Open Source Drives Digital Twin Adoption

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INTRODUCTION

"Digital Twin" has been listed as an emerging technology during past years and more and more companies offer Digital Twin as part of a foundation for their digital offerings. However, there has not been consensus on what a Digital Twin is and what characteristics it should have. Some refer the origin of Digital Twin to an academic paper, where Digital Twin was defined as a combination of physical product, virtual product and their connections [1]. Some also claim that Digital Twin existed in industrial applications under different names[2]. One could observe that lack of a common definition for Digital Twin has led to many flavors of this concept, sometimes making readers wonder whether Digital Twin is more than just a buzzword at all. Several literatures discussed the definitions[3] [4] [5] and requirements[6] [7] that Digital Twins could have.

As the first step to clarify the role of Digital Twin in various sectors, various consortiums and committees such as the Industrial Internet Consortium (IIC)[8] and Plattform Industrie 4.0[9] each

[1] M. Grieves, "Digital twin: Manufacturing excellence through virtual factory replication," White paper, 2014. [Online]. Available: *http://www.apriso.com/library/Whitepaper_Dr_Grieves_DigitalTwin_ManufacturingExcellence.php*

[2] Somayeh Malakuti, Jan Schlake, Christopher Ganz, Eric Harper, Heiko Petersen, "Digital Twin: An Enabler for New Business Models", Automation 2019

[3] E. Glaessgen and D. Stargel, "The digital twin paradigm for future NASA and U.S. Air Force vehicles," in Proc. 53rd AIAA/ASME/ASCE/AHS/ASC Struct. Struct. Dyn. Mater. Conf., 2012. [Online]. Available: https://arc.aiaa.org/doi/pdf/10.2514/6.2012-1818

[4] Stark R, Anderl R, Thoben K-D, Wartzack S. WiGeP-Positionspapier: „Digitaler Zwilling". ZWF 2020.

[5] Elisa Negri, Luca Fumagalli, Marco Macchi, editors. A Review of the Roles of Digital Twin in CPS-based Production Systems. Elsevier 2017.

[6] Moyne, James & Qamsane, Yassine & Balta, Efe & Kovalenko, Ilya & Faris, John & Barton, Kira & Tilbury, Dawn. (2020). A Requirements Driven Digital Twin Framework: Specification and Opportunities. IEEE Access. PP. 1-1. 10.1109/ACCESS.2020.3000437.

[7] Digital Twin Requirements in the Context of Industry 4.0, Product Lifecycle Management to Support Industry 4.0, 2018, Volume 540, ISBN: 978-3-030-01613-5, Luiz Fernando C. S. Durão, Sebastian Haag, Reiner Anderl, Klaus Schützer, Eduardo Zancul

[8] IIC Industrial Internet of Things Vocabulary, https://www.iiconsortium.org/vocab/

[9] Digital Twin and Asset Administration Shell Concepts and Application in the Industrial Internet and Industrie 4.0 - An Industrial Internet Consortium and Plattform Industrie 4.0 Joint Whitepaper - https://www.plattform-i40.de/PI40/Redaktion/EN/Downloads/Publikation/Digital-Twin-and-Asset-Administration-Shell-Concepts.html

provided a definition of this concept; likewise, a definition is provided by the Digital Twin Consortium (DTC)[10]. Followed by the definition, various architectural aspects that must be considered in the design of Digital Twin have been proposed[11]. These include, for example, information models, APIs, connectivity to physical twins, data ingestion mechanisms, security and interoperability of Digital Twins. Other organizations, such as the Open Industry 4.0 Alliance[12], focused on creating a network of manufacturers to drive industries into adopting the Digital Twin technologies of Industry 4.0 based on existing definitions and standards.

Each vendor may offer its proprietary Digital Twin solution. However, systems of systems, or, in general, complex systems, consist of components offered by different vendors. Therefore, individual Digital Twins need to eventually interact towards forming system-level Digital Twins and/or to enable cross-vendor interactions. Consequently, interoperability of Digital Twins (e.g., their meta model and APIs) in complex systems becomes inevitable.

To accelerate the development of Digital Twins within or across companies, there is an inevitable need for open standards for Digital Twins, as well as Open Source implementations to promote the agile development and adoption of those standards [13] [14] [15]. Alongside the IIC and Plattform Industrie 4.0, as the importance of this topic has grown, multiple new organizations such as DTC, Industrial Digital Twin Association (IDTA), and Open Manufacturing Platform (OMP) have recently been founded to develop these topics further.

