

A Service-Oriented Architecture for the Digital Thread of Smart Products

(Discussion Paper)

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Abstract

The Digital Thread is a key enabler for managing the lifecycle of smart products, ensuring data continuity across design, production, and usage phases. In Cyber-Physical Production Systems (CPPS) and Cyber-Physical Product Networks (CPPN), this continuity supports traceability, analytics, and intelligent decision-making. This work proposes a service-oriented architecture for the digital thread, focusing on modularity, semantic interoperability, and data sovereignty. The architecture is built around a set of layers that incorporate: (i) a Data Lake tier to seamlessly collect data from data providers at the shop floor level and make it available to the upmost architectural layers; (ii) a multi-perspective data model, to aggregate and explore smart product data over the entire product lifecycle; (iii) a three-layered service model that spans from intra-factory to inter-organizational collaboration. By promoting service composability and interoperability across systems and organizations, it lays the foundation for resilient, adaptive infrastructures in Industry 4.0 and 5.0 scenarios.

Keywords

Smart Products, Digital Thread, Internet of Services, Cyber-Physical Production Networks

1. Introduction

In the context of Industry 4.0 and its evolution toward Industry 5.0, the Digital Thread has emerged as a key enabler for ensuring data continuity and traceability across the entire lifecycle of smart products. It enables a seamless flow of information—from design and manufacturing to usage and end-of-life—thereby supporting real-time analytics, predictive maintenance, and agile decision-making [1]. However, despite its strategic relevance, current implementations of the Digital Thread often suffer from limitations such as tight coupling to specific platforms, lack of modularity, and poor support for cross-organizational interoperability and data sovereignty.

Moreover, while Smart Products are increasingly capable of sensing, processing, and communicating data, their integration into coherent, scalable, and secure digital ecosystems remains a challenge. Existing architectural approaches frequently neglect the need for service composability, semantic abstraction, and decentralized control, which are essential to operate in complex, data-intensive environments like Cyber-Physical Production Systems (CPPS) and Cyber-Physical Product Networks (CPPNs).

This paper addresses these gaps by proposing a service-oriented architecture that rethinks the Digital Thread as a modular, multi-tiered infrastructure. The architecture is built around a set of layers that incorporate: (i) a Data Lake tier to seamlessly collect data from data providers at the shop floor level and make it available to the upmost architectural layers; (ii) a multi-perspective data model, to aggregate and explore smart product data over the entire product lifecycle; (iii) a three-layered service model, that spans from intra-factory to inter-organizational collaboration. By enabling the dynamic composition of data-driven and AI-based services, the proposed solution promotes flexibility, scalability, and resilience—key features for the next generation of smart manufacturing systems. This paper is an extended abstract based on an extensive survey about technologies, challenges, and opportunities of Digital Threads and Smart Products in service-oriented supply chains [2].

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The paper is organised as follows: Section 2 introduces the research background and related work; the overview of the proposed multi-tiered architecture is given in Section 3, while architectural layers are shortly presented in Sections 4-6; Section 7 presents two relevant case studies in which the architectures has been declined; finally, Section 8 closes the paper.

2. Background and Related Work

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). In the following, we briefly summarise the main principles revolving around the concept of Digital Thread, which have been promoted by works like [3, 4].

- **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 [5].
- **Real-time data analytics** – The analysis of data generated throughout the product lifecycle ensures 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 [6].
- **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 [7]. 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).

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 [8]: *awareness*, *data representation* and *interaction*. The synergy of these components constitutes the foundation of the so-called *measurement chain*.

- **Awareness** – A Smart Product 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 Smart Product. 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 Smart Products, relative position, user presence) and statistical data about usage patterns (e.g., number of uses, time of use). Awareness of a Smart Product depends on its *sensors* and the *electronics front-end*.
- **Data representation** – A Smart Product must be able to properly represent the collected information from sensors in an organic form. Representation within a Smart Product is not

simply a matter of organising raw sensor data, but requires a model that can depict the Smart Product, its operativity and its operational context in order to produce meaningful information. Moreover, an effective representation of the collected data allows an easier interoperability of the Smart Product with other systems in the Smart Factory. Data representation depends on the *electronics front-end* and *IoT and communication* parts of the Smart Product.

- **Interaction** – Lastly, interaction is fundamental since it allows to both capitalise on the data collected from the Smart Product 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 Smart Products, thus leading to a flexible and adaptable production ecosystem. Interaction depends mainly on *IoT and communication*.

