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SURVEY

Digital Thread for Smart Products: A Survey on Technologies, Challenges, and Opportunities in Service-Oriented Supply Chains

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ABSTRACT In Smart Manufacturing, the recent opportunities provided by the Information and Communication Technologies have paved the way to a seamless connection of the manufactured product throughout its entire lifecycle, leading to the diffusion of the concepts of Smart Product and Digital Thread, which leverage digital technologies to assure a continuous flow of data encompassing the design phase of a product, manufacturing, operation, maintenance and also its eventual disposal or recycling. This compelling need to obtain a unified view of information associated with Smart Products has stimulated the so-called Internet of Services (IoS) paradigm, allowing for the sharing of products data and the execution of functions among various participants in intertwined supply chains. In these contexts, service-oriented architectures are being more and more employed to meet the complex and ever-evolving data analysis requirements, particularly when implementing Digital Thread solutions for Smart Products, where several issues must be considered, ranging from the heterogeneity of (Big) data to data sovereignty and data access policies, as information may cross the borders of multiple actors participating in intertwined supply chains. This survey discusses about the technological solutions and challenges to implement Digital Threads for Smart Products in Smart Manufacturing contexts, providing insights on opportunities for future research directions. In addition, the survey proposes a comprehensive multi-tier service-oriented architectural model to jointly tackle (Big) data heterogeneity, data sovereignty and data access policies issues, as they are only partially addressed by the research efforts examined in the literature review.

INDEX TERMS Service-oriented architectures, smart products, digital thread, Internet of Services, cyber-physical production network, smart factory.

I. INTRODUCTION

Stimulated by the wave of innovation and opportunities in Smart Manufacturing, enterprises have witnessed significant vertical integration, spanning from the shop floor to the business level. In this landscape, Smart Products play a pivotal role in the evolution of Smart Factories, as they are equipped with technology specifically designed to enhance the production processes, facilitate communication and integration across the manufacturing ecosystem. This integration eases the collection, management, and analysis of data, transforming it into actionable insights through data-driven applications [124]. A recent opportunity in the industrial scenario, enabled by the potentiality of Smart Products, is the Digital Thread, conceived as a continuous flow of data to connect and integrate information associated with various stages of a production process, throughout the entire lifecycle of a product. It represents an evolution of the traditional

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concept of the Digital Twin of the product [78], offering an integrated and dynamic perspective of a product lifecycle, serving purposes such as traceability, quality assurance, monitoring, and production optimization. This compelling need to obtain a unified view of information associated with manufactured products has stimulated the so-called Internet of Services (IoS) paradigm which, along with the Internet of Things (IoT), facilitates a shift from vertical towards horizontal integration and seamless collaboration both within the borders of a single actor of a supply chain (i.e, in a Cyber-Physical Production System, CPPS) and across intertwined supply chains (i.e., in a Cyber-Physical Production Network, CPPN). In particular, the IoS paradigm allows for the sharing of data by encapsulating business functionalities as *services* within *service-oriented architectures* apt to meet the complex and ever-evolving data analysis requirements of supply chain actors [49]. Nevertheless, when implementing Digital Thread solutions for Smart Products, several data-related aspects have to be considered, ranging from the heterogeneity of (Big) data (which may undermine the scalability and modularity of service-oriented architectures) as well as data sovereignty and data access policies (due to the fact that information may cross the borders of multiple actors, in turn participating in intertwined supply chains) [12].

A. COVERAGE OF EXISTING SURVEYS

In the literature, there is a plethora of surveys presenting the capabilities and principles of Smart Manufacturing, along with related key enabling technologies and research streams (e.g., [59], [108], [128], [140]). Nonetheless, they discuss on the challenges of Smart Manufacturing from a high viewpoint, not specifically directed towards achieving the implementation of a Digital Thread. In a similar way, literature reviews and surveys made upon research efforts dealing with the transformation of products into services to enhance customers' value and revenue, fostering the so-called *servitisation* paradigm [141], are out of the scope of our analysis, being the servitisation a concept originating from a business perspective. Indeed, in our survey we conceive services under an information technology and software engineering perspective. Complying with the premises above, we discuss in the following about surveys explicitly focusing on Digital Threads or mentioning techniques for implementing a Digital Thread. A summary of the contributions of each survey is detailed in Table 1. The review of Mies et al. [85] discusses on how to achieve a Digital Thread with data-driven approaches to enhance the scalability, quality, and reproducibility of additive manufacturing to support qualification objectives. The survey of Bonnard et al. [17] presents the state-of-the-art data models employed for Digital Thread, advocating the need for a more advanced and adaptable Digital Thread data model, to address the complexities and requirements of the Additive Manufacturing community. Schlemitz et al. [6] surveys the technologies and approaches to foster interoperability in smart manufacturing environments, with a particular emphasis on the integration strategies with the Industrial Internet of Things and Digital Threads. Abdel-Aty and Negri [1] survey technologies, roles, and functions of a Digital Thread throughout the product lifecycle, suggesting a theoretical framework to highlight the importance of a seamless data flow in the manufacturing process of a product. Zhang et al. [138] investigate on the existing definitions of Digital Thread from the literature, highlighting the rationale behind key technologies, and present several application scenarios which would benefit from the adoption of a Digital Thread paradigm.

B. MOTIVATIONS AND RESEARCH QUESTIONS

As evidenced from Table 1, most of the existing surveys focus on vertical aspects of a specific research area, disregarding a thorough analysis under the perspective of achieving a Digital Thread in Service-Oriented supply chains. In addition, when proposing architectural models for Digital Thread, the surveys in Table 1 often lack a detailed consideration of the inherent data-related challenges that have to be taken into account, such as *Big Data* and *data heterogeneity*, along with issues of *data sovereignty* and *data access policies*. This survey represents an attempt to provide a comprehensive overview of how the former data-related challenges are addressed into solutions for achieving Digital Thread implementation. Since Smart Products play a pivotal role in achieving a Digital Thread, this survey also provides a high-level overview of characteristics Smart Products should adhere to for a Digital Thread. The expected targets of this survey are young researchers and practitioners, who are approaching the problem of investigating Smart Products and Digital Thread challenges in the factories of the future. In fact, given the highly fragmented landscape of approaches in literature, which address specific aspects, an overview of methods and techniques for Smart Products and Digital Thread data management, from the collection to the analysis, is still missing. Therefore, through this survey, we aim to answer the following Research Questions (RQs):

RQ1 What are the distinctive characteristics of Smart Products and how do they relate to the implementation of a Digital Thread?

RQ2 How is the service-oriented paradigm fostered in the research efforts apt to Digital Thread implementation?

RQ3 To what extent data management issues are addressed (with a particular concern on Big Data heterogeneity, data sovereignty, and data access policies)?

RQ4 Does a widely adopted and universally recognised architectural model for implementing Digital Threads exist?

RQ5 What are the current gaps, limitations, and future research directions regarding Digital Thread for Smart Products in service-oriented supply chains?

TABLE 1. **Summary of existing surveys on digital threads under a service-otiented technological perspective (✓: coverage provided, ~ partial coverage, ✗: coverage not provided).**

Survey work	**Year**	**Scope**	**Analysis of Smart Products characteristics (RQ1)**	**Service-orientation design principles (RQ2)**	**Data-related issues (e.g., modelling, heterogeneity, sovereignty, access policies …) (RQ3)**	**Proposes architectural model for DTH (RQ4)**	**Future research directions and opportunities (RQ5)**
Mies et al. [85]	2016	Review on data-related issues for Additive Manufacturing Digital Threads	✗	✗	~ (Data capturing)	✗	✗
Bonnard et al. [17]	2019	State-of-the-art data models for Digital Thread	✗	✗	~ (Data models)	✗	✓
Schlemitz et al. [6]	2024	Data collection and process standardisation for Digital Threads	✗	✗	✗	~ (Integration framework)	✗
Abdel-Aty et al. [1]	2024	Baseline concepts for Digital Thread and proposal of a theoretical design framework	✗	✗	✗	~ (Theoretical framework)	✗
Zhang et al. [138]	2024	Technologies for implementing the Digital Thread and application scenarios	✗	✗	✗	✗	✓
Our survey	2024	Digital Thread for Smart Products: fundamentals, existing architectures, data-related issues and architectural model proposal	✓	✓	✓	✓	✓

C. ORGANIZATION OF THE SURVEY

This paper is structured as follows: in Section II, we introduce background definitions and fundamentals, related to multi-tier architectural models, service-oriented design principles, along with the challenges in Smart Products and Digital Thread implementation. Section III discusses about the methodology fostered to conduct the literature review, along with inclusion and exclusion criteria. Section IV presents the literature concerning Smart Products as data providers and service-oriented architectures for CPPN (including aspects related to service composition, data management and data modelling). These sections answer **RQ1** to **RQ4**. Section V illustrates the service-oriented architectural solution we propose to enable Digital Thread for Smart Products, considering data heterogeneity, sovereignty, and access policies issues. Section VI provides insights on future research directions tightly coupled with the themes discussed in this survey. These two sections strive to address **RQ5**. Finally, Section VII closes the paper.

II. BACKGROUND DEFINITIONS AND CHALLENGES

In this section, we present an excerpt of the background knowledge apt to support the comprehension of the contents of this survey, considering the aforementioned concepts, that is: (i) reference multi-tier architectural models employed for information integration, at the basis of Digital Thread solutions (Section II-A); (iii) foundations of service-oriented design principles, apt to develop the solution logic of services within Service-Oriented Architectures (Section II-B); (iv) characteristics and design principles of Digital Threads and Smart Products (Section II-C). To conclude, this section provides insights on the challenges and threats to Digital Thread implementation that have been investigated in the scope of this survey (Section II-D).

