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Clarifying concepts of Metaverse, Digital Twin, Digital Thread and AAS for CPS-based production systems

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Abstract: With the quick advent and spreading of Industry 4.0, the paradigm of Cyber Physical Systems (CPS) is becoming a reality in production systems. As the term CPS suggests, the advanced production systems are made of a digital element and a physical one that work together to reach the desired functionality. The virtual element is made of various entities that are typically generically described as "a digital representation of a physical system". However, this general definition often is referred to terms that are actually belonging to different concepts. These terms are Metaverse, Digital Twin, Digital Thread, and Asset Administration Shell. These terms often are independently used in literature and industrial initiatives without any clear understanding of how they relate to one another or what they signify. This paper wants to contribute to the scientific discussion on these concepts and aims at analyzing their meanings and key features through a literature study, by proposing a hierarchical view on the relationships between them, their roles and functions for CPS-based production systems.

Keywords: Asset Administration Shell, Digital Thread, Digital Twin, Metaverse, CPS, Production Systems.

1. INTRODUCTION

Fundamental developments toward collaborative communication and operation in industry have been brought about by the Industry 4.0 era. One of the crucial paradigms of this era is the fact that production systems are now thought of in terms of Cyber Physical Systems (CPS). As the word implies, the new production equipment and systems will not only have a physical element, but also a digital element that is as important as the physical one. The digital element is typically composed of different entities, all generically defined as "representations of the physical system" from literature and industrial initiatives descriptions. These entities are the metaverse, Digital Twin (DT), digital thread, Asset Administration Shell (AAS). In some publications, some of these terms are used interchangeably, like the DT and AAS, DT and metaverse, DT and digital thread. Additionally, to this overlapping of terms' usage, they have received varying definitions in literature. This paper wants to bring a contribution to the scientific discussion that utilizes these concepts, by proposing a clear understanding of these terms based on literature definitions and their history. The proposed outcome of the paper is a high-level framework that visualizes the relationships of these concepts, and distinguishes their roles and functions in order to help the readers set the various concepts in the right place in the physical and virtual world of the CPS. As a result, also industry practitioners will benefit from this research, by gaining an in-depth comprehension of the underlying concepts, hence staying ahead of the curve by driving innovation in their organizations and fostering collaborations with academia based on a shared and mutual understanding.
The paper is structured into 5 sections: section 2 describes the objectives and methodology, section 3 presents the state of the art about the history and the definitions of the analyzed concepts, section 4 discusses the proposed framework and section 5 provides some conclusions.

2. OBJECTIVES AND METHODOLOGY

Literature proposes four distinguished concepts, but some publications still overlap in their definitions or usage of the analyzed terms. The objective of this paper is to clarify and distinguish the concepts of metaverse, DT, digital thread, and AAS and identify their relationships, their roles, and functions for CPS-based production systems. Another objective is to offer a unique and shared framework to be used as a common reference by researchers and practitioners dealing with these concepts in order to avoid future confusions and overlapping between terms.
The followed methodology is based on the review and synthesis of the relevant literature of the definitions and applications in industry of the analyzed concepts. The following search query was used for the collection of the papers from Scopus database: ("Asset Administration Shell" OR "Metaverse" OR "Digital Twin" OR "Digital Thread") AND ("Production" OR "Operation*" OR "Manufacturing"). The articles chosen are the ones presenting a clear understanding and application of one or more of the terms of metaverse, DT, digital thread, and AAS with a focus on CPS-based production systems.

3. STATE OF THE ART

A state of the art of the history and the definitions on the metaverse, DT, digital thread, and AAS is presented to have a better understanding of how authors have addressed these terms and the correlations between them.

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3.1 History and definitions of Metaverse

"Metaverse" first appeared as an element of science fictions novels. Typically, it is traced back to 1992 Neal Stephenson's cyberpunk and dystopic novel "Snow Crash" (Joshua, 2017) The word is a combination of "meta" and "universe", meaning "trascending the physical universe". The term has been in the subsequent years connected to various concepts, like: lifelogging, virtual shared spaces, spatial internet, mirrored worlds, and others (Lee et al., 2021).