Related work on multi-layered architectures for Digital Threads and Smart Products. Service-Oriented Architecture (SOA) has been widely adopted in distributed systems, including industrial contexts, due to its modularity, reusability, and maintainability benefits [9, 10, 11]. Their modular nature has also been a key enabler in the design of data architectures supporting the Digital Thread and Smart Products. Please refer to [2] for a more detailed comparison. Standard implementations include W3C web services (SOAP/WSDL), RESTful services, and Enterprise Service Buses (ESBs), all aimed at facilitating communication and integration. In Smart Manufacturing, SOA promotes modular architectures where reusable services are interconnected through standardized interfaces [9]. However, many existing solutions address isolated objectives—such as energy efficiency [12], anomaly detection [13], predictive maintenance [14], or process monitoring [15]—without tackling broader service composition and governance challenges. Within Cyber-Physical Production Systems and Networks (CPPS/CPPN), SOA is recognized for enabling adaptive and extensible service orchestration [16]. Yet, scalability issues emerge when managing large numbers of services, particularly regarding discovery, coordination, and lifecycle governance. To cope with such complexity, multi-tier SOA architectures have been proposed. Examples include six-tier systems for context-aware maintenance [17], modular five-tier frameworks for heterogeneous environments [18], and layered architectures integrating IoT and edge components [11, 19, 20]. These efforts highlight the need for flexible, semantically rich architectures capable of supporting cross-tier integration and service interoperability in dynamic industrial ecosystems.

Despite the advancements reviewed, a unified architectural framework spanning from the IoT level to the IoS level remains largely missing. The architecture presented in this work, developed under the MICS (Made in Italy – Circular and Sustainable) Extended Partnership¹ and supported by the Next-GenerationEU Initiative, is designed to address this shortcoming.

3. Architecture overview

The architecture we propose is represented in Figure 1 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 (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, paying attention to data sovereignty, data security issues and data protection issues (Three-layered Service Model for CPPN tier);

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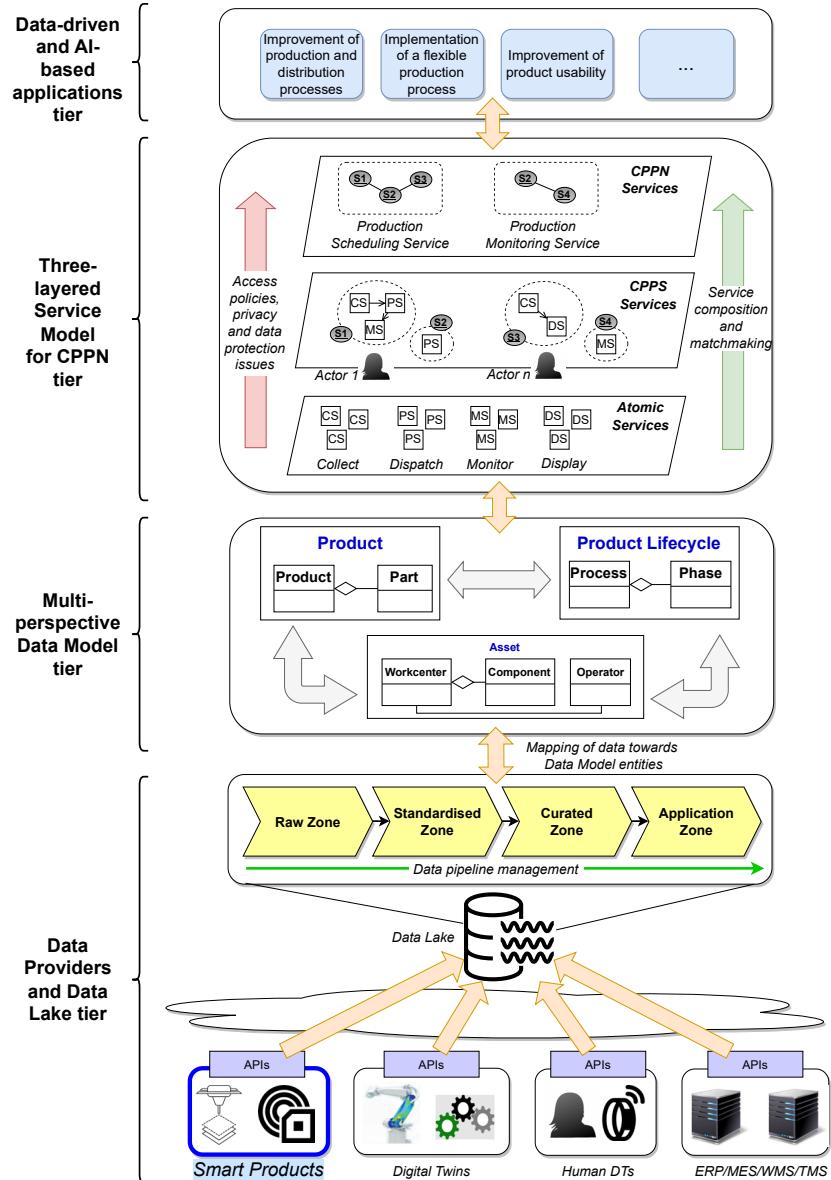


Figure 1: Proposed service-oriented architecture to implement Digital Threads for Smart Products in a Smart Manufacturing context.

