A Service-Oriented Architecture for implementing Digital Threads in Smart Products Design

Devis Bianchini[1], Massimiliano Garda[1]
[1]University of Brescia, Dept. of Information Engineering, Via Branze 38, 25123 Brescia, Italy
{devis.bianchini, massimiliano.garda}@unibs.it

***Abstract*—In the 4.0 era, the notion of Digital Thread offers an opportunity for seamless connectivity and integration of information throughout a product lifecycle. In this landscape, the Internet of Services (IoS) paradigm is increasingly employed to meet the complex and evolving data analysis needs and to provide an interconnected view of information collected over the design, production and usage of the so-called Smart Products. This paradigm must address various challenges, including the heterogeneity of Big Data, data sovereignty, and data access policies, as information often traverses borders across multiple actors, both in Industry 4.0 supply chains and modern Smart Cities applications. This paper proposes a comprehensive multi-tier service-oriented architecture designed to address the aforementioned issues. The architecture is being investigated in a research project within the MICS (Made in Italy – Circular and Sustainable) Extended Partnership and received funding from Next-GenerationEU.**

***Index Terms*—Service-oriented architectures, Internet of Services, Smart Cities, Smart Products, Digital Thread**

I. Introduction

The advent of Smart Cities has brought significant transformation in the way urban infrastructure is designed, manufactured, and managed. One of the key components of this transformation is the proliferation of Smart Objects or Smart Products [6], which are embedded with sensors and other technologies to collect and transmit data throughout their entire lifecycle for decision-making purposes. To manage the vast amount of data generated by these devices, the concept of Digital Thread has been developed. In particular, a Digital Thread is 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 [3]. In this respect, Digital Threads can be used to inform decision-making, optimise city operations, and enhance the overall quality of life for citizens. The Internet of Services (IoS) plays a crucial role in the implementation of Digital Threads, as it enables the exchange of data and services between devices, applications, and users. The IoS paradigm, along with the Internet of Things (IoT), facilitates a shift from vertical towards horizontal integration and seamless collaboration between product designers, producers and Smart City citizens, who use the products in their daily life. In the context of Smart Cities, the IoS favours the integration of various Smart Products, allowing them to communicate with each other and share data in real-time. For example, in the city of Barcelona, the IoS is used to integrate data coming from traffic cameras, parking sensors, and air quality monitors[1]. This integration enables the city to optimise traffic flow, manage parking spaces more efficiently, and monitor air quality in real-time. Another example can be seen in the city of Copenhagen[2], where a smart waste management system has been implemented, that uses sensors and other technologies to track waste levels and composition in real-time. Nevertheless, when implementing Digital Thread solutions for Smart Products, the IoS paradigm must address various challenges, 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 [2]).

This paper proposes a comprehensive multi-tier service-oriented architecture designed to address the aforementioned issues. The proposed architecture is being investigated in a research project within the MICS (Made in Italy – Circular and Sustainable) Extended Partnership and received funding from Next-GenerationEU[3].

II. Architecture overview

The proposed architecture is shown 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, paying attention to data sovereignty, data security and data protection issues (*Multi-perspective Data Model tier*);

(3) modelling and composing services at various levels of granularity, both within a single actor and across different

[1]https://datasmart.hks.harvard.edu/news/article/how-smart-city-barcelona-brought-the-internet-of-things-to-life-789

[2]https://stateofgreen.com/en/news/city-of-copenhagen-launches-the-worlds-first-big-data-platform-for-cities/

[3]https://www.mics.tech/projects/8-7-digital-thread-for-smart-product-in-service-oriented-supply-chains/