But it is now something that reaches out from science fiction to us as a facilitator of the digital transformation touching all aspects of our daily lives, from business activities to entertainment and social interactions (Lee et al., 2021). This is done with virtual environments that are becoming mature enough to support the realization of a metaverse as a virtual world, where users can continuously connect and interact in real-time without leaving the real world (Ando et al., 2013).

It acquired momentum during the global pandemic (He et al., 2023; Siyaev and Jo, 2021), where the limitations in travels, connections and increased "remote anything" (work, gym, entertainment, cultural events, family and friends' gatherings…) covered the last step in the cultural change of acceptance of the virtual world as a natural companion to our physical lives, also for domains that were only superficially touched before (as example: family gatherings).

Metaverse is already well explored in the literature for various uses, such as for example in education (across various disciplines: medicine (Almarzouqi et al., 2022), mathematics (Arif and Nurhayati, 2022),…). For companies, the proposal of metaverses spans from enterprise metaverse to marketing applications, and to industrial applications, such as in maintenance (Siyaev and Jo, 2021). But the literature is still immature. The applications discuss the technologies to create metaverses but very little discussion on the business and managerial benefits is proposed (Catak et al., 2022; He et al., 2023; Laviola et al., 2022; Lee et al., 2021).

The main enabler of the metaverse is a unified, persistent and shared Internet-based world, which leverages on emerging technologies such as Virtual and Augmented Reality, Internet of Things, 5G, computer vision, and Artificial Intelligence, Deep Learning, to name a few (Lee et al., 2021; Park and Kim, 2022). It is clear that a concept strongly related to metaverse is the one of DT. In fact, according to some authors, the development of the metaverse needs three phases, of which creating DT is the first, then the emergence of *digital natives* and finally *co-existence of physical—virtual reality* (Lee et al., 2021). Also, Lee and Kundu (2022) state that the metaverse is the DT of a workspace. The definitions of metaverse in literature are various, as reported in Table 1.

Definitions
(Stephenson, 1992): A persistent, immersive 3D virtual environment in which everything from business to entertainment could be engaged in by any user, anywhere in the world, with access to a terminal.
(Collins, 2008): Multiple and myriad digital mirrors of the real world existing alongside multiple and myriad digital worlds that do not represent the real world, all used for a variety of purposes, tied into a variety of communication methods, and populated by any user with Internet access, as well as a steady stream of data originating from objects and devices in the real world.
(He et al., 2023): The metaverse is a shared virtual three-dimensional world that is interactive, immersive, and collaborative.
(Arif and Nurhayati, 2022): Metaverse is a medium with a virtual environment that allows users to connect, communicate, work, learn, play, and transact like in the real world. In addition to improving the immersive learning experience, metaverse also enhances the interactive learning experience for students.
(Almarzouqi et al., 2022): Metaverse system is a digital space accessible through a virtual environment that allows people to enjoy immersive experiences and interactions.
(Siyaev and Jo, 2021): Being a mirror of the real world with enhanced features, metaverse provides assets and values in digital form various industries can benefit from. […]The Metaverse as a term is used to describe the concept of a future iteration of the internet, made up of persistent, shared, 3D virtual spaces linked into a perceived virtual universe.

Table 1: Literature definitions of metaverse

It is clear that the metaverse is about user experience and involvement, many definitions use the terms "immersive virtual reality experience" (or similar) (Almarzouqi et al., 2022; Collins, 2008; He et al., 2023). As Park and Kim (2022) state, the metaverse is not about 3D rendering of physical systems, but it is about offering services to users and has a social meaning, i.e. it is a virtual place where people can interact and share experiences. The metaverse entails:

- 3D imaging and display (He et al., 2023);
- live and remote (one-to-one or one-to-many) interactions, where participants can remotely see and interact as if they were together, in the forms of live streaming (e.g. participating to 3D vocal concerts streaming, family gatherings, design meetings, online courses …), remote consultations, and others (He et al., 2023);
- Virtual settings with user interaction methods (Almarzouqi et al., 2022);
- Interoperability of various virtual tools, through gateways (the metaverse can be thus seen as a unified portal to connect different tools and virtual worlds) (Almarzouqi et al., 2022; Lee et al., 2021; Siyaev and Jo, 2021);
- Synchronous access of a theoretically unlimited number of people (Almarzouqi et al., 2022).