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).

4. 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 repository to collect, store and integrate heterogeneous (Big) data in a pay-as-you-go manner.

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 between Smart Products. In the architectural model depicted in Figure 1, Smart Products are further enhanced by providing proper Application Programming Interfaces (APIs) to: (i) hide the complexity behind connectivity and communication protocols, thus assuring an

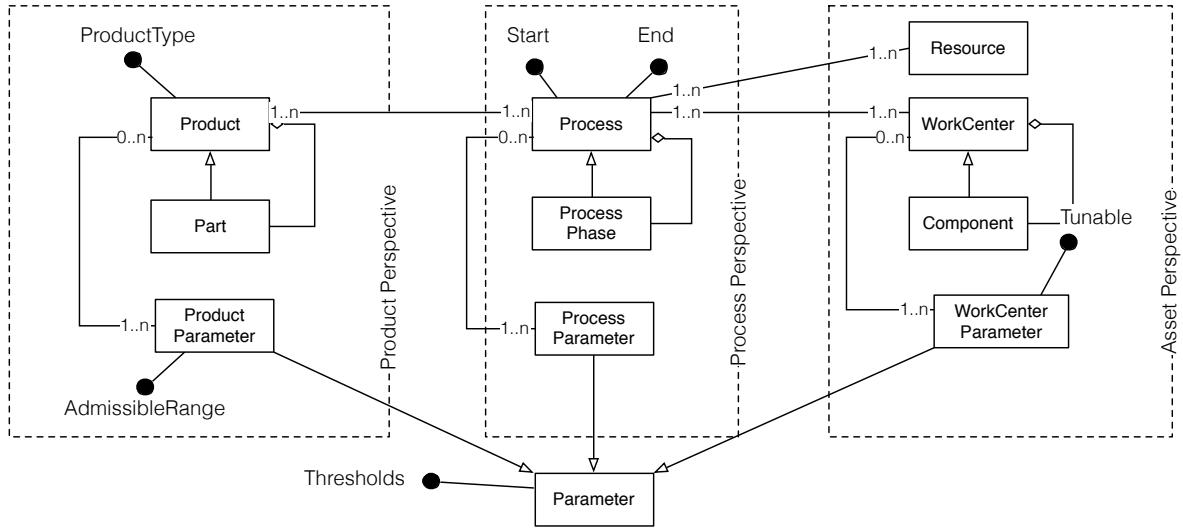


Figure 2: Multi-perspective conceptual data model template for the CPM data requirements analysis.

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.

Data Lake tier. 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 [21]. To this aim, in the architectural model, we envisage the adoption of a Data Lake adhering to a *zone-based organisation*, 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: (a) *raw zone*, containing the heterogeneous data sources in their original format; (b) *standardised zone*, where data is abstracted regardless of its original format through datasets, upon which data standardisation operations are applied; (c) *curated zone*, where datasets required for the execution of use cases of data-driven and AI-driven applications are shaped into a tabular structure; (d) *application zone*, where the tables of the Curated Zone are joined together to serve various data-driven and AI-driven applications. The evolution of Data Lakes into more advanced architectures, such as Data Lakehouses, remains relevant as long as zone-based design principles are maintained.

5. 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. Figure 2 shows an abstraction of the considered multi-perspective data model, already presented in [22]. In the following we describe each perspective separately and how they relate to each other.

- *Product.* Each product is composed of a set of parts, which are identified by a part code and

can be composed of other sub-parts. This relationship between product parts is represented through a recursive hierarchy making the navigation structure of a product flexible. The hierarchy represents the *Bill of Material* (BoM), that will be further specialised into different kinds of BoM in the data model design step.

