Article

Not peer-reviewed version

High-Level Architecture for Interoperable Digital Twins

Mamadou Kaba Traoré *

Posted Date: 11 October 2023

doi: 10.20944/preprints202310.0659.v1

Keywords: Digital Twin; Smart City; Interoperability; High-Level Architecture

Article

High-Level Architecture for Interoperable Digital Twins†

Mamadou Kaba Traoré

IMS UMR 5218, University of Bordeaux 1; mamadou-kaba.traore@u-bordeaux.fr

† This article is a revised and expanded version of a paper entitled "Digital Twin for Smart Cities:. An Enabler for Large-Scale Enterprise Interoperability", which was presented at I-ESA'2022, Valencia (Spain), March 23-25, 2022.

Abstract: Infrastructure and urban network operators, city users and industrialists are faced with complex issues to ensure the sustainability of the service, maintain, operate and develop their urban systems, while integrating environmental, economic and societal impacts and being resilient to unexpected geopolitical and climatic upheavals. Digital Twins are now recognized as the cornerstone of digital transformation. In the field of smart cities, they can enable all stakeholders to collaborate across disciplinary silos and foster digital transformation in urban and territorial projects to ensure sustainability, resilience and increased inventiveness. However, the application of the Digital Twin technology to Smart Cities lacks of standards. This paper proposes a high-level architecture for Digital Twins as an enabler of various levels of interoperation between key actors of a Smart City. Such a technology-agnostic architecture, when implemented in a given use case, results in a middleware for large scale interoperability between stakeholders of multiple supply chains of this territory.

Keywords: Digital Twin; Smart City; interoperability; high-level architecture

---

1. Introduction

As nearly 70 percent of the world's population will live in urban areas by 2050 [1], urbanization is a defining trend of the 21st Century due to the resulting pressure on urban production and service systems. This includes the expansion of public transport networks, energy supply chain, waste management circuits, mechanisms to address security of people and assets, and measures to prevent disease spreading and to preserve air quality. This comes in the context of the rise of the climate change challenge [2] and thus the need for a drastic reduction of carbon footprint in all major urban activities such as mobility and transportation, and energy consumption and production. Thus, building and shaping inclusive, livable, safe and sustainable urban areas which are called Smart Cities [3], is an essential development priority.

In recent years, there has been a growing interest in the concept of smart cities, i.e., connected cities, which favor the use of digital and technological innovations in order to deal with urban issues that have existed for a long time. As no simple response exists for such high-stake issues (such as simply closing a traffic to face a peak in atmospheric pollution), current tools for analyzing and evaluating the performance of decisions prove inadequate [4]. Indeed, although they sometimes provide fairly accurate diagnoses, these tools remain sector-specific and ignore multi-scale systemic interactions (such as the link between urban transport, weather, and population dynamics). Moreover, the underlying models become obsolete as the system they represent changes. Therefore, new analysis models require features to integrate heterogeneous levels of explanation of the same system, and self- updating capability as well. In such a context, approaching smart city management through the Digital Twin technology [5-6] offers a viable solution to cope with system complexity, provides rapid analysis of multidisciplinary data and delivers readily understood outputs. The idea is to use simulations, visualizations, and data-driven diagnoses to optimize cities. Data-rich digital models of the city that replicate its physical features and capture its logical processes in real time would allow improving energy consumption, mobility efficiency, waste management, security and safety monitoring, health crisis mitigation, and infrastructure management.

Therefore, the Digital Twin of a Smart City is of high strategic importance to public decision-makers, as well as to private operators and citizens. Particularly when major challenges occur including catastrophe weather events and preventable infrastructure failure. For example, in 2017, the London Grenfell Tower Fire [7], which occurred due to the systemic failure of building safety regulations by the local government resulting in the use of combustible retrofit external cladding, led to 72 deaths and 70 injured. The use of combustible cladding was found to be endemic across UK cities, affecting the housing of 675,000 citizens and a remediation cost of £3.5 billion. In 2021, a once in a 1000-year rainfall event caused flooding of the Zhengzhou underground railway [8], killing 12 people and the evacuation of 100,000 citizens from the city. Numerous other examples show that the smart city technology through modelling and visualization can be used as an impartial auditor of high-risk complex construction projects, identify non-compliance with safety regulations, and model the impact of extreme events (such as earthquakes, tsunami, fires, floods, hurricanes, pandemics, etc.) on city infrastructures and habitants [9].