This paper elaborates on the challenges in adopting the Digital Twin concept in practice and the motivations for having open standards and Open Source activities to address these challenges. In addition, the paper provides an overview of the activities of some organizations around these topics in more details. We discuss the challenges that will arise if there will be multiple open standards and Open Source implementations of Digital Twins.

[10] https://www.digitaltwinconsortium.org

[11] Industrial Internet Consortium, “Digital Twins for Industrial Applications White Paper”, https://hub.iiconsortium.org/portal/Whitepapers/5e95c68a34c8fe0012e7d91b

[12] https://openindustry4.com

[13] https://www.din.de/resource/blob/65354/619baa1958b89b8a7b6cd9be2b79f223/roadmap-i4-0-e-data.pdf

[14] https://www.ietfjournal.org/open-standards-open-source-open-loop/

[15] https://www.ietfjournal.org/three-years-on-open-standards-open-source-open-loop/

CHALLENGES OF DIGITAL TWINS

The challenges to adopt Digital Twin in the industry can be summarized as follows:

- **Lack of a common definition and understanding of the Digital Twin concept:** The term "Digital Twin" has been coined in academia in 2003, and ever since, many different definitions and flavors of it have emerged, which usually focus on particular use cases in which a Digital Twin is adopted. However, there is also the view that the concept of Digital Twin has existed in industry for several decades, under different names. The lack of a common definition and understanding of the Digital Twin concept risks it being degraded to the level of a buzzword. Various consortiums such as IIC, Plattform Industrie 4.0 and DTC have tried to address these challenges.
- **Backend data integration:** Digital twin is a means for providing holistic access to the otherwise dispersed and siloed data. This requires architectures and solutions for integrating data within and across boundaries of organizations, dealing with heterogeneity of data sources, data formats, APIs and security rules.
- **Standardized information model:** To increase interoperability across data sources within and across the boundaries of organizations, standardized information, standardized meta-models, and APIs are required to describe Digital Twins. As for other industrial practices, companies may face the "standardization deadlock" problem, where on one hand there might be insufficient practical experience to drive standardization needs, and on the other hand the practical experiences might lead to proprietary solutions. This requires that architectures and solutions adopt the "on-demand interoperability", where proprietary Digital Twins can be translated to standard ones on-demand, upon the availability of standards.

Finally, as the fast-changing market is accelerating the innovation cycle, it is crucial to ensure the adoption of a new technology, such as the Digital Twin, as fast as possible. Otherwise, Digital Twin might lose its momentum in making an impact on the current cycle of digital transformation. Although current standardization efforts driven by multiple organizations around the globe aim at establishing the Digital Twin and its adoption in the market, the standardization processes are usually lengthy and slow. However, an aligned collaboration between these organizations could potentially accelerate this process and would lead to higher quality. To address this challenge, an open collaborative approach to leverage the synergies of these organizations and make the standardization more agile is important and beneficial to a faster adoption of Digital Twins. We introduce and discuss such an approach in the following sections.

DRIVING DIGITAL TWINS THE OPEN SOURCE WAY

In 2019, the Gartner Hyper Cycle listed Digital Twins as being on the "Peak of Inflated Expectations." Some still feel it is just a buzzword but the world is moving on. Digital twins now can be reflected on the "Slope of Enlightenment". In 2020, several new organizations were founded or kicked-off to establish Digital Twin technology in industrial settings. Hence, the aim is clear: Smooth the way to reach the "Plateau of Productivity."

A remarkable realization common to almost all of the Digital Twin related organizations is the consideration of Open Source development as an important pillar for promoting the faster adoption of Digital Twins.

These organizations, in addition to IIC, Plattform Industrie 4.0, and Open Industry 4.0 Alliance, are involved in the development and promotion of Digital Twins and are briefly described below. They include: the OMP, the DTC, GAIA-X, Clean Energy and The Smart Manufacturing Innovation Institute (CESMII) [16] and the IDTA. Although CESMII has been founded earlier, CESMII is additionally listed in this section because it recently started Open Source activities.