Manufacturing companies willing to explore the potentialities of metaverse should take into account that (Almarzouqi et al., 2022; Lee et al., 2021):

1) it demands highly skilled workforce to be able to correctly deploy and operate it;
2) it requires new models of leadership and management;
3) it necessitates a technological data infrastructure that is reliable and persistent, because all data interactions should be stored properly (which include communications, payments, user identity, history, objects, and entitlements …). All information should be accesible even after the involved users exit from the virtual reality;
4) it can be the venue for simulation of equipment, systems and for the collaboration of various departments of the company;
5) it can be accessed by and used to connect different devices, such as wearable devices for the operators, robots, but also personal laptops and tablets, mobiles; all devices that could have a virtual access to personal avatars in the metaverse for the users.

According to various authors, the role of the metaverse for the industry may be huge. As examples, it can be used for training operators on simulated environments in the place of expensive or very heavy equipment, with the possibility to interact among trainers and trainees, saving considerable amounts of money (Siyaev and Jo, 2021). According to Lee and Kundu (2022), other processes, such as maintenance activities, launch of new manufacturing systems, remote monitoring and control could also be supported by the industrial metaverse.

3.2 History and definitions of Digital Twins

DT is a digital representation of a physical system, with the ability to synchronize the digital information to the physical system throughout its whole life cycle (Grieves and Vickers, 2017). Within the Industry 4.0 paradigm, particularly in the manufacturing field, the DT has a specific role; it uses simulation and mathematical models, sensed data, and real-time data to mirror the physical system in order to forecast and optimize production process activities in real time at each life cycle stage (Cimino et al., 2019; Kritzinger et al., 2018). A draft of NASA's technical roadmap from 2010 contains the first mention of the term DT which was also referred to as "Virtual Digital Fleet Leader" (Singh et al., 2021). The definition of DT was created by NASA, who defined it as "an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin" (Singh et al., 2021). Ever since multiple definitions have emerged in literature. One of the characteristics of the DT is stated in (Schleich et al., 2017): the ability to forecast the system's reaction to an unforeseen event before it happens. By contrasting the analysis of these occurrences and the present response with the behavioral predictions that were established, predictions of this kind can be formed. A DT in its full shape can be reached depending on the capabilities of data sharing and collection as well as the thoroughness of the simulations used (Errandonea et al., 2020).
The DT has received attention for its capabilities and potential of linking the physical world to the virtual world. A sample of the definitions in literature is presented in Table 2.

Definition
(Gabor et al., 2016): Special simulation, built based on the expert knowledge and real data collected from the existing system, to realize a more accurate simulation in different scales of time and space.
(Bajaj et al., 2016): A unified system model that can coordinate architecture, mechanical, electrical, software, verification, and other discipline-specific models across the system lifecycle, federating models in multiple vendor tools and configuration-controlled repositories.
(Negri et al., 2017): The Digital Twin (DT) is the virtual and computerized counterpart of a physical system that can be used to simulate it for various purposes, exploiting a real-time synchronization of the sensed data coming from the field.
(Tao et al., 2018): Integrated multi-physics, multiscale, and probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin.
(Cimino et al., 2019): Virtual copies of systems that are able to interact with the physical counterparts in a bi-directional way.
(Lu et al., 2020): Acting as a mirror of the real world, provides a means of simulating, predicting and optimizing physical manufacturing systems and processes.