- *Process*. The process represents the various processing phases that must be executed to obtain the final product: each processing phase includes different sub-phases. A recursive hierarchy is used to model this relationship as well. The relationship between the product and the process can be very complex, depending on the organisation of the production network (consider for example the distinction between purchase orders and production orders). Some parts of the final product could be bought from suppliers instead of being produced internally or externally.
- *Work centers and resources*. The process is executed using work centers and resources. A work center comprises one or more machines. The hierarchical relationship in this case is between the work center and the component machines, that in a recursive way may be composed of other parts (for example, an oil pump, electrical engines, spindles, and so forth). The hierarchical organisation of assets reflects the IEC62264/IEC61512 standards of the RAMI 4.0 specification [23]. Resources can be of different kinds (e.g., operators, tools, software).
- *Parameters*. Different kinds of parameters are used to monitor the behaviour of the production network according to the three perspectives. On each product part in the BoM some *product parameters* are measured, for instance to be used in quality controls. Values of these parameters must stay within acceptable ranges. On each process phase, proper *process parameters* are measured as well, concerning the phase duration, that must be compliant with the end timestamp of each phase, as established by the production schedule. *Work center parameters* are gathered to monitor the working conditions of each work center at different levels. Parameters are monitored through proper thresholds, established by domain experts who possess the knowledge about the production process. Parameter bounds are used to establish if a critical condition has occurred on the monitored work center or one of its components.

6. Three-layered service model

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, in order to provide: (i) a clear distinction between composite services, that are internal to single actors, and those that span across actors boundaries, at the supply chain level; (ii) compliance with data sovereignty and granular access control requirements. In the following, we provide a brief overview of the three layers that compose the proposed data service model.

Atomic Services Layer These services represent atomic activities on data from the perspective of each individual actor. These services encompass operations such as accessing data from the field and from Enterprise Information Systems, conveyed in the underlying (Big) data storage tier, or from other actors (Collect); sharing specific information with other actors (Dispatch); monitoring or processing data internally (e.g., filtering, transformation, or storage) for implementing flexible data pipelines such as anomaly detection and predictive maintenance of industrial assets, or process and product quality assessment (Process&Monitor); and visualizing data for internal purposes (Display). These activities span the entire data lifecycle at the smallest granularity level. Atomic services facilitate modular design, allowing for efficient reuse in diverse compositions.

CPPS Services Layer The CPPS services represent composite services that (recursively) aggregate various atomic services within the borders of a single factory. These services cater to the specific business roles of individual actors of the production network, offering flexibility, while managing access policies. They facilitate resilience and adaptability within the CPPS, which are associated with the production lines of each actor [9].

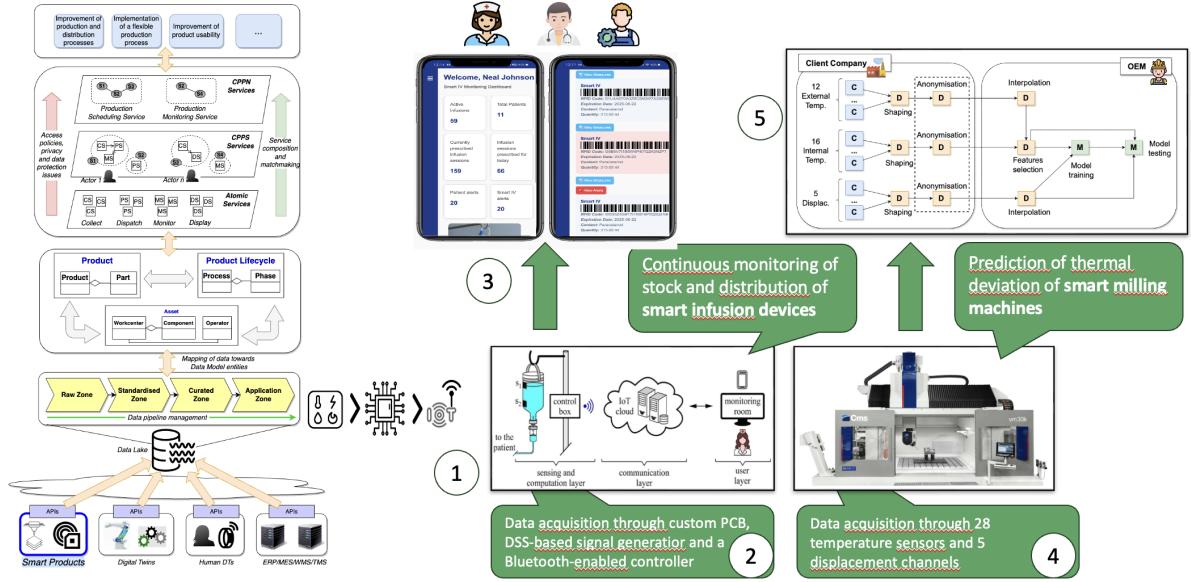


Figure 3: Two representative case studies that implement the proposed multi-layered architecture.