A. MULTI-TIER ARCHITECTURAL MODELS

Different reference architectural solutions have been suggested in the literature for the integration of information throughout the entire lifecycle of a product to accomplish the Digital Thread paradigm. Nonetheless, there is no single unified architecture that is used across all industrial sectors and application contexts. Despite adopting their own ad-hoc solutions, a widely-recognised paradigm adopted in Digital Thread information integration consists in organising architectures over multiple layers (also referred to as *tiers*) [44], [53], [63]. Multi-tier architectures are software architectures leveraged to divide an application into multiple logical layers (tiers), each of them responsible for specific functionality, in compliance with the renowned *separation of concerns* design principle. Multi-tier architectures offer several advantages, including scalability and maintainability, ensuring that changes made to one tier do not affect the others, thus providing a structured approach to building complex applications. In the following, we recall the description of the most common multi-tier architectures used in industrial scenarios for Digital Thread (i.e., the three-tier, four-tier and

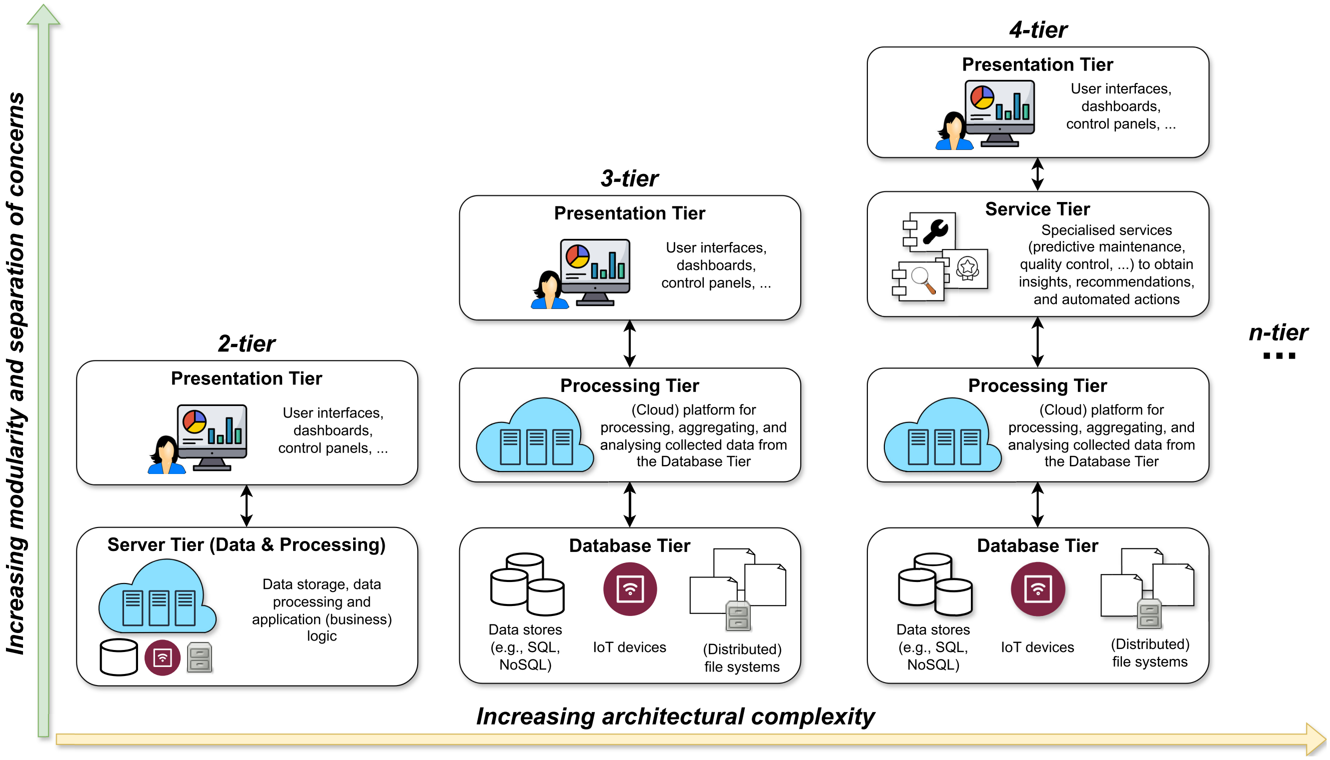

FIGURE 1. Evolution of multi-tier architectures for smart manufacturing application scenarios.

n-tier architectures, illustrated in Figure 1) sketched in [53]. Noteworthy, **one-tier** and **two-tier** legacy architectures are no longer being used in Smart Manufacturing scenarios, due to their limited connectivity and synchronisation capabilities, hindering the efficiency of data-driven applications.

1) THREE-TIER ARCHITECTURES

In industrial contexts, a typical three-tier architecture comprises: (i) a *Database Tier*, (ii) a *Processing Tier* and (iii) a *Presentation Tier*, containing specialised client applications used to access other tiers. The Processing Tier acts as an intermediary between the database and the client, providing access to business logic mechanisms that generate dynamic content from the Database Tier. By decoupling these logic mechanisms from the client, a three-tier architecture simplifies client design and streamlines IT maintenance and functionality upgrades. In the industrial landscape, three-tier architectures have facilitated the development of solutions like Product Lifecycle Management (PLM), Manufacturing Execution System (MES), and Enterprise Resource Planning (ERP).

2) FOUR-TIER ARCHITECTURES

A four-tier architecture leverages the principles and organisation of three-tier architectures but introduces an additional tier to further segregate and manage functionalities. Therefore, the resulting tiers, from the lowest to the highest, are: (i) the *Database Tier*, where data is stored and managed; (ii) the *Processing Tier*, acting as an intermediary between the database and the upper tiers, accomplishing the execution of business logic; (iii) the *Service Tier*, the newly introduced tier (with respect to the three-tier architecture) that provides specific services and functionalities (e.g., data processing, analytics, or integration with external systems) to the upper applications; (iv) the *Presentation Tier* gathering various user applications and interfaces exploited to access and interact with the underlying data through the Service Tier. In four-tier architectures, the Service Tier processes data to deliver insights, recommendations and automated actions. Typically, four-tier architectures are employed in Smart Manufacturing contexts to ease the implementation of IoT technologies and Big Data analytics, capitalising on the inherent scalability and modularity of the architecture to manage intelligent manufacturing systems.

3) N-TIER ARCHITECTURES

Architectures with more than four tiers are commonly employed to ensure robust frameworks for building large-scale, enterprise-grade applications. The additional tiers are devoted to accomplishing a finer-grained separation of concerns and specialisation of provided functionalities, enabling organisations to design highly distributed and scalable systems capable of handling diverse workloads and requirements. Generally speaking, these systems have to meet the evolving needs of modern businesses across various intertwined supply chains. For instance, additional specialised tiers can be added to encapsulate the core business logic and rules governing the application behaviour (*Business Logic Tier*) and to facilitate communication and data exchange between different subsystems, applications, and external services (*Integration Tier*).

B. SERVICE-ORIENTED DESIGN PRINCIPLES

As formerly mentioned, four-tier and n-tier architectures are advocated in Smart Manufacturing contexts as they boost flexibility and enhance data integration capabilities. In these architectures, the functionalities offered by the *Service Tier* are deployed adhering to the so-called *service-oriented design principles*, whose foundations are described in the following paragraphs.

1) SOA DESIGN PRINCIPLES

The aforementioned service-oriented design principles are the cornerstone of a software design approach called *Service-Oriented Architecture* (in brief, SOA) [97]. Applications designed according to a SOA are composed of interoperable and reusable *services*. Roughly speaking, a service is a self-contained, loosely coupled module that performs specific functions and communicates with other services (e.g., over a network). In SOAs, services are conceived as independent entities from the underlying platform and, more generally, from the whole technology stack. SOAs meet the flexibility, scalability, and reusability of four-tier and n-tier architectures, by decomposing complex applications into more manageable components (services), which can be developed, deployed, and maintained independently, allowing for easier updates and modifications without impacting the whole architecture. In the following, we list the SOA principles descending from [39]:

- **Loosely Coupled** – since the interaction between services in an SOA leverages standardised interfaces, thus assuring an independent evolution;
- **Reusability** – as services are, by design, reusable across different application scenarios, reducing coding redundancy;
- **Discoverability** – in a SOA, services are collected in a *registry*, a directory allowing applications to easily discover and invoke them;
- **Interoperability** – as, through the employment of services, different systems and technologies can be connected together by using standardised protocols and data formats for communication.

2) SOA ROLES

A SOA is characterised by three main roles, namely the *service provider*, the *service requester* or *consumer*, and the *service registry*, which are illustrated in Figure 2 and briefly described in the following.

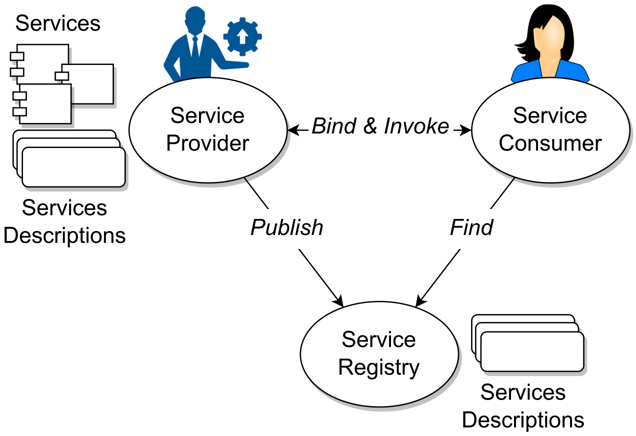

FIGURE 2. Service-oriented architecture roles and mutual interactions.

- **Service provider.** This actor is responsible for creating, implementing, and hosting services that offer specific functionalities or capabilities. Moreover, this actor has to ensure that services are available, handling also service deployment, versioning, and management. For instance, in the scope of a CPPN, providers may be the actors of a supply chain.
- **Service consumer.** This actor issues requests for services provided by other components or systems within the SOA. The interaction with services is based on sending requests and receiving responses over the network, leveraging interfaces to invoke functionalities offered by the service providers. Again, in a CPPN, consumers are the actors of the supply chain, (also referred to as *prosumers* if they are simultaneously providers and consumers of services).
- **Service registry.** It is the central repository (or directory) that holds the information (e.g., metadata) about available services within the SOA. It allows service providers to publish their services and for service consumers to discover the services they need. Metadata contained in the registry ensures service discovery and invocation. Examples of service registries are UDDI (Universal Description, Discovery, and Integration) registries [27], directories in API gateways, or custom-built service catalogues within organisations.