Table 2: Literature definitions of Digital Twin

A variety of definitions have been discussed for the DT ever since its introduction. However from the definitions and applications a few characteristics can be deduced, mainly (Tao et al., 2018, 2019; Al-Sehrawy and Kumar, 2021; Negri et al., 2021): (i) *Bi-directionality*: the physical product 'intelligence' is increased to actively modify its real-time behavior in response to the 'recommendations' given by the virtual object. While the virtual product can be enhanced to be more realistically representative of the physical product's actual state. (ii) *Simulation models*: DT opens the pathway towards real-time simulation. (iii) *Horizontal integration*. (iv) *Vertical integration*: Combining every stage of a single system's lifecycle and subsequent lifecycles of systems with a similar domain. (v) *Fidelity*: The mirroring level of virtual object to physical object and viceversa. (vi) *Field synchronization*.

3.3 History and definitions of Digital Thread

The term 'digital thread' first appeared in literature in 2009 by Fulghum et al. (2009) for cyber-security within the aerospace industry. Researchers have continued to study the use of digital thread mainly in aerospace and defense applications (Tuegel, 2012) as the data needed for implementing a model. In literature it has been demonstrated how a digital thread allows to be more efficient in using information that is generated throughout the product life cycle. From planning and design of a product (Hedberg et al., 2022), through fabrication and support (Hedberg et al., 2016), and ultimately end of life decisions (Deng et al., 2021). From a high-level perspective authors agree on the fact that the digital thread is a collection of data that allows to have the right information whenever and wherever it is needed, improving traceability, interoperability, and sharing.
The digital thread has been studied in the aerospace industry heavily. The Aerospace Systems Design Laboratory at the Georgia Institute of Technology has launched numerous initiatives to put the elements of the digital thread into practice and to further study them. Kim et al. (2022) studied the digital thread within a Model Based Systems Engineering framework to show how certification requirements and artifacts are managed. There is an increasing need for cost and time savings since commercial aircrafts are becoming more complicated and sophisticated (Gharbi et al., 2018). The design process is particularly difficult to trace due to the large number of variables, restrictions, and disciplines involved as well as the global scope of commercial aviation firms; due to this, the digital thread has received growing attention for its capabilities to provide a solution to this issue (Gharbi et al., 2018). The interest in the digital thread also filters through to the manufacturing industry in general, where its use for additive manufacturing data management has been studied (Mies et al., 2016) as well as for engineering product design decisions (Singh and Willcox, 2018). While the research articles and industrial projects on the digital thread are on the rise, a more high-level understanding of what it is, and what its roles and functions are, is missing. Due to this lack of standardization the digital thread is related to many other

research and industrial keywords, such as the 'product passport' or the 'digital passport', as well as the DT itself. Sometimes literature uses the various concepts as if they were synonyms. In fact, in literature the relationship between the digital thread and the DT is not fully standardized. Dawes et al. (2019) used the digital thread as a data driven geometry to support the simulation based DT. On the contrary, Podskarbi and Knezevic (2020) analyzed the DT as the main enabler for a digital thread by creating a structured DT that interprets data coming from different sources. In a review performed by Cox et al. (2021) to study the "Digital X" terms available in literature, the term "digital thread" has been found to have multiple definitions revealing the lack of standardization and agreement as to what the term represents. The first real definition for 'digital thread' appeared in 2015 by Kim et al. (2015) where the information and the information path that are gathered and stored when manufacturing a single part are specified as being the digital thread. From 2015 to today, several authors introduced different definitions in literature describing different features for digital thread. For example, Steuben et al. (2016) related the digital thread to a common software tool chain, while Pang et al.(2021) referenced the digital thread as a main tool related to DT. Table 3 is a sample collection of the various definitions of "digital thread" available in literature.

Definition
(Kim et al., 2015): The information and information path that is gathered and stored when manufacturing a single part.
(Steuben et al., 2016): A common software toolchain, known as the ''digital thread''.
(Hedberg et al., 2016): The term "digital thread" to convey the data flows between engineering, manufacturing, business processes and across supply chains.
(Helu et al., 2017): The digital thread links disparate systems across the product lifecycle and through-out the supply chain. It enables the collection, transmission, and sharing of data and information between systems across the product lifecycle quickly, reliably, and safely.
(Sundaram and Brownlow, 2018): The digital thread was created to reflect vertical and horizontal traceability across the functional baselines as well as the physical and logical interfaces with external systems.
(Singh and Willcox, 2018): Digital Thread links information generated from all stages of the product lifecycle (e.g., early concept, design, manufacturing, operation, postlife, and retirement) through a data-driven architecture of shared resources (e.g., sensor output, computational tools, methods, and processes) for real-time and long-term decision making.
(Pang et al., 2021): A digital thread refers to a data-driven architecture that links all information generated and stored within the DT enabling it to flow seamlessly through the entire PLM phase from invention to disposal.