CPPN Services Layer The CPPN services represent a composition of other services (either atomic or CPPS services) from multiple actors across the entire supply chain and in intertwined supply chains. On the one hand, CPPS services align with data governance best practices that are specific to each individual actor, ensuring that internal data management is secure and compliant with law regulations (since they implement complex functionalities based only on data owned by single actors). On the other hand, CPPN services are designed to adapt to the evolving data process requirements at the supply chain level, where the partnership of actors (e.g., suppliers) and the customers' requirements may change over time. This dynamic environment requires data services that are modular and flexible, enabling seamless reconfiguration to accommodate shifting requirements and maintain interoperability across the network.

At the topmost tier of the proposed architectural model, there are several data-driven and AI-based applications capitalising on the underlying services, 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. 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. Organisations may obtain actionable insights also from customer feedback, social media and market trends, enabling them to deliver personalised offerings and services.

7. Case studies

The proposed multi-tiered architecture has been instantiated and tested in two representative case studies, both developed in the context of the MICS (Made in Italy – Circular and Sustainable) Extended Partnership. These use cases—one in the healthcare domain and one in industrial manufacturing—serve to validate the applicability of the architectural layers across different scenarios and are summarised in Figure 3.

In the first case study, a traditional **infusion (IV) bag was transformed into a Smart Product** by integrating a fully printed, non-contact capacitive sensor (step ① in Figure 3). This sensor, developed using printed electronics techniques, enables the wireless monitoring of fluid levels through changes in resonant frequency. In the *Data Providers and Data Lake tier*, a data source was realized through a sensing and communication chain consisting of a custom PCB, a DDS-based signal generator, and a Bluetooth-enabled Arduino microcontroller, transmitting data to a Raspberry Pi system for initial storage and integration (step ② in Figure 3). In this case, the data preparation steps through the Data Lake zones concerned standard techniques and methods for data shaping and cleansing. A preliminary implementation of the *Multi-perspective Data Model* was adopted to structure the sensor readings and contextual parameters (e.g., fluid type, container geometry) within a lifecycle-aware schema. Concerning the *Three-layered service model*, data acquisition and local pre-processing were implemented as Atomic Services, further composed into more articulated data analytics pipelines to build CPPS and CPPN services. These composite services have been designed to enable both monitoring activities on the status of the Smart IV during usage within hospital structures (single actor) and tracking of the Smart IV conditions over its entire lifecycle (Digital Thread over the Smart IV supply chain). This enabled the implementation of advanced functionalities in the *Data-driven application layer*, accessed through a Web application and devoted to different categories of users, namely, nurses, doctors and healthcare operators (step ③ in Figure 3).

The second case study, developed in collaboration with an industrial partner, focuses on **thermal error monitoring in five-axis milling machines**. In this scenario, 28 temperature sensors and five displacement channels were used to build a predictive model of thermal deformation ad *Data Providers* (step ④ in Figure 3). The zones of the *Data Lake tier* were designed for the collection and alignment of time series data from heterogeneous sensors. A structured dataset was created through data interpolation and filtering operations, feeding the *Multi-perspective Data Model* with features mapped to both asset (machine) and process (displacement) perspectives. At the *Three-layered service model layer*, Atomic Services were effectively designed to implement distinct operations such as sensor data ingestion, interpolation, and feature selection. CPPS Services were realized by composing these atomic operations into a Python-based analytical workflow capable of training and testing regression models (MLRA and LASSO) for predicting axis displacement. Looking forward, this pipeline is being refactored into a set of reusable atomic services that will feed into a more flexible and discoverable service ecosystem. An orchestration, implemented as a CPPN service, was also envisioned, where predictive services may be exposed to other actors in the production network (step ⑤ in Figure 3). Moreover, the integration of an LLM-based interface is under development to support service discovery and pipeline composition by non-technical users, thus concretely addressing the *Data-driven and AI-based applications tier*.

8. Concluding remarks

This paper has introduced a service-oriented architecture for implementing the Digital Thread of smart products within CPPN, that supports semantic interoperability, data sovereignty, and scalable integration of AI-based applications. The two presented case studies, in healthcare and manufacturing domains, demonstrate the feasibility and versatility of the solution. These results reinforce the potential of service-oriented models as a foundational strategy for enabling resilient, intelligent, and adaptable systems in Industry 4.0 and 5.0 scenarios.

Declaration on Generative AI

During the preparation of this work, the authors used ChatGPT-3.5 to perform grammar and spelling check. The authors take full responsibility for the publication's content.

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