3) MICROSERVICES

A recent architectural trend in service design is the adoption of Microservice-oriented Architectures (MOAs). Unlike traditional SOAs, MOAs emphasise loosely coupled, lightweight services specifically designed to perform discrete functionalities. This approach involves developing an application as a collection of small, independent services, each running in its own process and communicating through lightweight mechanisms, often via HTTP-based resource APIs [122]. In this respect, microservices enhance modularity, flexibility, and ease of maintenance in large-scale software systems, allowing developers to work on different parts of an application independently, using frameworks and data stores best suited for each service. This approach also enables rapid development, distribution across multiple nodes and fault isolation, since a failure in a single microservice is less likely to impact the overall architecture.

4) SERVICE COMPOSITION

As the complexity of services continues to grow, managing interactions and coordination among different services becomes increasingly challenging. Consequently, service composition stands out as a pivotal challenge in both Service-Oriented Architectures (SOAs) and Microservice-oriented Architectures (MOAs) [34], [70]. Service composition enables developers to leverage existing service functionalities to rapidly build and deploy new applications, promoting modularity, reusability and interoperability by allowing services to be combined and reused across different deployment ecosystems and applications. Recalling the aforementioned service-oriented design principles, service composition supports the concept of loose coupling, since services remain independent and can be easily replaced or updated without affecting the overall system functionality. Two well-established patterns for service composition are *orchestration* and *choreography*. Orchestration ensures centralised control, enforces business logic, and provides transactional support, while choreography is designed for decentralised coordination and collaboration among services, a characteristic often leveraged in MOAs due to the inherent loose coupling of microservices.

C. DIGITAL THREADS AND SMART PRODUCTS

1) DIGITAL THREADS

In modern Smart Manufacturing environments, the concept of *Digital Thread* has emerged as a pivotal paradigm to integrate data collected across the different stages of a product lifecycle. The Digital Thread is referred to as a *transformative* approach, leveraging digital technologies to assure a seamless flow of data encompassing the design phase of a product, manufacturing, operation, maintenance and also its eventual disposal or recycling. Amongst its goals are the enhancing of the efficiency of production processes as well as enabling real-time decision-making (e.g., applying focused optimisation strategies along the supply chain, capitalising on the information extracted by applying data analysis algorithms on the collected data) [138]. In the following, we briefly summarise the main principles revolving around the concept of Digital Thread, which have been promoted by works like [78] and [106].

- **Product data integration** – Different systems, software and data repositories are typically employed to collect product lifecycle data. The Digital Thread paradigm boosts product data utilisation through a seamless data exchange and communication along the product design, production, maintenance and possibly dismission or recycling process, providing the vision of a cohesive and integrated system, overcoming the proliferation of isolated data silos.
- **Real-time data analytics** – The analysis of data generated throughout the product lifecycle ensures to obtain actionable insights which may be exploited by organisations to make proactive decisions (e.g., to predict and address maintenance needs). In a Digital Thread scenario, such data-driven decisions are based on the most current and accurate information available, thus supporting continuous improvement and innovation.
- **Lifecycle transparency** – Data related to a product has to be accessible throughout its entire lifecycle. Transparency refers to the fact that stakeholders would be provided (if required) with detailed insights on the stages of the product lifecycle, ranging over design, manufacturing, and operational processes, thus enhancing accountability and quality assurance. Along with transparency, security measures and access controls may be introduced to protect sensitive information from unauthorised access and tampering (e.g., to ensure compliance with regulatory production standards).

2) SMART PRODUCTS

Generally speaking, a Smart Product (which in literature is also referred to with the more generic term *Smart Object*) is equipped with a set of intelligent components that broaden its capabilities in three main directions [64]: *awareness*, *data representation* and *interaction*. The synergy of awareness, data representation, and interaction constitutes the foundation of the so-called *measurement chain* (an example is depicted in Figure 3), which constitutes the cornerstone of Smart Products development. In the following, we delve into the definition of the three aforementioned Smart Product (SP) characteristics.

a: AWARENESS

First of all, an SP must possess a sophisticated level of awareness, not only regarding its own state but also of the complex and dynamic context in which it operates. This implies a diverse array of *sensors* and *communication devices*, designed to capture and interpret a multitude of parameters essential to the functionality of the SP. These sensors are tightly application-dependent and, apart from the classical physical measurements such as temperature, humidity, and structural integrity, they may also gauge other environmental factors (e.g., sensing the presence of other SPs, relative position, user presence) and statistical data about usage patterns (e.g., number of uses, time of use). By contextualising these raw measurements, an SP can distinguish patterns and anomalies that lead the SP to evolve into a perceptive entity capable of adapting and responding to its environment. As evidenced in Figure 3, awareness of a SP depends on its *sensors* and the *electronics front-end*.

b: DATA REPRESENTATION

Beyond awareness, an SP must be able to properly represent the collected information from sensors in an organic form.

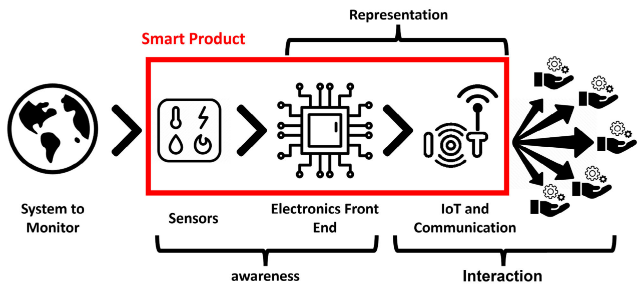

FIGURE 3. **General structure of a smart product measurement chain.**

Representation within a Smart Product is not simply a matter of organising raw sensor data but requires a model that can depict the SP, its operativity and its operational context in order to produce meaningful information. In this respect, an SP can process the raw sensor data and organise it into proper data structures, to achieve useful information that can provide insights into the behaviour of the SP, as well as of its surroundings. Moreover, an effective representation of the collected data allows an easier interoperability of the SP with other systems in the Smart Factory. From Figure 3, data representation depends on the *electronics front-end* and *IoT and communication* parts of the SP.

c: INTERACTION

Lastly, interaction is fundamental since it allows to both capitalise on the data collected from the SP to provide direct feedback to users and, in the scope of a Digital Thread implementation, assure data propagation along the stages of the product lifecycle. The latter point envisages also the interaction between different SPs, thus leading to a flexible and adaptable production ecosystem. With reference to the measurement chain in Figure 3, interaction depends mainly on *IoT and communication*.

D. CHALLENGES IN SMART PRODUCTS AND DIGITAL THREAD IMPLEMENTATION

In this section, we highlight the challenges and threats to Digital Thread implementation that are pivotal for our survey work. These challenges will be also recalled when conducting the literature review, to enable a critical comparison of the surveyed works.

1) SMART PRODUCTS AWARENESS ISSUES

As highlighted in Section II-C, awareness characteristic of Smart Products (SPs) is grounded on sensors and electronics front-end, steering the entire measurement chain. In fact, it is fundamental for both SP data representation and interaction (which enables the sharing of SP data along the phases of the product lifecycle, to achieve a Digital Thread). To ensure a proper degree of awareness in application scenarios like Smart Factories, where SPs may have to be wireless and capable of operating for long periods without human intervention, several concurrent issues should be taken into account and balanced (e.g., the existence of processors embedded in the SP, data transmission protocols and power consumption, the latter influencing any kind of operation performed by a SP [45], [94]).

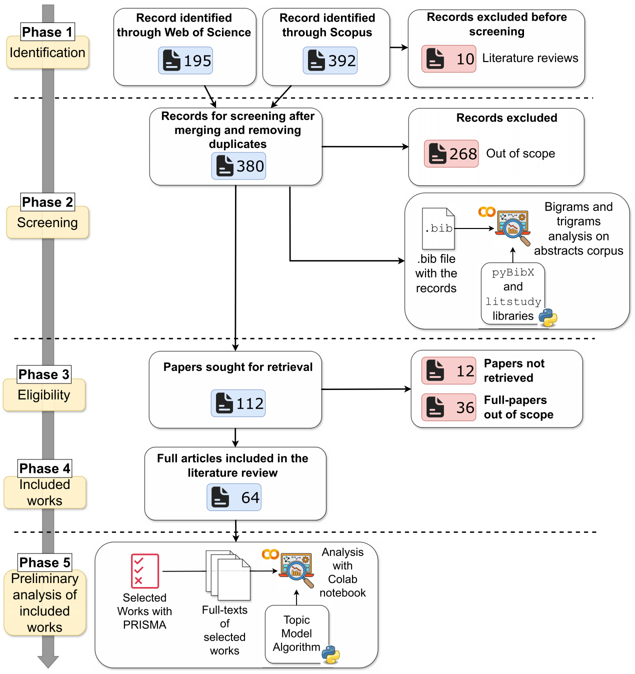

FIGURE 4. **Overview of the PRISMA statement steps.**

2) (BIG) DATA MODELLING AND HETEROGENEITY ISSUES

Data generated across the various stages of the product lifecycle comes from a plethora of sources (e.g., Smart Products, relational databases, NoSQL data stores, legacy systems). In particular, such data is typically referred to as *Big Data* since it is characterised by large volumes, possesses unstructured formats (e.g., semi-structured or unstructured data), and is often generated at high speeds, requiring increased storage and processing capabilities. These characteristics constitute the so-called 3Vs (Volume, Variety and Velocity) of Big Data. Hence, proper storage solutions and technologies apt to cope with the cumbersome nature of Big Data, collected to achieve the Digital Thread, are advocated (e.g., polystores, Data Lakes) and have to be tailored upon the target application domain [115]. Moreover, to enable an effective analysis and exploration of this deluge of Big Data, multi-perspective data models can be employed. For instance, in the case of the product lifecycle, a multi-perspective model enables a holistic view of the data collected during the stages of production, facilitating an in-depth understanding of complex phenomena, patterns, and relationships hidden within the data regarding the product, the related production phases and the industrial assets employed for manufacturing. Analysing data according to multiple perspectives ensures to focus the attention only on the subset of data deemed as important for the analysis made by domain expert users, tackling data variety and offering an intuitive and effective view over available data [55].