Table 3: Literature definitions of digital thread

As emerges from Table 3, the given definitions incorporate different concepts. Authors seem to agree on these characteristics of the digital thread: (i) the definitions are restricted to data and information; (ii) the main function is linking separate entities; (iii) the lifecycle perspective. Some authors used keywords such as 'information path' (Kim et al., 2015), 'software toolchain' (Steuben et al., 2016), and 'digital flows' (Hedberg et al., 2016) to give a more precise definition. The key functions of the digital thread are:

1. Linking or sharing information across the product lifecycle (Helu et al., 2017; Pang et al., 2021; Singh and Willcox, 2018);
2. Collecting and storing data and information (Helu et al., 2017; Kim et al., 2015);
3. Allowing for traceability (Kim et al., 2015; Sundaram and Brownlow, 2018).

3.4 History and definitions of Asset Administration Shell

The AAS was brought forward in 2016 as an element of the so called 'Industry 4.0 component' defined within the Reference Architectural Model of Industry 4.0 (RAMI 4.0). The 'Industry 4.0 component' is meant to describe every Industry 4.0 asset with its accompanying AAS that provides a description of the asset in the digital world. The AAS is represented in a lightweight and easy to share .aasx file format. The Plattform Industrie 4.0 introduced a metamodel for the standardization of the information model of the AAS, within this metamodel the AAS is made up of a Header and a Body. The Header provides information regarding the identification of AAS and assets while the Body is made up of submodels and submodels' elements that represent the description of the asset. The creation of AAS models can be done using various methodologies: using customized techniques such as mapping AAS elements to OPC UA nodes (Cavalieri and Salafia, 2020), or pre-existing open source tools that simplify the creation methodology like the AASX Explorer (github.com/admin-shell-io) or Papyrus (www.eclipse.org/papyrus). Research within the AAS is still focused around understanding its diverse application methodologies and its technical and modelling capabilities. A stream of literature is studying the role of the AAS in Industry 4.0 and its connection with other digital technologies, especially the DT. In scientific literature, the AAS is often used interchangeably with DT, even though its analyzed characteristics do not match those of the DT, and is better suited to be a supporting information tool or model (Abdel-Aty et al., 2022). Yet, the relationship between these two digital technologies is complex and requires further investigation(Quadrini et al., 2023). Within literature there seems to be an agreement on what an AAS is and its role in the Industry 4.0 paradigm. It is well agreed that the AAS is an essential element of the Industry 4.0 component along with the asset it represents virtually. Table 4 presents an outlook on the definitions in literature.

Definition
Industrie 4.0 Plattfform: Digital representation of an asset.
(Wagner et al., 2017): Virtual digital and active representation of a I4.0 Component in an I4.0-System.
(Ye and Hong, 2019): Virtual digital representation of the I4.0 asset that plays a pivotal role in establishing communication among I4.0 Component.
(Khan et al., 2017): AAS gives a digital representation of all information being available about and from physical component.

Table 4: Literature definitions of AAS

3.5 Remarks

After reviewing the definitions of the analyzed concepts in literature, it is now possible to discuss the initial challenge that motivated the paper in the introduction: what is the difference in the analyzed concepts if all of them can be generically referred to as "digital representations of physical systems"? It is clear that the capability to mirror the real world in the virtual reality is actually conceived at different levels, as it will be better detailed in Section 4.

The metaverse can be considered a reflection of the real world, but it may also be independent of it (He et al., 2023). It could expand to a "fully invented" virtual world, where experiences and interaction methods do not have counterparts in the real world, except from the connection with the user who is a real person and accesses it with a virtual avatar.

