air conditioning system. The heating system also has several sensors such as heating valve, valve adjustment, set point, and snow melting network pressure. These features are slightly different in the underfloor heating system, which focuses on underfloor heating flow water. Another heating appliance is Convector, which provides information about exhaust air, heating valve, supply,and input filter. Finally, for controlling the mileage and power of lighting and sockets, a metering system is mounted in the building. Fig. 6 shows the data dashboard for the Väre building, which helps better visualize the data collected from the diverse sources in the building. For visualization, we have selected two data values: room temperature and CO_2 for the period of one week in Fig. 6. Data analytic is necessary as it converts data into more concrete information to promote for example fault detection. Since the data are collected from multiple sources, this form of data integration helps analyze the hidden patterns which are impossible to uncover from a single data source and it also helps in incorporating Artificial Intelligence (AI) into DT for better reasoning, problem solving, and recommendations. The data can be integrated from any number of data sources in any period of time.

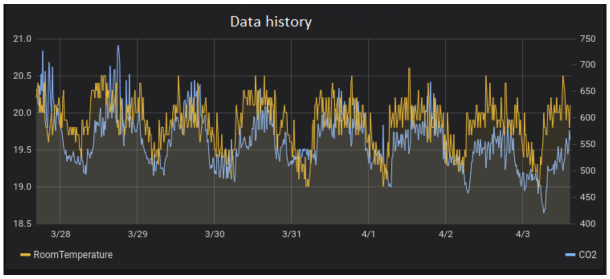

Figure 6. Väre Data analytic (historical sensor data)

Step 3: Simulation of the physical product to its virtual representation

To build a functional DT, it is necessary to present in virtual environment the actions and behaviours of the physical

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[1] https://smartcampus.aalto.fi/omi/html/webclient/index.html

products in the real-world system. Further, simulating various possible behaviors of multiple products and investigating the correctness or effectiveness of all behaviors on the overall system can support system optimization in the real environment. For instance, adjusting the temperature setting can impact the energy usage of the system. Such a claim can easily be studied by simulating different algorithms to obtain the temperature data and analyze the results.

Step 4: Perform recommended behaviours by commanding the physical product

O-MI enabled actuators can employ write request, call request or subscribe to gain input. Write and call requests can be used to push input to an actuator from other device or user. It is also possible to open a real-time input connection from other devices by event-based subscription, as subscription result messages are applied in the same manner as write requests.

Step 5: Secure, real time and two-way connections between the physical product and its virtual counterpart

The connections in Väre are enabled by technologies such as sensors, Wi-Fi, open messaging standards, and O-MI reference implementation. The sensors in Väre yield abundant data, which need to be stored and managed intelligently to perform actuation and smart observations. A standard data messaging interface and data format (i.e. O-MI and O-DF) are employed for data exchange which facilitate seamless integration of different sensors and support event-centric or time-centric data exchange. Messages can also be passed by means of a middleware (e.g. O-MI reference implementation) to manage guaranteed message delivery. In the Väre building, a transformer program is used to fetch data from the control room of Väre building automation. It then transforms the data into O-DF and sends write requests to the O-MI Node. Väre building automation is set up in a private network with wired connections. It means the Databus and internal networks are located in a closed environment, and no data inquiries are accepted from outside, which makes the system secure on the sensor side.

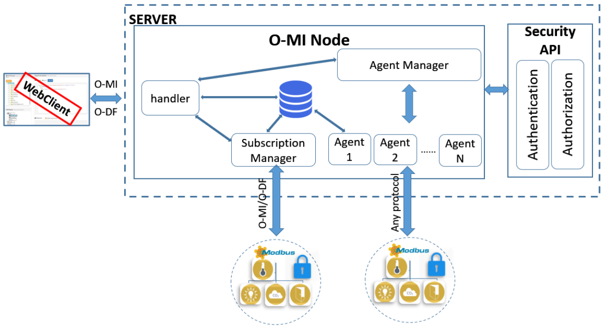

Figure 7. Service components over DTIS for Väre

The real-time sensor information is sent over the O-MI open standards to the O-MI server, where the client can access the real-time data concerning the systems installed in the building. The maximum delay encountered in the data retrieval on the Väre dashboard is two hours, which is due to the sequential update of the information from all sensors to avoid server overload. The O-MI *Read* operation help retrieve information from devices, sensors, databases, or other O-MI nodes. The O-MI client also has the provision of the *Write* request used to write data originating from sensors, events or other devices to O-MI nodes. Interaction between the components of the O-MI Node reference implementation is presented in Fig.7. The server mainly communicates with O-MI/O-DF messages, which are processed by the handler and data then flow between the required internal components. *Read* requests fetch data from the database and data from *Write* request can flow to database, Agent Manager, and Subscription Manager, depending on where the data are needed. Agents can tap to write or read requests via Agent Manager and specify any extra business logic, virtual devices or implement proprietary protocols for devices. Subscription manager handles event and interval subscriptions and makes O-MI callbacks with the requested data to the recipients of the subscriptions. Finally, when requests are received, the O-MI Node communicates with the Authentication and Authorization modules, in order to verify if the request is authorized to be executed for each item in the request.

Step 6: Data collection from different sources

In the Väre building, most of the sensors are connected to distributed centers through a wired Databus to the building automation equipment (German DEOS). The data are transmitted to SmartCampus Server via an internal data network (Aalto ITS operated). From this server, the data can be accessed with secure connections. Additionally, the Väre building management collects information regarding the number of visitors and their locations history. The shops located in the building could apply such information if this was made public. A complimentary sensor is also adopted to collect customer feedback with smiley buttons to enhance the building environment.

Comparative Analysis

To formulate a functional DT, it is important to follow the two requirements and six steps mentioned above. Considering these criteria, the functionalities of previous DT solutions are compared in Table II. As seen in the table, most of the existing studies partially or rarely support all the listed requirements and steps. Such comparison validates the utility of our system as a DT-based information model which can act as a reference in designing DT information models.

V. CONCLUSION

In an IoT context, this paper opens up new research directions for providing a new solution for implementing PLIM. PLIM mostly focuses on physical spaces and their existing information; however, the representation of the virtual counterpart, known as virtual space, and the connection between these two spaces is missing, alongside the updated information

Table II

Comparative Analysis: ✓ means supported, ✗ means not supported, and ρ means partially supported.

DT phase	**[7]**	**[8]**	**[9]**	**[10]**	**[11]**	**[12]**	**[13]**	**Proposed**
Req.1	✓	✓	ρ	✗	✓	✓	✓	✓
Req.2	ρ	✗	✗	✗	✓	✓	✓	✓
Step 1	✓	✗	✓	✓	✓	✓	✓	✓
Step 2	✓	✗	✗	✓	✓	✗	✓	✓
Step 3	✗	✓	✓	✓	✓	✗	✗	✓
Step 4	✓	✓	✓	✗	✗	✓	✓	✓
Step 5	ρ	✗	✗	✗	ρ	ρ	ρ	✓
Step 6	✗	✗	✗	✗	✗	✗	✓	✓

of products in connection with PLC phases. Motivated by this need, this paper merges PLIM, covering data availability of physical objects during their lifecycle, with DT covering the entire lifecycle of physical and virtual spaces and their connection to present a comprehensive information system. Such an information system can be employed in all smart environments such as smart campus. As a proof of concept, the paper illustrates how DT can be adopted by means of PLIM in smart buildings.

As future work, we will focus on the security over such a PLIM system, which is an important aspect of any information system. This PLIM can easily be employed in larger networks like smart campus where the information regarding the entire building is collected in one place. We also plan to show how such a system can work in other smart systems in the future.

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