3) ROLE-BASED DATA ACCESS POLICIES

Every actor operating in a supply chain has a specific role, depending on the business objective (e.g., a production network usually involves the presence of a production leader, one or more suppliers and so forth). An actor covering a role should have access solely to authorised data pertinent to such role and the source of the data [119]. Generally, the complexity of these access policies is tightly coupled with the organisation of the production network.

4) DATA SOVEREIGNTY AND PRIVACY ISSUES

With the advent of General Data Protection Regulation (GDPR) principles,[1] safeguarding the ownership of data generated by each actor has become of paramount importance, especially in dynamic and complex contexts such as intertwined supply chains, where actors serve different supply chains assuming different roles. Therein, the amount of exchanged data between actors may be significant, and privacy and data protection considerations become essential [5], [52]. In this respect, each actor has to identify which data must be kept private and which data can be shared amongst the actors of the supply chain he/she operates in.

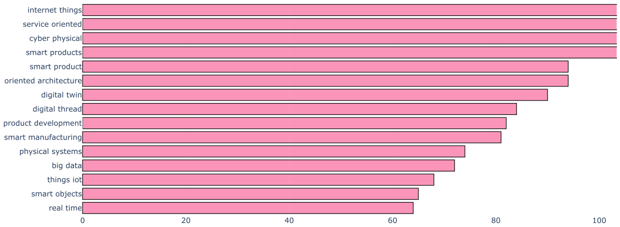

FIGURE 5. Top 15 most frequent bigrams resulting from the analysis of the corpus of 380 abstracts.

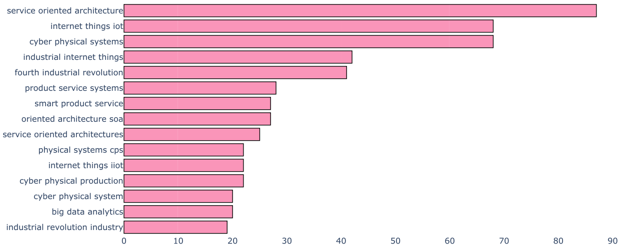

FIGURE 6. Top 15 most frequent trigrams resulting from the analysis of the corpus of 380 abstracts.

TABLE 2. Inclusion (IC) and Exclusion (EC) criteria for the PRISMA approach.

Type of criteria	Definition
IC	Publication year between 2013 and 2023
IC	Papers published in peer-reviewed journals or conferences proceedings (full papers, short papers, poster papers, workshop papers, demo papers, work-in-progress papers)
IC	Paper written in English Language
EC	Description papers (both from conferences and workshops), doctoral consortium papers, systematic literature reviews
EC	Commentary and position papers providing only theoretical discussions

III. REVIEW METHODOLOGY

To perform the survey, a systematic literature review protocol was followed to maximise the reproducibility, reliability and transparency of the results. In particular, the systematic literature review has been conducted following the renowned PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement [87], whose phases and steps are reported in Figure 4. Even though not explicitly envisaged by PRISMA, the latter step depicted in the figure (i.e., the preliminary analysis of included works) has been performed (using Natural Language Processing – NLP – algorithms) to further ascertain that the selected works provide coverage for addressing research questions.

A. THE PRISMA STATEMENT

1) IDENTIFICATION

We chose two reference databases, namely Scopus and Web of Science, as the most popular and widely used databases for academic research and publication [117]. In particular, both databases contain tens of millions of records from tens of thousands of journals, conference proceedings, and book series. This vast coverage ensures access to a plethora of scientific content from different research fields, which is pivotal when conducting a thorough literature review. The query string submitted to the chosen databases (to be searched within the title, abstract and keywords of the papers) contains terms constituting the core topics touched by our survey: (“Digital Thread” `OR` “Smart Product” `OR` “Service-Oriented Architecture”) `AND` “Smart Manufacturing”. The latter part of the query string narrows the search of records to the Smart Manufacturing context. The search was conducted in February 2024 and the records resulting from the queries upon the two databases were aggregated and the duplicates duly removed. Taking advantage of Natural Language Processing (NLP) techniques, the 15 most frequent bigrams and trigrams occurring in the corpus of the abstracts have been found (Figure 5 and Figure 6). In particular, we used the functionalities provided by LitStudy [51] and pyBibX [101] Python libraries, using a Google Colaboratory (in brief, Colab) Notebook to generate the plots. From the figures, it is possible to verify that, before delving into the screening and the selection of the studies, the abstracts

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[1] GDPR is a comprehensive data protection law implemented in the European Union (EU) and the European Economic Area (EEA) that governs the collection, use, and processing of personal data of individuals within the EU and EEA.

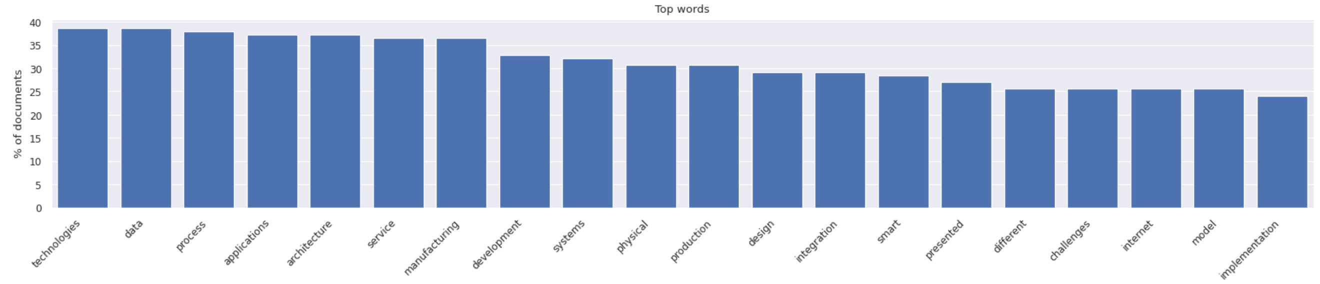

FIGURE 7. Top 20 words distribution for the included works.

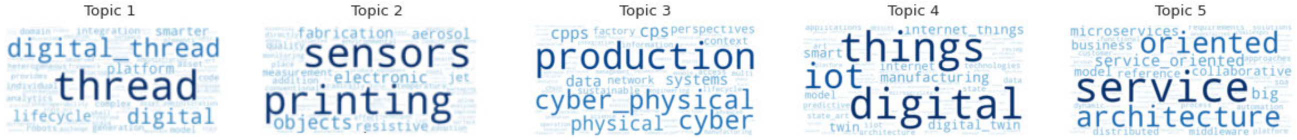

FIGURE 8. Word cloud for the topic model upon the included works.

TABLE 3. Topic model (5 topics) for the included works.

Topic #	Tokens
1	'thread', 'digital_thread', 'digital', 'lifecycle', 'platform'
2	'sensors', 'printing', 'objects', 'electronic', 'fabrication'
3	'production', 'cyber_physical', 'cyber', 'physical', 'cps'
4	'digital', 'things', 'iot', 'manufacturing', 'internet_things'
5	'service', 'oriented', 'architecture', 'service_oriented', 'big'

of the retrieved records appear to frequently mention key concepts related to the terms included in the query.

2) SCREENING AND ELIGIBILITY

Table 2 gathers a summary of the Inclusion Criteria (IC) and Exclusion Criteria (EC) employed for screening the retrieved records. The screening process was conducted independently by two experts fostering the aforementioned criteria. In particular, the two experts organised information related to title, authors, year, publication venue and abstract from each retrieved record into a collaborative spreadsheet. Discrepancies between the two experts were solved through a discussion and, inherently, records of papers not meeting the inclusion criteria were excluded, annotating the motivation in the spreadsheet. Downstream the screening phase, full texts of potentially relevant papers were retrieved and assessed for eligibility by both experts, applying again a discussion to resolve discrepancies. Records without full-texts available have been discarded.

3) INSIGHTS ON INCLUDED WORKS AND DATA EXTRACTION

Before delving into the extraction of relevant information from the included papers to address research questions identified in Section I, *topic modelling* has been exploited to obtain a synthetic overview of the full-text corpus of selected works (i.e., the output of Phase 4, Figure 4). Roughly speaking, topic modelling is an NLP technique that discovers abstract topics in a collection of texts and latent semantic structures, unveiling relationships between words and going beyond a classical frequency analysis to the benefit of interpretation of document content. Indeed, the aim is to further demonstrate that the identified topics in the selected works cover research areas relevant to answering the Research Questions formulated in Section I. In particular, we leverage a topic modelling algorithm to automatically detect a set of topics (maximum number of topics set to 5, to preserve interpretability and utility of results, preventing overfitting and capturing irrelevant patterns in the text), each of them described using a small set of words. Each document was assigned a weight depending on these topics. Figure 8 visually reports the word clouds associated with the identified topics (see Table 3 for details regarding the topics). In the figure, the size of the words indicates the relevance of each word to the topic. The inspection of the word clouds demonstrated and confirmed that the systematic PRISMA approach was successful in narrowing down the focus of the selected publications. Lastly, to complete the review process, additional columns were appended to the collaborative spreadsheet to keep track of relevant information extracted from the included papers to address research questions. Both experts completed the spreadsheet independently. Afterwards, the two spreadsheets were compared and possible differences were discussed until a unique and agreed shared spreadsheet was created to start the literature review presented in the following section.

IV. LITERATURE REVIEW

This section offers a comprehensive overview of the literature identified according to the method discussed in Section III.