This is different from the concept of DT, which is synchronized with the system and also has feedback loops that actuate decisions on the real system (Kritzinger et al., 2018). It is true that Borangiu et al. (2020) state that, even if the connection between the DT and the real world would drop, the DT won't stop existing, however, it is not the "natural" state of the DT with respect to the real system, it is more a transition phase while waiting for the bi-directional connection to be re-established.

The Digital Thread and AAS are supposed to be updated on the current status of the system, despite having a sort of versioning storage, to host also all information of the system from the past and to be able to store the history of data and information coming from the whole lifecycle of the system.

4. ROLE WITHIN THE MANUFACTURING SYSTEMS

From what stated in Section 3, it is necessary to better clarify the differences between the analyzed concepts. The current Section proposes a framework that gives a hierarchical view on the relationships, the functions and the roles of the key concepts under analysis, i.e. the metaverse, DT, digital thread, and AAS, in CPS-based production systems.

To the authors' view, the key concepts are on different hierarchical levels, each level representing a piece of the puzzle of the level above.

The ***metaverse*** is a digital universe parallel to the physical one, in which "theoretically infinite" content is developed and cooperatively operated by all users (Lin et al., 2022). It is a virtual world that connects different tools to offer a very wide range of experiences to the users. The ***DT*** are "building blocks" of the metaverse, namely the part which contains the models to represent the reality in virtual form and the synchronization to the real world to keep the models mirror the reality. As example, it contains the simulation models or the data-driven algorithms. Therefore, it contains the structural knowledge about the physical system that is represented, or the algorithms to obtain it from the data and with the synchronization the contingent information are kept updated. It can be considered building blocks of the metaverse because the latter does not only contain models representing the reality, as remarked in section 3.5, but may also contain models not represeting reality; so the metaverse can include one or more DTs and a series of other platforms, software tools, accesses and interfaces to grant the user experiences and interactions, that are not covered by the DT.

In order to be able to effectively represent a physical asset virtually, the DT needs a supply of data and information, this is provided by ***digital threads***. Multiple digital threads provide the DT an aggregate approach to data from various parts along the product lifecycle and throughout multiple lifecycles of the same asset. So the digital thread stores data and information to support the DT, but this concept is not overlapping with DT, as digital threads do not contain simulation models nor data-driven models nor algorithms. In the proposed framework, the digital thread is not a building block of the DT, it rather acts as a supporting tool/mechanism that provides the DT a wide variety and volume of data and information from multiple different sources. In fact, the DT does not depend on being connected to a digital thread. However, the connection between the DT and digital thread opens up exciting capabilities.

The ***AAS*** is a "building block" of the digital thread, being a specific data and meta-data model with predefined standards and formats which compose the digital thread of an asset.

Having sketched the various levels, it is clear that each level offers a different role and function within the digital representation of CPS-based production systems, as reported also in Figure 1.

Metaverse: The main **role** can be described as providing accessibility to expand the human experience within the digital world; its **function** is to offer the main access point for humans and allowing the human-experienced interlace of the physical with the digital world and the interactions of various users on the digital world.

DT: To define its **role**, the authors took the DIKW pyramid introduced in 1988 as reference (Ackoff, 1989), which represents the relashionships between data, information, knowledge, and wisdom. The role of the DT is to use the data and information provided by the digital thread to generate knowledge and wisdom about the system, thanks to the simulation capabilities of what-if analysis, predictive modeling, also thanks to the synchronization with the real world. While data, information, and knowledge deal with the past (i.e what happened and what is known, connected to the descriptive and diagnostic functionalities of the DT), wisdom deals with the future (connected to the prediction and prescription functionalities of the DT). Its **functions** are to monitor (descriptive and diagnostic functionalities), support optimization, test and predict (predictive and prescriptive functionalities) production processes throughout its lifecycle process (Agrawal et al., 2022).

Digital Thread: The **role** of the digital thread is the collection, management, and sharing of the data and information along the product or process value chain. Raw data is obtained from the field from sensors or IoT devices and stored in the AAS level, in the digital thread data is transformed into information by ascribing a meaning to them. Its **function** is to provide data and information to DT, and to grant data sharing, and traceability capabilities.