Furthermore, a remarkable trend in the general Open Source community is that, increasingly, they do not aim just for Open Source code development, but for Open Source code and open specification development together.

For the Linux Foundation and Eclipse, it was a learning curve to not just focus on Open Source code development. The Joint Development Foundation (JDF) that focuses on open specification development joined the Linux Foundation in 2018[17]. Eclipse defined its own specification process in 2019[18]. The Internet Engineering Task Force (IETF) also identified Open Source as an essential development model to overcome the challenges of the tedious traditional standards processes and keep them on pace with fast innovation cycles [14] [15].

OASIS Open Foundation follows a similar hybrid approach to support open collaboration for developing standards[19]. Hence, the understanding now seems to be that standardization and Open Source are coming closer together to be more effective in both developing and promoting open specifications, open standards and Open Source.

[16] https://www.cesmii.org/production-of-zero-defect-zd-slabs/

[17] https://www.linuxfoundation.org/en/press-release/jdf-joins-lf-family/

[18] https://www.eclipse.org/community/eclipse_newsletter/2019/january/EFSP_vs_JCP.php

[19] https://www.oasis-open.org

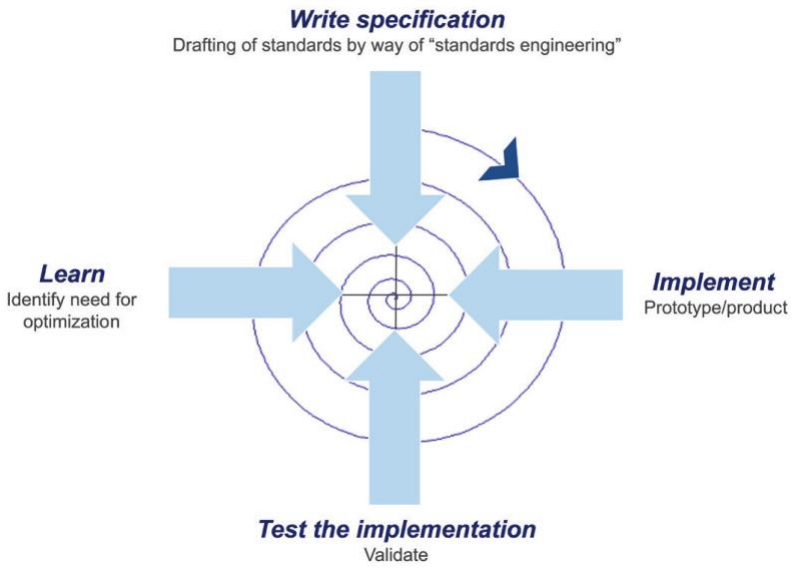

Fig. 1: Agile standardization using Open Source as a development model according to SCI 4.0 [13] (with permission from DIN Deutsches Institut für Normung e.V.)

In 2020, the Standardization Council Industrie 4.0 (SCI 4.0) that is creating the German standardization roadmap[13] claimed "Agile Standardization" to be the way to go. Agile Standardization means a joint development of the consensus-based standard development used in Standardization Development Organizations (SDO) together with Open Source communities. Thus, from both sides, faster innovations and reactions are possible: The standard is adapted from experiences gained during Open Source development and vice versa; the standard can be tested very quickly to see whether it really fulfills all the requirements. This is illustrated in Figure 1.

In joining the work of code and specification development, however, it is neither "code first" nor "specification first", but how to create synergy between the two parallel efforts by working very closely together. This is the approach of OMP[20], DTC, IDTA, GAIA-X, and CESMII.

Open Manufacturing Platform (OMP)

The OMP was founded in 2019 by Microsoft and BMW. Bosch, ZF and AB InBev joined at the beginning of 2020. OMP has a different strategy than IDTA, DTC, CESMII, and GAIA-X. OMP is a project under the umbrella of the Joint Development Foundation. It is the only initiative in this area set up as an Open Source project from the very beginning. The goal is to "accelerate

[20] https://open-manufacturing.org/

innovation in Industrial IoT to shorten time to value."[21] OMP aims for both published best practices and encourage open code development. It is not dedicated to Digital Twin technology only, but the Semantic Data Structuring working group, contributes to it. This working group addresses the "*needs to share, join and reuse heterogeneous data of the manufacturing domain by applying common semantics for various stakeholders through comprehensive semantic data homogenization and by conveying manufacturing data along with contextual information*."