Specifically, we organise the discussion in three sections, in turn, associated with three key areas:

- Smart Products as modern devices embedding sensing capabilities for enabling the subsequent collection of data throughout the whole lifecycle of the product (Section IV-A);
- Service-Oriented Architectures (SOAs) and Microservice-Oriented Architectures (MOAs), with a particular focus on their employment in the context of Smart Manufacturing and Cyber-Physical Production Networks (CPPN) and on the usage of service composition to empower the capabilities of service architectures in both customising service solutions and managing the interaction and coordination between services (as discussed in Section IV-B);
- data management issues in CPPN (i.e., Big Data heterogeneity, data sovereignty and data access policies) and data models for providing a holistic view over product lifecycle data (Section IV-C).

A. SMART PRODUCTS

The development of Smart Products (SP) is often proposed in the literature as a way to easily interconnect machines, tools, and workers to rationalise the production process, resulting in a set of distributed data providers along the Smart Factory. Bearing in mind the characteristics of SP presented in Section II-C (i.e., awareness, data representation and interaction), we analysed the literature regarding works employing SPs. In particular, Table 4 gathers papers, identified through the literature review, mentioning the employment of SPs, categorised depending on the three fundamental characteristics steering the development of SPs. By observing Table 4, it appears evident a strong imbalance between the three characteristics of SPs, with data representation and interaction being the most influential in the majority of the research efforts, disregarding awareness (in particular, its metrological components). However, as emphasised in Section II-D, awareness conceals paramount importance in implementing solutions for measuring the most relevant physical quantities across the stages of the product lifecycle to implement the Digital Thread paradigm. To this aim, printed electronics are employed to ensure SPs' awareness, capitalising on their flexibility (due to the high variety of materials) and their ability to embed custom sensors (and electronics) to address target application measurement requirements.

1) PRINTED ELECTRONICS SUPPORTING SMART PRODUCTS AWARENESS

In the literature, different kinds of sensors are currently implemented by printed electronics on SPs. The first possible characterisation is to select them according to the production technology (e.g. micro-dispensing, inkjet printing, aerosol jet printing, piezojet, gravoure) that can present different features that must be taken into account during the sensor design process [14]. On the other hand, a different classification can be performed on the transduction principle. The most notable are: temperature sensors, strain gauges, capacitive sensors and pressure sensors.

TABLE 4. **Classification of works considering the three characteristics of SPs (✓: characteristic supplied).**

Work	Awareness	Data representation	Interaction
[71]	✓		
[133]	✓	✓	
[105]	✓		
[36]	✓		
[118]	✓	✓	✓
[67]	✓	✓	✓
[68]	✓	✓	
[93]			✓
[66]			✓
[60]		✓	✓
[81]			✓
[75]		✓	✓
[112]			✓
[50]		✓	✓
[104]		✓	✓
[74]		✓	✓
[86]		✓	✓
[73]			✓
[123]			✓
[92]			✓
[113]		✓	✓
[139]			✓
[127]		✓	✓
[100]			✓
[65]		✓	✓
[33]			✓
[135]		✓	✓
[132]			✓
[47]		✓	✓
[76]			✓
[83]		✓	✓
[58]		✓	
[79]		✓	
[30]		✓	
[56]		✓	
[116]		✓	
[129]		✓	
[80]		✓	
[137]		✓	
[9]		✓	
[2]	✓	✓	✓
[23]	✓	✓	✓
[26]	✓	✓	✓
[18]	✓	✓	✓
[19]	✓	✓	✓

Among the temperature sensors, different transduction principles are currently presented in the literature. Thermocouples offer precise temperature gradient detection but often lack accuracy in providing absolute temperatures, limiting their utility in many applications. Positive/negative coefficient thermistors (PTC and NTC) are widely researched in printed electronics [40], although their non-linearity and reliance on rigid, non-printable materials pose challenges [22]. On the other hand, resistive temperature detectors (RTDs) vary their resistance based on the bulk resistivity of the constituent material, typically a metal [31], [41], [42]. Fabrication techniques for RTDs, including printed and additive manufacturing, are frequently discussed in the literature due to their ability to facilitate rapid prototyping, adaptability to non-planar surfaces, and compatibility with a wide range of materials. These capabilities hold significant promise for the advancement of SPs technology [14], [19].

Strain gauges on the other hand are the main devices to measure forces applied to objects by evaluating their deformations. In standard electronics strain gauges are composed by conductive materials in a wavy pattern that can be attached or glued to the object under test. At the state of art, many additive manufacturing techniques such as ink-jet, screen, aerosol, gravure and shadow-mask printing are attracting interest for the production of strain gauges [8], [16], [62], [72], [134]. The printing approach also allows embedding the strain gauge onto the surface of the target object without a glueing process, thus improving the overall adhesion and measurement process [20], [38].

A capacitive sensor associates the capacitance (and its change) between two or more conductors in a dielectric environment with the variation in the parameter of interest. The main transduction process can be related both to the change of the sensor geometry or the change of the dielectric constant of the dielectric material. Capacitive sensors have been utilised for different applications such as pressure, flow, level and chemical concentration measurement as well as proximity sensing [110].

Pressure sensors in particular are vital in many applications such as robotics, prosthetics and diagnostics. Different pressure transducers have been explored in the literature. Among those the main used are piezoresistive, piezoelectric, capacitive, and optical [77], [96], [102]. In particular, capacitive pressure sensors are interesting due to their high sensitivity, good repeatability, temperature independence, low power consumption and high spatial resolution [24].

B. SERVICE ARCHITECTURES FOR CPPN

1) SERVICE-ORIENTED ARCHITECTURE (SOA)

Service-Oriented Architecture (SOA) has gained widespread adoption in structuring distributed computing systems, including industrial applications [21], [95], [125]. Leveraging independent, self-contained services as fundamental building blocks offers numerous advantages, such as ease of maintenance, reusability, and streamlined development processes [10]. Several methods have been proposed for developing SOA-based systems, including web services following W3C standards (XML, SOAP, and WSDL), the Representational State Transfer (REST) architectural style, and Enterprise Service Buses (ESBs), which act as intermediaries facilitating service communication and integration.

In the context of Smart Manufacturing, SOA has been employed to promote modular architectural design, where reusable modules are interconnected through straightforward interfaces to implement specific functions [21]. However, many existing approaches in advanced Smart Manufacturing solutions tend to focus on addressing specific needs within the production network, such as energy efficiency [82], anomaly detection [107] and predictive maintenance on work centers [91] and process monitoring [89], while not fully addressing the common challenges encountered in service-oriented applications.

Shifting the focus toward SOA-based solutions for implementing and managing services within Cyber-Physical Production Systems (CPPS) or Cyber-Physical Production Networks (CPPN), Zhang et al. [136] underline how SOA enables adaptive, flexible, and extensible development, integration, management, and replacement of distributed applications through loosely coupled connections of manufacturing services. However, they emphasize that managing a large number of services within CPPS or CPPN can lead to increased complexity and give rise to challenging issues, such as service discovery, composition, coordination, and governance.

To address these challenges, various SOA implementations have been proposed to encapsulate industrial devices and processes as services, often incorporating multi-tier structures reflecting the complexity of the industrial landscape. For example, Sipsas et al. [118] propose a context-aware system for collaborative maintenance with a six-tier architecture that encompasses sensors, metrology, data aggregation, context-awareness services, and shop-floor applications. Pahlevannejad et al. [95] propose a service-oriented and modular architecture for highly heterogeneous industrial environments, consisting of five conceptual tiers: product, production, supply, integration, and IT system. In a similar vein, Badarinath and Prabhu [10] introduce a four-tier SOA-based architecture for integrating IoT devices in manufacturing systems, with tiers comprising sensing and data acquisition, network, services, and applications. Park et al. [99] devise a four-tier SOA with tiers dedicated to devices, networks, services, and applications. Meanwhile, Alexopoulos et al. [7] propose an event-based SOA for context-aware manufacturing systems, consisting of edge, platform, and enterprise tiers, each addressing specific aspects of data integration, context-aware services, and business applications.

2) MICROSERVICE-ORIENTED ARCHITECTURE (MOA)

The adoption of microservices as an architectural pattern for the computing infrastructure required in Smart Manufacturing scenarios is increasingly cited in the research literature as a promising alternative to traditional SOAs. For instance, Vresk and Čavrak [126] propose an implementation of a MOA to virtualize IoT devices, where data produced by each device is exposed through RESTful APIs. Similarly, Rufino et al. [111] provide a three-tier microservices-based platform for managing industrial and management processes. The MAYA platform [25] leverages microservices to control and integrate IoT devices with an Enterprise Information System. In this case, microservices also support production planning, monitoring, and analysis using simulation and Big Data analytics. Elhabbash et al. [37] introduce MARTIN, a scalable MOA for predictive maintenance, capable of collecting,

TABLE 5. Summary and comparison of existing service-oriented architectures – Sections IV-B and IV-C (✓: coverage provided, ∼ partial coverage, ✗: coverage not provided).