AAS: its **role** is to support the digital thread being a data and meta-data structuring and management tool. While the digital thread is treated as an all-encompassing term for a collection of artifacts that allow data sharing and interoperability, the AAS already has a specific metamodel, as discussed in section 3.4, that provides the **function** of data structuring, standardization, and interoperability. Along with the easy-to-share format and submodel structure, the AAS offers also the function of allowing data collection and exchange with various stakeholders due to the efforts of standardizing its data structure by various platforms and authors in literature.

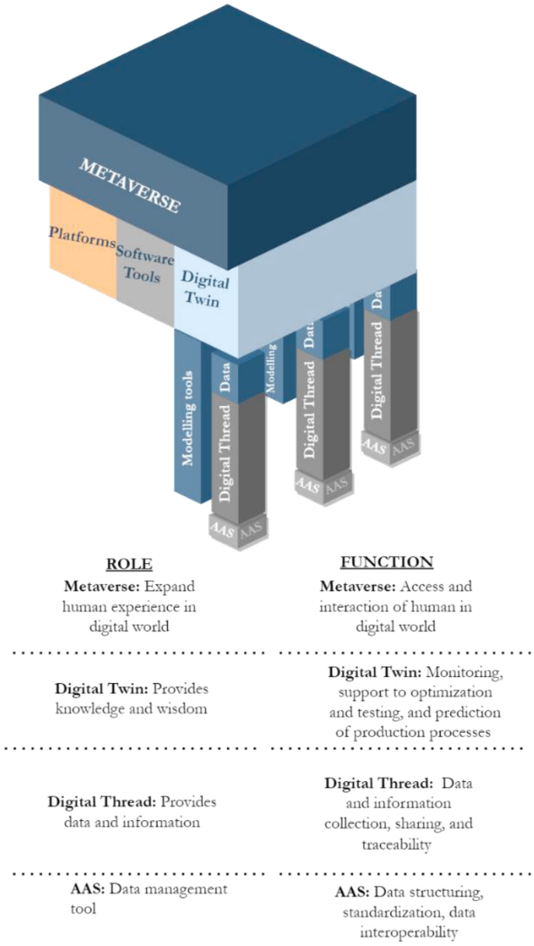

Figure 1: Framework of relationships, roles and functions of the Metaverse, DT, AAS, digital thread for production systems

5. CONCLUSIONS

This work aimed to clarify the relationship between the concepts of metaverse, DT, digital thread, and AAS for CPS-based production systems, as many times these concepts are generally referred to as "digital representations of real systems" with overlapping usage and definitions in the literature. The history of each term has been analyzed followed by a presentation of the most common definitions found in literature. Following this analysis, a hierarchical view on the relationships between them has been proposed where: (i) the metaverse represents the digital world as experienced by the user, made up of several building blocks, including the DT; (ii) the DT contains the models to represent the reality in virtual form and the synchronization to the real world to keep the models mirroring the reality; (iii) supplying a stream of data and information to the DT is the role of the digital thread as a data and information support tool; (iv) finally the AAS is a building block of the digital thread represting a tool to allow its implementation and deployment. The roles and functions of each technology have also been presented within the hierarchical view proposed.

This work provides researchers and practitioners a first contribution for a clearer understanding of the roles, the functions and relationships between these digital technologies on which more discussion and practical validations can be built. The standardized understanding proposed by the framework encourages collaborations between practitioners and researchers based on a shared understanding of the discussed concepts, hence fostering innovative solutions that are tailored to the specific needs of their industry.

The potentialities of future works based on this initial contribution span into different fields. One of the most promising is to study the importance of ensuring digital continuity, through the various levels of AAS for digital thread as enabler of an effective circular production approach. Having the relevant data and information stored at micro, meso and macro level, throughout the whole lifecycle of products, services and CPS-base production systems, and then connecting them to higher levels of Digital Twins and metaverse, allows users to make informed, more accurate and globally-optimal decisions for a more sustainable production.

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