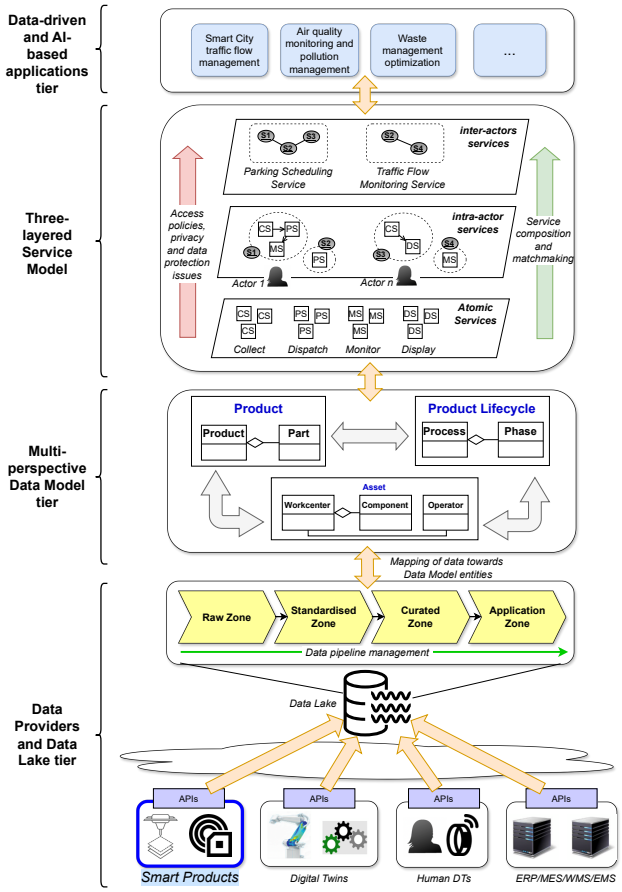

Fig. 1: Proposed service-oriented architecture for implementing Digital Threads in Smart Product design.

actors over the product lifecycle, to provide domain-oriented and demand-oriented services, driven by changing customers' needs (*Three-layered Service Model*);

(4) developing and testing data-driven and AI-based applications in Smart Cities and Industry 4.0 scenarios, prone to the execution of various use cases (*Data-driven and AI-based applications tier*).

III. Related Work

The proposed architecture is conceived to divide an application into multiple layers, each responsible for specific functionality, thus ensuring scalability and maintainability. In [5] multi-tier architectures used in industrial scenarios for Digital Threads are discussed. The three-tier architecture typically consists of a Database, a Processing and a Presentation Tier, the latter acting as an intermediary between the database and the client ones. The four-tier architecture adds an additional tier, the Service Tier, which provides specific services and functionalities, such as data processing, analytics, or integration with external systems. One-tier and two-tier architectures are no longer used in Industry 4.0 and Smart City scenarios, due to their limited connectivity and synchronisation capabilities, hindering the efficiency of data-driven applications. The n-tier architecture is used for building large-scale, enterprise-grade applications, where additional tiers are added to encapsulate the core business logic and rules governing the application behaviour and to facilitate communication and data exchange between different subsystems, applications, and external services. The cutting-edge features that characterise our proposed architecture rely on the modular organisation of data through the multiple tiers, oriented towards a Digital Thread vision of Smart Product data: (i) in the Data Model, the product lifecycle phases are clearly highlighted and, for each phase, the evolution of the product structure (i.e., the so-called Bill of Materials) and assets involved in product design, production, maintenance and disposal are properly conceptualised; (ii) at the bottom, the data quality workflow through the Data Lake zones is guided by the aforementioned Data Model; (iii) at the top layers of the architecture, modular atomic services are designed based on the product, product lifecycle and assets perspectives, distinguishing between specific phases of the data management lifecycle (collect, dispatch across actors, monitor and display), thus enabling to focus each service on a target perspective and addressing data access, data sovereignty and scalability issues according to a divide-and-conquer strategy.

IV. Concluding Remarks and Research Challenges

The multi-tier architecture briefly sketched in this paper is compliant with the reference architecture of the CINI National Lab on Smart Cities and Communities, that includes service-oriented architectures among the technologies for the realisation of basic services delivered by a potential laboratory platform. Future work will be focused on new solutions for service composition, namely: (i) *domain-oriented vs demand-oriented* composition, to shift the focus from composition driven by business domain knowledge to the delivery of customised service solutions starting from on-the-fly citizens' needs [4]; (ii) *LLM-based service discovery and composition*, aimed at relying on LLMs like ChatGPT to support the deployment of a service-oriented architecture starting from available atomic data services [1].

References

[1] Marco Aiello and Ilche Georgievski. Service composition in the ChatGPT era. *Service Oriented Computing and Applications*, 17(4):233–238, 2023.

[2] Ada Bagozi, Devis Bianchini, and Valeria De Antonellis. Context-based resilience in cyber-physical production system. *DSE*, 6(4):434–454, 2021.

[3] Tiziana Margaria and Alexander Schieweck. The Digital Thread in Industry 4.0. In *(IFM)*, pages 3–24, 2019.

[4] Haomai Shi, Hanchuan Xu, Xiaofei Xu, and Zhongjie Wang. How big service and internet of services drive business innovation and transformation. In *Advanced Information Systems Engineering*, pages 517–532, 2022.

[5] Frank Siqueira and Joseph G. Davis. Service Computing for Industry 4.0: State of the Art, Challenges, and Research Opportunities. *ACM Computing Survey*, 54(9):188:1 – 188:38, 2021.

[6] Amin Ullah, Syed Myhammad Anwar, Jianqiang Li, Lubna Nadeem, Tariq Mahmood, Amjad Rehman, and Tanzila Saba. Smart cities: the role of Internet of Things and machine learning in realizing a data-centric smart environment. *Complex Intell. Syst*, 10:1607–1637, 2024.