The OMP GitHub repository provides open publications, specifications, and source code: https://github.com/OpenManufacturingPlatform.

Digital Twin Consortium (DTC)

DTC was formed under the umbrella of the Object Management Group (OMG), a standards organization that supports the development of open standards. The DTC is not a standards organization, but provides guidance to address market confusion, interoperability challenges, and managing the risk of implementing Digital Twins in industrial and commercial settings.

The DTC industry working groups have a vertical market focus and currently consist of Manufacturing, Infrastructure, Healthcare and Life Sciences, Aviation and Defense and Natural Resources groups.

The horizontal working groups include the Marketing and the Technology, Terminology and Taxonomy (3T) focus areas. The 3T Working Group has further subgroups that focus on Security and Trustworthiness, as well as Open Source and Platform Stacks.

A primary focus for the DTC is the overall Digital Twin lifecycle and the different requirements of a Digital Twin as it evolves through its lifecycle. The Digital Twin lifecycle includes the digital thread, as well as that of the physical entity or asset that it supports.

The DTC provides an Open Source repository where vendors and end users can contribute various elements to accelerate the adoption of Digital Twins. Contributions may include Open Source code implementations, collaborative documents for guidance and training, Open Source models, or other assets that are of value to the Digital Twin community.

The cross-pollination by the different industry-focused working groups provides the opportunity for different industries to learn from each other and improve collaboration around architectures, tools and open-source contributions.

Industrial Digital Twin Association (IDTA)

[21] https://azure.microsoft.com/en-us/blog/the-future-of-manufacturing-is-open/

The IDTA[22] was founded in September 2020[23] by Verband Deutscher Maschinen- und Anlagenbau[24] (VDMA)[25] – the largest network organization in the European mechanical engineering industry – and Zentralverband Elektrotechnik- und Elektronikindustrie[26] (ZVEI)[27] – the German Electrical and Electronic Manufacturers' Association - together with Bitkom[28] – Germany's digital association - and 20 companies: ABB, Asentics, Bitkom, Bosch, Bosch Rexroth, Danfoss, Endress Hauser, Festo, Homag, KUKA, Lenze, Pepperl Fuchs, Phoenix Contact, SAP, Schneider Electric, Schunk, Siemens, Trumpf, Turck, Volkswagen and Wittenstein.

The goal of the IDTA is to bring the Digital Twin to the next level, make is enterprise ready by utilizing Open Source development model and to provide a one-stop-shop for the industrial Digital Twin, known as the Asset Administration Shell in Industrie 4.0. Five areas of focus were identified: Open Technology, Integration, Quality Management, Training and Marketing.

Besides specifications of Digital Twins[29], with focus on cross-company interoperability ("Open Technology"), the IDTA will also push the further standardization of so-called submodel templates ("Integration"), i.e., standardized (domain) knowledge needed for different use cases and data-driven business models that can be shared via the standardized API of the Asset Administration Shell. In addition to genuine submodel templates for Asset Administration Shells, existing and future OPC UA Information Models[30] will also be considered as a basis.

Existing Open Source activities in the context of the Asset Administration Shell will be supported under the umbrella of IDTA. There are already several Open Source projects in place that implement the Asset Administration Shell (AAS):

- **admin-shell-io** (https://github.com/admin-shell-io): This project hosts an open editor with a graphical user interface for Asset Administration Shells (AASX Package Explorer),

[22] www.industrialdigitaltwin.org

[23] https://www.zvei.org/en/press-media/pressarea/user-organization-industrial-digital-twin-association-founded

[24] German: Mechanical Engineering Industry Association

[25] http://www.vdma.org/

[26] German: electrical and electronic manufacturers' association

[27] https://www.zvei.org/

[28] https://www.bitkom.org/EN/EN

[29] https://www.plattform-i40.de/PI40/Redaktion/EN/Standardartikel/specification-administrationshell.html

[30] https://opcfoundation.org/developer-tools/specifications-opc-ua-information-models

an AAS Server, AAS specifications as well as schemata (aas-specs), training screencasts, and FAQs.