Work	Main scope	Multi-tier architecture (# tiers)	(Big) Data modelling and heterogeneity issues	Role-based data access policies	Data sovereignty and privacy issues
Catarci et al. [21]	Service-based Digital Twin model	✗	✗	✗	✗
Matsunaga et al. [82]	Sustainability, energy efficiency and CPPS	✗	✗	✗	✗
Nordal et al. [91]	Industry 4.0 architecture for predictive maintenance	✓(3)	✗	✗	✗
Zhang et al. [136]	Information modelling and architectures in CPPS	✓(4)	✗	✗	✗
Sipsas et al. [118]	Industry 4.0 system for decision support	✓(6)	✗	✗	✗
Pahlevannejad et al. [95]	Modular architecture for hybrid production cells	✓(5)	✗	✗	✗
Badarinath et al. [10]	Architecture for realising IoT applications in manufacturing	✓(4)	✗	✗	✗
Park et al. [99]	Service-oriented platform for ensuring sustainability of dyeing industry	✓(4)	✗	✗	✗
Alexopoulos et al. [7]	Platform for developing context-aware services	✓(3)	✗	✗	✗
Vresk et al. [126]	Service middleware to connect IoT devices	✓(2)	✗	✗	✗
Rufino et al. [111]	Service architecture for IIoT to cope with device heterogeneity	✓(3)	✗	✗	✗
Ciavotta et al. [25]	Platform to empower shop-floor CPS	✓(4)	✓	∼ (Security aspects)	✗
Elhabbash et al. [37]	Scalable service architecture for for predictive maintenance in Smart Factories	✗	✓	✗	✗
Ibarra-Junquera et al. [54]	Proposal of a flexible, scalable, and robust service-based framework	✗	✗	✗	✗
Nikolakis et al. [90]	Design, development and deployment of a flexible and modular platform supporting smart predictive maintenance	✓(2)	✓	✗	✗
Yang et al. [132]	Service-oriented architecture for People-centric IIoT,	✓(3)	✗	✗	✗
Derhamy et al. [29]	Architecture for System of Systems composition	✗	∼ (Graph data model)	✗	✗
Ferrer et al. [43]	Architecture for implementing a Private Local Automation Cloud in the scope of CPSs	∼ (5 views)	✗	✗	✗
Glock et al. [48]	Service-based middleware for a plug-and-produce approach to dynamically scale a system network	✓(4)	✗	✗	✗
Lemoine et al. [69]	Self-assembling solution based on self-controlled service components taking into account QoS	✗	✗	✗	✗
Mena et al. [84]	Abstraction of IoT devices inspired by the concept of Digital Twin leveraging the advantages of (micro-)services architectures	✗	✗	✗	✗
Pontarolli et al. [103]	Implementation and performance analysis of micro-services orchestration for process control applications	✗	✗	✗	✗
Radchenko et al. [109]	Description of Digital Twins as a sequence of jobs to organise a flexible cloud computing support for the Digital Twin execution	✓(4)	✗	✗	✗
Dobaj et al. [32]	Proposal of a micro-service architecture for the IIoT	✓(4)	✗	✗	✗
Bigheti et al. [15]	Proposal of a micro-service oriented architecture for I4.0 applications	✗	✗	✗	✗
Bagozi et al. [13]	Methodology for the design of a multi-perspective data-oriented service portfolio	✓(3)	∼ (Heterogeneity not addressed)	✓	✓
Jarke et al. [57]	Reference architectures for the Internet of Production, data privacy and sovereignty	✗	✗	✓	✓
Kashmar et al. [61]	Access control models	✗	✗	∼ (Access models)	✓
Stock et al. [121]	Modelling approach for CPPS	✓(3)	✓	✗	✗
Stock et al. [120]	Fingerprinting for CPPS, to increase security and build a secure identity for CPPS	✓(3)	✗	∼ (Security aspects)	✗
Park et al. [98]	Architectural framework for Digital-Twin based for CPPS	✗	✓	✗	✗
Magraria et al. [78]	Conceptual models for Digital Thread	✗	✓	✗	✗

storing, and analyzing data for decision-making based on machine state. Ibarra-Junquera et al. [54] present a flexible, scalable, and robust framework based on microservices and container technology, promoting a publish/subscribe paradigm. This framework enables the addition or removal of components online without the need for system reconfiguration, all while maintaining temporal and functional constraints in industrial automation systems. Nikolakis et al. [90] discuss the design, development, and deployment of a flexible and modular MOA platform supporting smart predictive maintenance operations, enabled by microservices and virtualization technologies. The platform has been tested in a simulation environment, aimed at replicating a controlled robotic manipulator, simulating failures for predictive analytics.

3) SERVICE COMPOSITION IN SOAs AND MOAs

In the realm of SOA solutions, Yang et al. [132] introduced an SOA for the Industrial Internet of Things (IIoT) and developed a reference middleware for smart devices that facilitates service composition through the concept of service coalitions. Derhamy et al. [29] devised a composition method within the Arrowhead framework, employing a graph model to identify and validate possible compositions. Ferrer and Lastra [43] presented an architecture for Private Local Automation Clouds comprised of Cyber-Physical Systems with a service-oriented interface, employing an orchestrator to sequence operations for executing manufacturing processes. Glock et al. [48] described the software architecture of a service-based middleware that enables the collaborative operation of automated cranes, facilitating orchestrated collaboration between cranes.

Service composition challenges have also been addressed in microservice-based solutions, as seen in [69], where the authors developed an environment for microservice composition, considering functional, structural, and Quality of Service (QoS) requirements. The architecture designed by Mena et al. [84] abstracts Cyber-Physical Systems and IoT devices with microservices, relying on REST invocations for interaction with microservices and achieving orchestration through collaborative tasks.

In the Smart Manufacturing context, orchestration of microservices has been employed for process control, as demonstrated by [103] in their control of an industrial plant, with an experimental evaluation within the scope of manufacturing systems. Specialized architectures [109] focus on managing Digital Twins, utilizing microservices, often combined with data streaming middleware, for computing, communication support, and orchestration workflows, primarily for data processing and analysis. MOAs, such as the one proposed by Dobaj et al. [32], introduce mechanisms for exchanging monitoring data acquired by IoT sensors, leveraging a choreography-based approach where local transactions publish domain events triggering transactions in other services. Similarly, the MOA suggested by [15] envisions two hierarchical levels of microservices: Infrastructure, responsible for fundamental functions like communication, device control, and data acquisition, and Business/Processes, used for process supervision and monitoring. The latter often involves composition with other services, executed through choreographies.

C. DATA MANAGEMENT ISSUES AND DATA MODELLING IN CPPN

A challenging issue in the design of CPPN regards the shift from a vertical integration approach, commonly fostered in CPPS, towards the horizontal integration of different smart factories participating in a CPPN. Indeed, this aspect calls for proper data management strategies for the collection, organisation, analysis, and exploration of data regarding the CPPN, demanding to balance data management over multiple perspectives, going beyond a single viewpoint, either the product, a single machine or even a set of machines and human resources, as done in CPPS approaches. From an information systems perspective, significant effort has been invested in the creation of a coherent standardised information meta-model to enable the exchange of sensitive and valuable data [57]. On such a trail, authors in [61] propose to introduce proper access policies, i.e., the definition of permissions at the application level, exploiting the renowned Role-Based Access Control (RBAC) mechanism. Authors in [121] describe a model-based approach (and a corresponding web-based GUI) to compose CPPS based on predefined building blocks, abstracted as smart services. Smart services are connected to each other and hierarchically organised, instead of assuming a holistic view of CPPS. Ontologies have been also proposed in [120] to face interoperability issues. In these papers, the focus is on CPPS within a single production line. In [98], authors model Digital Twins behind CPPS for product customisation. An information model is proposed to provide data about product, process, plan, plant, resource. The approach in [98] provides five types of services: production planning, automated execution, real-time monitoring, abnormal situation notification and dynamic response. In [78] the authors focus on the use of models for designing Smart Products along their lifecycle, being agnostic about the specific technologies, and binding to specific implementations of such features only when needed. The focus of the latter papers is on the Smart Product, whose representation evolves during the product lifecycle (but no data is collected on the design, production or maintenance stages). The notion of Digital Thread proposed by commercial solutions such as PTC Windchill is implemented as a sequence of interleaved Bill of Materials (BoMs), such as Engineering BoM, Manufacturing BoM, as-built, as-maintained, without collecting data on the process and on the work centres during the product lifecycle. A recent work addressing data management issues is the effort of Bagozi et al. [13] wherein authors propose to introduce access policies at the application level, similarly to the idea of the RBAC proposed in [61]. In addition, regarding CPPS and CPPN data modelling, with respect to [98], in the information model of Bagozi et al. the concepts of process and plan are associated with the concepts of production phases and phase execution. Moreover, resources are properly hierarchically organised within plants. Lastly, the proposal of Bagozi et al. is agnostic about the services to implement in the supply chain, providing a methodology to model services on top of the product, process and industrial assets perspectives. Even though mainly focused on the production phase, their work paves the way to possible extensions for implementing a Digital Thread over the whole stages of the product lifecycle, enabling a fruitful connection also with the process and industrial assets perspectives.

V. PROPOSED SERVICE-ORIENTED ARCHITECTURAL MODEL FOR SMART PRODUCTS DIGITAL THREAD

As evidenced in Section IV (especially by means of the summaries provided by Table 4 and Table 5), the surveyed works only partially address the challenges presented in Section II-D. In fact, amongst the selected works for this survey, there is no research effort striving to propose an architectural model to meet together all the identified challenges. Moreover, most of them tackle a specific topic or suggest architectural solutions articulated over multiple tiers that are mainly oriented towards the integration of different technologies, disregarding aspects related to Big Data issues, role-based data access policies and data sovereignty issues. Therefore, in this section, we present a multi-tiered architectural model devised to meet the challenges elicited in Section II-D. Noteworthy, this architectural model is not constrained to any application domain and can be potentially adapted to any production ecosystem.

A. ARCHITECTURE OVERVIEW

The architecture we propose is represented in Figure 9 and it is organised over distinct technological tiers, each one focusing on specific methods, models and techniques for:

1) data collection from Smart Products (fabricated using sustainable materials and printed electronics to minimise energy consumption and to facilitate operational control and communication with other Smart Products) and other data providers to yield data integration according to a *schema-on-read* approach, typical of Data Lake architectures, and apt to face Big Data variety, volumes and velocity (**Data Providers and Data Lake tier**);
2) data modelling in the cyberspace, according to the different perspectives of the product, process (or product lifecycle) and industrial assets, paying attention to data sovereignty, data security issues and data protection issues (**Multi-perspective Data Model tier**);
3) modelling and composing services at various levels of granularity, both within a single actor, across actors in the same supply chain, and across different supply chains, to provide domain-oriented and demand-oriented services, driven by changing customers' needs (**Three-layered Service Model for CPPN tier**);
4) developing and testing data-driven and AI-based applications in an intertwined supply chain scenario, prone to the execution of various use cases (**Data-driven and AI-based applications tier**)

B. DATA PROVIDERS AND DATA LAKE TIER

This tier gathers: (i) *Data Providers*, including Smart Products and other data sources (encompassing data collected from Digital Twins, ERPs and so forth); (ii) a *Data Lake*, acting as a centralised repository to collect, store and integrate heterogeneous (Big) data in a pay-as-you-go manner.