- **BaSyx** (https://projects.eclipse.org/projects/technology.basyx): This project hosts - besides other modules - SDKs or the Asset Administration Shell.
- **PyI40AAS** (https://git.rwth-aachen.de/acplt/pyi40aas): This project hosts a Python module for manipulating and validating AAS.
- **SAP AAS Service** (https://github.com/SAP/i40-aas): This project hosts a system based on Docker images implementing the RAMI 4.0 reference architecture (including AAS).
- **NOVAAS** (https://gitlab.com/gidouninova/novaas): This project provides an implementation of the AAS concept by using JavaScript and Low-code development platform (LCDP) Node-Red.

Building an attractive and active Open Source community based on these existing and new activities is one of the important goals of the IDTA.

GAIA-X

GAIA-X[31] was officially founded in 2020[32]. GAIA-X is a European project aiming at developing common requirements for a European data infrastructure. Therefore, interoperability, transparency, and openness are key factors for success. Digital twins will play an enabler role for data exchange across company borders. This is illustrated in the use case "Collaborative Condition Monitoring"[33]. Open standards and its Open Source derivatives such as the one developed within the Industrial Data Spaces (IDS)[34] are playing a major role in GAIA-X.

CESMII

CESMII, the Clean Energy and Smart Manufacturing Innovation Institute, was founded in 2016. In January 2021 CESMII and the IIC agreed to a liaison to "accelerate the development, adoption, and monetization of Industrial IoT (IIoT) technologies, infrastructure and solutions to deliver

[31] https://www.data-infrastructure.eu/GAIAX/

[32] https://www.isst.fraunhofer.de/en/news/press_releases/2020/PI_GAIA-X_foundation.html

[33] https://www.bmwi.de/Redaktion/EN/Artikel/Digital-World/GAIA-X-Use-Cases/collaborative-condition-monitoring.html

[34] GAIA-X and IDS Position Paper: https://internationaldataspaces.org/download/19016/

transformative business value for manufacturers through digital transformation"[35]. One of its goals is to realize interoperability via collaboration and standardization. Digital twins play an important role in this effort. The focus in this area is on so-called smart manufacturing (SM) profiles. An OPC UA information model serialization was chosen for these profile specifications.

Together with the OPC Foundation, CESMII is working on the UA Cloud library[36]. The goal is to provide open data models via a globally hosted cloud database. These data models shall be useable in Digital Twin implementations. SM Profiles, a code sample for the CESMII API, and more are available in CESMII GitHub repository (https://github.com/cesmii).

Comparison of Activities and Organizations

As the organizations introduced above share a similar goal – provide the foundations for an interoperable Digital Twin – they differentiate themselves in the focus of their activities as well as how "open" they are. Table 1 summarizes the activities of the organizations mentioned in this paper, highlighting their main contribution and focus[37].

[35] https://www.automation.com/en-us/articles/january-2021/industrial-internet-consortium-smart-manufacturing

[36] https://www.automation.com/en-us/articles/october-2020/new-international-initiative-opc-ua-cloud-library

[37] Note: The authors acknowledge that the metrics introduced in Table 1 are purely based on heuristic evaluations with the object to estimate the overlap of the activities within a criterion. The authors stress that no statistical analysis have been carried out.

Table 1 Overview of Organizations Driving the Digital Twin Technology

Organization	General Guidance	Focus on Digital Twins	Focus on Manufacturing Application	Open Code	Open Specification	Open Development Model
OMP	○	◔	●	●	◑	●
IDTA	○	●	●	●	●	●
DTC	●	●	◑	●	○	●
GAIA-X	○	◔	◑	●	●	●
CESMII	○	◔	●	●	●	●
IIC	●	◔	◑	○	○	○
Plattform Industrie 4.0	●	◔	●	○	●	○
Open Industry 4.0 Alliance	○	◔	●	○	○	○

Legend:
- ○ None / no activity
- ◔ Few activities
- ◑ Many activities
- ◕ Most activities
- ● All activities

From all organizations evaluated in this paper, IDTA and DTC are the ones that exclusively focus their activities on Digital Twins. However, while IDTA focuses on manufacturing applications of Digital Twin, DTC also considers its wider usage across different vertical domains spanning from natural resources to infrastructure, healthcare, and life science. Both are covering full deployment with security and trustworthiness from edge to cloud. Other organizations such as OMP, GAIA-X, CESMII, Open Industry 4.0 Alliance, IIC, and Plattform Industrie 4.0 do not limit their activities around Digital Twins, but also consider topics such as Cloud, Edge, data sovereignty, etc. Of these organizations, only the IIC and GAIA-X has a wider focus beyond manufacturing.