1) DATA PROVIDERS

Apart from data collected from traditional Smart Manufacturing data sources (such as Digital Twins, ERP and MES systems), Smart Products enable the creation of a seamless flow of data and information throughout the stages of product lifecycle thanks to the interplay of awareness, data representation and interaction characteristics of SPs. The architectural model depicted in Figure 9 focuses on the interaction characteristic of SPs, which is further enhanced by providing, downstream of the measurement chain of SPs, proper Application Programming Interfaces (APIs) to: (i) hide the complexity behind connectivity and communication protocols, thus assuring an exchange of data also with other providers within the Data Providers tier; (ii) provide standardised interfaces for propagating data towards the upper tiers of the architectural model. For the APIs, we suggest the adoption of REST (Representational State Transfer) paradigm principles, apt to ensure easy development, maintenance, and interoperability also with the plethora of different technological solutions fostered at the upper tiers.

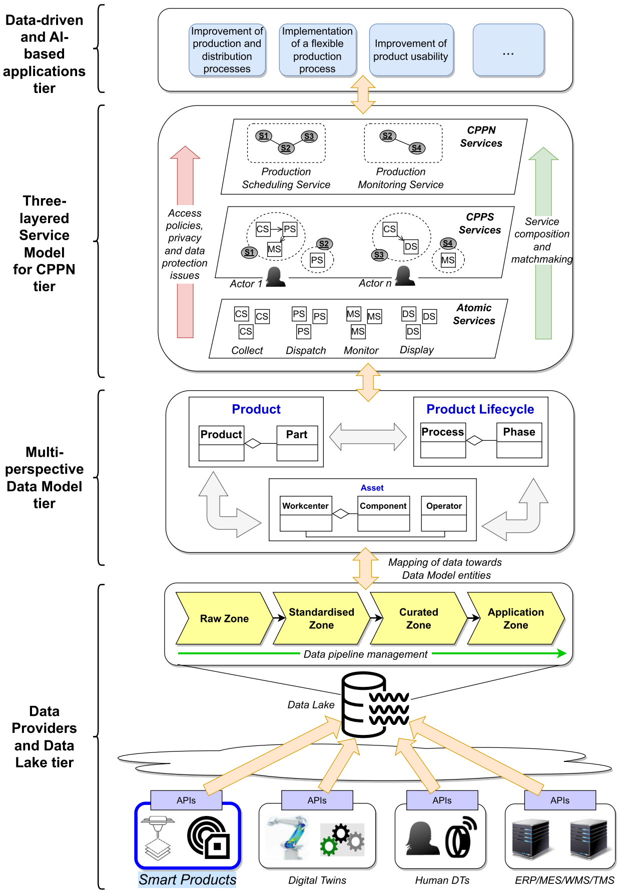

FIGURE 9. Proposed service-oriented architecture to implement digital threads for smart products in a smart manufacturing context.

2) DATA LAKE ARCHITECTURE

Big Data collected from Smart Manufacturing data sources is characterised by heterogeneity in the formats it assumes, ranging from commonly used formats like CSV and JSON to relational and NoSQL databases. This inherent heterogeneity represents a compelling challenge for data integration within the Smart Manufacturing landscape. Recent initiatives have suggested the adoption of Data Lake repositories to store and share both structured and unstructured data, given their flexibility, schema-on-read nature and the possibility of developing pay-as-you-go or on-demand solutions to progressively integrate data, thus coping with the cumbersome nature of Big Data. Indeed, a Data Lake facilitates seamless integration, analysis, and extraction of valuable insights, empowering organisations to make informed decisions. To this aim, in the architectural model, we envisage the adoption of a Data Lake adhering to a *zone-based organisation* [46], leveraging an underlying file system apt to manage structured and unstructured data (e.g., the Apache Hadoop Distributed File System - HDFS). Indeed, zone-based architectures have proven to be effective for postponing data transformation and elaboration until data consumption is strictly required at the upper tiers. In particular, we conceive a Data Lake organised over four zones, encapsulating data management operations, namely:

1) *Raw Zone*, containing the heterogeneous data sources in their original format, where each data source has its own path within the file system supporting the Data Lake repository;
2) *Standardised Zone*, where data is abstracted regardless of its original format through datasets,[2] upon which data standardisation operations are applied (e.g., format conversions, conversion between different units of measure, append of technical metadata regarding the type and the length of a file, criteria to identify missing data values and actions to apply);
3) *Curated Zone*, where datasets required for the execution of use cases of data-driven and AI-driven applications are shaped into a tabular structure;
4) *Application Zone*, where the tables of the Curated Zone are joined together to serve various data-driven and AI-driven applications (e.g., improvement of production and distribution processes, enhancement of the flexibility of the production process, improvement of product usability).

C. MULTI-PERSPECTIVE DATA MODEL TIER

In the architecture, we propose the adoption of a Data Model in cyberspace to integrate and explore data regarding three perspectives, namely, *product*, *product lifecycle* and *industrial assets*. Complying with the terminology of multi-dimensional data analysis, the perspectives of the Data Model include entities referred to as *dimensions*, representing distinct aspects apt to categorise and analyse data in a multi-dimensional space, assuring a more comprehensive and flexible data representation. Combinations of dimension instances (the so-called *facets*) allow for detailed and granular analysis of data residing in the Application Zone of the Data Lake. For the proposed architecture, we resort to the Data Model introduced in [13], whose perspectives are summarised in the following, tailored for a Digital Thread context.

- **Product perspective.** This perspective concerns product configuration over Product Lifecycle Management (PLM). Each *product* (in turn described through product details) is composed of a set of *parts* which are identified by a part code and are hierarchically organised into different *Bill of Materials* (BoM), depending on the specific phase of the product lifecycle that is being considered (e.g., Engineering BoM, Manufacturing BoM). Part codes belonging to different hierarchies can be connected to each other, e.g., in order to manage change propagation over the product lifecycle. For instance, the Manufacturing BoM (MBoM) regards the manufacturing process and reports the distinction between: (i) part codes that must be produced internally, connecting to a Production Order (PO); (ii) part codes that must be produced externally, by one of the suppliers of the supply chain, connecting to a Contract Work Order (CWO); (iii) part codes to be bought and then assembled in the final product, connecting to a Purchase Order. The final product, corresponding to the root of the BoM hierarchy, is associated with the PO as a Sales Order item.
- **Product lifecycle perspective.** The main entity of this perspective is represented by the *production phase*, which is in turn organised according to a hierarchy, where each phase is composed of a set of *sub-phases*, reaching a level of detail ranging from macro to micro industrial processes. For instance, production phases implement: (i) the PO of the final product, connected to the Sales Order item; (ii) the PO of one or more components of the final product, connected to the CWO item or the Purchase Order item and corresponding to the point of view of one of the suppliers in the supply chain. In this way, the information model brings together the viewpoints of all the supply chain actors. In the example above, the hierarchy of process phases is focused on the production step in the PLM, thus corresponding to the MBoM. However, this modelling can be seamlessly extended to the other phases of the PLM (e.g., engineering, maintenance) and the other kinds of the BoMs.
- **Asset perspective.** This perspective includes the *resources* involved in the realisation of the product (machinery, equipment, information systems, human resources). Work centres are the machines used in the manufacturing process and are hierarchically organised (e.g., following reference models such as RAMI 4.0). A work centre or a resource can be involved in many production phases during its lifecycle. A production phase can be executed and distributed on several work centres and may consume/require different resources.

D. THREE-LAYERED SERVICE MODEL FOR CPPN TIER

To address the intricate task of organising services within the context of the proposed architecture, we propose to foster a three-layered service model. This model outlines the structure for organising services for vertical and horizontal integration in the Smart Factory according to the following layers.

- **Atomic Services Layer.** At the foundational level, atomic services, internal to each CPPN actor, are

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[2] We do not deepen this aspect as it is out of the scope of the paper but, for instance, a dataset can be represented relying on Spark Dataset collections (https://spark.apache.org/docs/latest/sql-programming-guide.html).

classified with respect to the *action* they perform (i.e., acquisition, monitoring, dispatch, and data visualisation) and the *type of data* they manage, descending from the Data Model previously described, that is data on *products* (e.g., measures taken during product quality controls), on *product lifecycle* (e.g., delays of process phases) and on *industrial assets* used in the production process (e.g., measures taken with sensors for anomaly detection or predictive maintenance purposes).

- **CPPS Services Layer.** This layer hosts composite services aggregating atomic services at the factory level and caters to specific business roles of individual actors within the production network. These composite services prioritise flexibility to enhance resilience and adaptability within the Cyber-Physical Production System (CPPS). They operate within actor-specific boundaries, minimising critical requirements for data access and sovereignty.
- **CPPN Services Layer.** Encompassing composite services from multiple actors across supply chains (i.e., from multiple CPPS), this layer caters to changing customer demands and evolving conditions. Notably, these services pose challenges regarding data access and sovereignty, as they grant access to data from various actors across considered supply chains.

Recalling the SOA roles from Section II-B, in a Cyber Physical Production Network (CPPN) service providers and consumers are the actors of the supply chains. In our vision, each CPPN actor hosts its own services, acting as a node of a distributed registry, where services are published and discovered by all the actors collaborating in the CPPN [11], thus easing the communication and collaboration between the actors of a SOA, pursuing the flexibility and interoperability objectives typical of SOA ecosystems. This tier provides also support for the registration, discovery, and composition of services in the complex landscape of CPPN.

Authors in [21] suggest that the CPPN/CPPS tiers can be implemented as a set of orchestration software modules that, given the specification of the CPPN/CPPS actors (we will simply use the term actor), aims to achieve certain goals or Key Performance Indicators (KPIs) by composing actors adaptively through context awareness.

A taxonomy of service-based composition techniques employed in this area is presented in [88]. Here, authors map different approaches to implement context-aware adaptive business processes for *supply chains* to three categories:

- **Instance repair.** The supply chain process is precisely defined. If an unexpected exception happens (e.g., a machine breaks), automated techniques are employed to restore the state of resources to the expected one.
- **Instance planning.** Every time that a new product or batch of produces must be produced, automated reasoning is applied taking as input the most recent information about resources and producing as output an entire process to be followed for the supply chain. If, at a certain point of the execution, something (e.g., a broken resource) prevents the plan to be completed, automated reasoning is applied again.
- **Policy-based.** Automated reasoning is employed to obtain a policy, i.e., a function that for each step of the supply chain proposes the next action. Differently from the *instance planning* case, here if something unexpected happens, there is no need to reapply planning, as all the possibilities have been already computed.

Techniques falling into one of these categories model actors and/or processes as deterministic or stochastic state machines. The employment of stochastic state machines (see for example [28]) allows to model the uncertainty that is frequently present in smart manufacturing scenarios (e.g., probability of failure, expected quality - or cost - of the outcome of an operation).

While above mentioned composition techniques are focused on supply chains, usually neglects smart products, they can be easily extended to digital threads by modeling smart products as actors to be part of the composition.

E. DATA-DRIVEN AND AI-BASED APPLICATIONS TIER

At the topmost tier of the proposed architectural model, there are several data-driven and AI-based applications capitalising on the underlying services (i.e., invoking their functionalities), leveraging the data collected throughout the product lifecycle and conveyed in the Application Zone of the Data Lake. For instance, the purpose of these applications is to optimise supply chain operations, enhance the quality of the production and distribution process, increase the flexibility of the production process, and improve the usability of products. To this aim, such applications may implement Machine Learning algorithms apt to analyse data and identify patterns indicative of potential issues, allowing for proactive actions to be taken in a certain production stage (e.g., to prevent machine breakdowns that, apart from the potentially onerous expenses demanded for repairing the machine, would introduce delays in the production process), thus minimising downtime and optimising product lifecycle management. In addition, AI-based applications may empower resource and material provisioning, inventory and supply chain logistics, exploiting predictions made through Machine Learning models to ensure timely delivery of products and services to other supply chain actors and final customers. Regarding the latter, organisations may obtain actionable insights also from customer feedback, social media and market trends (which can be globally conceived as unstructured data providers for the Data Lake), enabling them to deliver personalised offerings and services, thus coping with the ever-evolving customer needs and preferences (e.g., by resorting to Natural language processing to analyse the aforementioned data).

VI. CHALLENGES AND OPPORTUNITIES FOR FUTURE RESEARCH DIRECTIONS

In this section, we provide a glimpse of recent compelling research directions regarding the topics covered by this survey.

A. ADVANCED SERVICE COMPOSITION METHODS

1) REQUIREMENTS-DRIVEN SERVICE COMPOSITION AND BIG SERVICE

Requirements analysis plays a pivotal role in service-oriented engineering. Various modeling approaches have been introduced to match stakeholders' requirements and streamline business processes. These include Service-Oriented Modeling and Architecture (SOMA), Model Driven Architecture (MDA), and Service Model Driven Architecture (SMDA), which aid in agile development and code generation based on human-readable specifications.

In recent years, a two-fold perspective service composition paradigm has emerged [130]. This paradigm encompasses: (i) *domain-oriented composition*, which focuses on aggregating and composing services according to their associated business domains, demands, and relationships; (ii) *demand-oriented composition*, aimed at delivering customized service solutions by starting from domain-oriented services to meet customer requirements aligned with their business goals.

This two-fold perspective has paved the way for the concept of the *Big Service* ecosystem [131]. In this ecosystem, software services process Big Data, and they are composed and aggregated from complex and interconnected multi-domain services. This allows for a flexible service composition that can adapt to changing customer needs and market requirements. One notable example of the application of the two-fold composition vision is RE2SEP [130], a paradigm of software service engineering. RE2SEP combines service-oriented requirement engineering for capturing customer demands and domain-oriented service engineering for developing adaptive service solutions within the Big Service ecosystem. The service orchestration proposed in RE2SEP introduces a new approach called Service Orchestration Based on Event-Driven Architecture (SOEDA), which uses event-driven architecture to offer more flexibility and adaptability compared to traditional approaches like Business Process Execution Language (BPEL).

Building upon the foundations laid out in [130], Shi et al. [114] underpin the reference architecture of Big Service and IoS. The work outlines a roadmap for business innovation and transformation, presenting a referential development and execution environment for Big Service and IoS. It also introduces various technological architectures for different application scenarios, structured in hierarchical layers that allow layer-by-layer service aggregation and the creation of different aggregation granularities, enabling the construction of complex service collaborations.

2) SERVICE COMPOSITION WITH THE SUPPORT OF LARGE LANGUAGE MODELS

Large Language Models (LLMs), based on deep neural network algorithms, have the ability to predict the next textual token in a series of tokens based on statistical occurrences in extremely large data sets. In recent years, LLMs like ChatGPT have attracted the attention of the research community due to their capability of generating programs and their potential impact on Service-Oriented Architectures, especially for the task of automatic service composition [3], [4]. In particular, an automatic composition of services would help ensure adaptability in information systems by executing any task relying on multiple services without a full knowledge of such services. This vision of composition, which inspired in the past several approaches for automated composition based on XML-based description of services [34], had a considerable limit regarding the fact that understanding the capabilities of a service is not straightforward by looking only at its interface. As remarked in [4], which is to date the first vision paper discussing the topic of automated service composition with LLMs, even though a step forward has been made by adding semantic information to service descriptions, the potentiality of the Semantic Web has been superseded by the deluge of data retrievable resorting to advanced search engines (e.g., the Google search engine). The parallel between autonomous driving and autonomous service composition made in [3] emphasises the fact that LLMs have the potential to promote the required innovation to shift from a partial automation to a conditional or even full automation of composition, revamping service composition techniques. The experiment performed by Aiello et al. with ChatGPT showcases that the chatbot was able to discover the services and compose them (to accomplish a trip organisation task, requiring the interaction amongst different Web services about weather, geography and trip conversion). Nevertheless, ChatGPT strove to interpret the interfaces of services and invoked non-existing API (i.e., suffered from the *hallucination* phenomenon). Even though the final output was only partially correct, requiring additional knowledge by a human, this new approach to automated service composition based on LLMs paves the way to three main research directions, identified by Aiello et al. as relevant for the field: (i) *prompt engineering*, that is how a request for composition of services can be properly made and how the request can be refined/corrected through several interactions with the chatbot; (ii) *composition verification and testing*, as composition generated through LLMs do not benefit from the inherent correctness delivered by existing formal languages; (iii) *execution monitoring*, as once the composition has been deployed, it has to be monitored in order to check whether it is performing as expected. These issues related to automated service composition and execution with the support of LLMs are still being investigated by the research community, and the interest towards them has been stimulated by the advent and availability of tools implementing LLMs such as ChatGPT.

B. BLOCKCHAIN TECHNOLOGY FOR DIGITAL THREAD

As remarked in this survey, achieving a Digital Thread entails dealing with production ecosystems involving multiple actors participating in intertwined supply chains, with different roles. In such a complex landscape, where actors have to interact and share data across various stages of production, distribution, and consumption, blockchain technology may come to the rescue. Indeed, blockchain technology has been effectively fostered as a viable solution to assure transparency, traceability and security of data generated throughout the production steps of the product lifecycle in service-oriented supply chains [114]. In particular, blockchain technology provides decentralised control and immutable transaction history, thereby improving accountability between parties. Furthermore, Smart Contracts, capitalising on distributed ledger technology, have the potential to enforce automated negotiation and agreement between parties without the direct involvement and intermediation of central authorities.

Even though the implementation of a Digital Thread would benefit from the adoption of blockchain technology for the reasons above, two major issues, tightly coupled to each other, have to be considered. The first one regards the fact that, when fostering blockchain technologies, deciding which data has to be stored on-chain or off-chain is pivotal to limit the impact on costs and scalability [35] (regardless of the type of blockchain, albeit blockchain technologies such as Ethereum are renowned to suffer from on-chain cost issues). The second aspect is related to the inherent complexity of the intertwined supply chain scenarios of CPPN, where actors may engage with heterogeneous blockchain technologies, each with its own technological infrastructure and interaction style. The latter issue, which is a hot topic in the *blockchain integration* research area, is tackled by offering the possibility to supply chain actors to seamlessly interact with different blockchain technologies (e.g., designing architectural solutions abstracting from details regarding the invocation smart contracts functionalities, to reduce costs and enhance scalability).

VII. CONCLUSION

In this survey, we presented the technological solutions and challenges to implement Digital Threads for Smart Products in the Smart Manufacturing context, providing insights on opportunities for future research directions. At the beginning of the paper, five Research Questions (**RQ1**-**RQ5**) have been formulated to guide the focus of the survey and to frame the literature review process, conducted according to the PRISMA statement (Section IV). As a contribution of this survey, we proposed a comprehensive multi-tier service-oriented architectural model (Section V) to tackle (Big) data heterogeneity, data sovereignty and data access policies issues since, as evidenced by the research efforts examined in the literature review, the former issues are only partially addressed. Such an architectural model is currently being proposed for adoption in the scope of MICS (an acronym for "Made in Italy Circolare e Sostenibile", translated as "Circular and Sustainable Made in Italy") Extended Partnership, including both public sector partners (i.e., universities and research centres) and industrial partners from three key sectors of the Italian industrial scenario, namely Fashion, Furniture and Factory Automation.

LIST OF ABBREVIATIONS AND ACRONYMS

DTH	Digital Thread.
DTW	Digital Twin.
CPPS	Cyber-Physical Production System.
CPPN	Cyber-Physical Production Network.
SOA	Service-Oriented Architecture.
MOA	Microservice-Oriented Architecture.
SP	Smart Product.
IoT	Internet of Things.
IoS	Internet of Services.
IoP	Internet of Production.
API	Application Programming Interface.
PLM	Product Lifecycle Management.
MES	Manufacturing Execution System.
ERP	Enterprise Resource Planning.
REST	Representational State Transfer.

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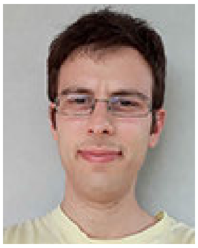

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