Regarding the development model driving the activities within these organizations, we recognize an increasing trend for open, collaborative models using Open Source as an approach to drive interoperability and standardization. As mentioned above, the newly funded organizations OMP,

IDTA, DTC, GAIA-X, CESMII are publishing the outcomes of their activities in repositories that are open for the community. In particular, their codes are available in repositories such as GitHub with the corresponding Open Source Licenses (e.g. Apache v.2.0, Eclipse v2.0, Mozilla Public License (MPL), MIT). Additionally, organizations such as OMP, IDTA, GAIA-X, CESMII are also "open sourcing" their specifications. Both lead to an open development where the community can both access the codes or the specifications and provide feedbacks on them as well. Furthermore, if the Open Source license allows, they can use, modify and share their contributions.

Organizations such as OMP, IDTA and DTC have recognized that the Open Source development model provides additional capabilities to simplify and to accelerate the specification and standardization process of new technologies. The Open Source model adds agility, quicker cycles of evolution and open collaboration, and vendor-neutral governance to the development of standards. In particular, as more information and communication technologies are embedded into products (e.g., industrial machines and parts), the demand for software and communication protocols are increasing. The concept of Digital Twin represents a suitable example of this paradigm shift and, accordingly, the concurrent development of standards and code via the Open Source model is a perfect match. Other technologies, such as Cloud Computing, already have proven that Open Source played an essential role in their successful adoption (e. g. Cloud Foundry[38], Kubernetes[39], Gardener[40]) in the market.

The Open Source activities of DTC and IDTA will provide valuable contribution via reference implementations for existing use cases and standards defining Digital Twins. As shown in Figure 1, the Open Source implementations will provide a validation platform to test and to optimize respective standards and specifications. Especially, the Open Source community can provide direct feedback to the projects and new requirements as well as improvement suggestions by creating issues or pull requests in the corresponding repositories. For example, Plattform Industrie 4.0 has published several documents specifying the details of Asset Administration Shell and submodel templates that can be used as a reference for other organizations in their activities in the last few years and is continuing to do so. At the same time, these organizations could contribute to the newer versions of these documents based on their knowledge gained through the activities around Open Source projects or transferring the Asset Administration Shell specifications and Open Source codes to other applications beyond manufacturing. While IDTA is focusing on manufacturing applications of Digital Twins and has already decided which standard to use as basis for further development and improvement, DTC is looking across

[38] https://www.cloudfoundry.org

[39] https://kubernetes.io

[40] https://gardener.cloud

different domains and does not recommend single standards but aims to give advice to enable clearer understanding of the current concepts of Digital Twins and available standards and technologies. DTC contributions seek to include Open Source code implementations, collaborative documents for guidance and training, Open Source models, or other assets of value to the Digital Twin community.

Additionally, the Open Source projects of the organizations OMP, CESMII, and GAIA-X will also be providing valuable contributions for the Digital Twins. OMP will be contributing with comprehensive semantic data homogenization for Digital Twins in the manufacturing context. Also, in the manufacturing context, CESMII efforts on the OPC UA Cloud Library, by providing open data models, is a crucial contribution to enable interoperable machine-to-machine (M2M) communication via Digital Twins. In a wider context, GAIA-X will contribute with use cases and implementations of components for Digital Twins to fulfill security and data sovereignty requirements.

Analogous to the modern development approach for software applications, interoperable Digital Twins will be assembled using the components developed within Open Source communities. Enterprises and vendors will be able to combine these Open Source components with their proprietary technologies to build applications and systems that make a differentiation in the market and that provide added value to their customers.

CONCLUSION

The development of standards for Digital Twin is an imperative for setting the necessary foundation to ensure its successful adoption in the market. However, it is clear that an effort based solely on establishing open standards is not enough. In particular, as in the case of Digital Twins and Industry 4.0 / IIoT, where machines are connecting to and converging into the IT world, the demand for enabling software is increasing. Adequate, widely supported and widely adapted Digital Twin Open Source software can establish de facto standards for the underlying architecture of Digital Twins. To keep the pace with faster innovation cycles, it is crucial to leverage the opportunity made available by Open Source as a development approach that has

been raised in several works [41] [42] [43]. In this context, driving Digital Twin development with the converged Open Source and open standard approach brings significant benefits, including:

- higher co-innovation and interoperability due to better collaboration between organizations, vendors, end-users and communities,
- faster validation of the specifications due to agile development of open standards by providing production-ready code,
- faster adoption of the technology due to the establishment of de facto standards,
- scalability of reference implementations into interoperable products for Digital Twins, and
- better cost-effectiveness and faster responsiveness to market demands and changes.

More than ever, the convergence of open standards and Open Source is crucial to enable interoperable Digital Twins since this convergence provides an open platform capable of dealing with technological complexity and market dynamics. Following the approach shown in Figure 1, early versions of the specifications, standards, and code of reference implementations are available to the Open Source community. Based on the feedback gained during the agile development, specifications, standards, and code of reference, implementations can achieve their necessary maturity level faster. As a result, the development cycles necessary to develop open standards become shorter. These open standards and specifications can be potentially submitted to ISO, IEC, DIN, or other SDOs. It is expected that the processes within these SDOs are also accelerated.

However, one must acknowledge the challenges that arises when multiple organizations provide different open standards and Open Source implementations for Digital Twins. Whether in an open collaborative model with the community or not, several organizations are developing specifications for Digital Twins and the information they provide is shaping their foundations.

These different organizations seem overlapping and competing at a first glance, and it may become a challenge for them to position themselves with each other and provide clear direction to their stakeholders. Therefore, the setup of collaborations and liaisons to align and complement activities between these different organizations are highly desirable for the good of the general community. Otherwise, there is the risk that the goal of faster implementation of

[41] https://iot.eclipse.org/community/resources/white-papers/pdf/Eclipse%20IoT%20White%20Paper%20-%20Open%20Source%20Software%20for%20Industry%204.0.pdf

[42] https://plc4x.apache.org/users/industry40.html

[43] https://openforumeurope.org/publications/standards-and-open-source-bringing-them-together/

interoperable Digital Twin remains elusive. As a result, fragmentation of the market due to lack of interoperability and confusion regarding “which standards should I use?” can be expected. Additionally, the complexity of Digital Twins might increase if all competing standards are needed, although they provide the same value. Similar to multiple organizations investing their efforts in defining and specifying similar standards, different Open Source projects aiming at the same or overlapping solutions might lead to confusion in the market and fragmentation of the technology. Moreover, different Open Source projects would miss the opportunity of having a sufficient number of active contributors leveraging the quality of the code instead of creating similar solutions competing with each other.

Going beyond setting up collaboration and liaison to align activities across organizations, the following recommendations could be explored in future discussions:

- A more detailed assessment of individual Open Source projects driven by the organizations evaluated in this paper could be addressed in future works (similar to the joint paper of IIC and Plattform 4.0 on the Digital Twin and AAS topic[9]). Based on this detailed assessment, a mapping of Open Source projects based on the identification of overlapping and unique features following predefined criteria (e.g. technology being used, open standard being implemented, manufacturing focus, etc.) of these projects could be performed. Using this mapping, activities and efforts of Open Source projects could be closely aligned in terms of their overlapping elements and refocused on the unique challenges they are solving. At the same time, such mapping can serve as a guide for the contributors as well as for users of the Open Source projects as to which Open Source project to contribute, or which Open Source Project should to be integrated in the products.
- Open source can be tested in testbeds to validate their applicability and interoperability by building, for example, Proof of Concepts (PoCs). Such testbeds provide a neutral environment where members, developers, and community exchange their experiences and align their activities.

Finally, in developing and promoting interoperable Digital Twin, it is neither "code first" nor "specification first", but the joint effort and synergy between the two parallel developments that will bring the expected accomplishment in the context of IIoT / Industry 4.0.

DISCLOSURE

Authors of this paper are members of the organizations classified in this whitepaper: IIC, DTC, GAIA-X, IDTA, CESMII, Open Industry 4.0 Alliance, or/and Plattform Industrie 4.0.

ACKNOWLEDGEMENTS

The views expressed in the *IIC Journal of Innovation* are the contributing authors' views and do not necessarily represent the views of their respective employers nor those of the Industrial Internet Consortium.

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