However, the application of the Digital Twin technology to Smart Cities lacks of standards. Major challenges remain, such as: (1) a holistic approach to smart city Digital Twin, leading to the heterogeneous integration of multi-scale, multi-data, and multi-objective models (including models for mobility, energy, safety, health, etc.); and (2) a standard deployment of a secure, interoperable and collaborative end-to-end architecture, to overcome the constraints of solutions that are either proprietary or ad-hoc. Motivated by these challenges, this paper proposes a high-level digital twin architecture, as an enabler of large-scale interoperability within and between smart cities. We discuss how such a technology-agnostic model can be implemented using existing standards, and how this can provide a middleware for digital enterprises involved in multiple supply chains (energy, transport, health, etc.) of a smart city.

The remainder of this paper is organized as follows: Section 2 briefly discusses related work. In Section 3, we briefly revisit the basic concepts of the Digital Twin technology, as many interpretations still co-exist. We also briefly revisit in Section 4 the concept of Digital Twin for Smart City and we introduce the concept of CityVerse. Section 5 presents our high-level architecture. Then, we propose in Section 6 how this architecture enables various levels of interoperability. In Section 7, we discuss some implications and perspectives of our work. Conclusions are given in Section 8.

2. Related Work

Few contributions related to architecting in a generic way a digital twin for smart cities can be found in the state of the art [10-14]. A snapshot of state-of-the-art smart city initiatives [15] shows that, even if the focus is on the use of the IoT in an urban planning context across a large spectrum of applications, none of the projects scale to modeling or metamodeling a digital twin of the city, due to most of them facing several challenges, all related to the issue of being flooded by data, details and complexity. Digital twins, even if considered as one of the top 10 strategic technology trends [16], are often limited to assets, and in a few cases to small/medium service lines. Recently, the European Union funded several Digital Twin projects in smart city-related areas, more notably the low-emission urban logistics networks (H2020 LEAD project) [17], and the LIVING-IN.EU community [18] and its LDT (Local Digital Twin) approach. Despite these efforts, the application of the Digital Twin technology to Smart Cities lacks of standards. Major limitations are due to the lack of the following: (1) a holistic approach to smart city Digital Twin, leading to the heterogeneous integration of multi-scale, multi-data, and multi-objective models (including models for mobility, energy, safety, health, etc.); and (2) a standard deployment of secure, interoperable and collaborative end-to-end architecture, to overcome the constraints of solutions that are either proprietary or ad-hoc. As a first step, there is a need for a high-level architecture for smart city's digital twin. We propose a candidate model and we discuss its implementation via existing standards.

3. Basic Digital Twin Concepts

The digital twin concept has surfaced as one of the current top strategic technology trends. It is based on the idea that a model which is used in different ways in place of a system of interest, is

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 October 2023 doi:10.20944/preprints202310.0659.v1

continuously synchronized with that system in order to reflect any real event happening to the system on the model, such that any management initiative can be assessed on this ever-updated artifact before transferring it to the system. Therefore, the model is more than a simple representation of the system, but a digital counterpart which is specifically bound to the system, rather than representing a family of systems of the same kind. NASA is a pioneer in the system-pairing approach for having simulated from the ground situations occurring in space, to guide astronauts. Yet while this approach brought the Apollo 13 crew back safe in 1970, it didn't use a Digital Twin, but a pair of physical twins (respectively located in space and in ground). The term Digital Twin first appeared in [19], and the underlying principle of a digital informational construct created as a separate entity and related to a physical system of interest was foreseen in [20]. In the context of product life cycle management, the model of a conceptual ideal was proposed and called Mirrored Spaces Model [21], and later Information Mirroring Model [22], and actually Digital Twin [23]. It has been defined as: "a set of virtual information constructs that fully describe a potential or actual physical manufactured product, from the micro atomic to the macro geometric level" [24]. This data-centric definition contrasts with the behavior-centric one given in [25], where a Digital Twin is "an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin". From a simulation perspective, the Digital Twin is a disruptive approach, as simulation experiments are based on current information provided by the system, rather than assumptions [26-27]. Used in this way, the Digital Twin serves both for representational purposes, and prediction-making on system behavior [28], which often appear as a set of integrated sub-models that reflect different system characteristics [29]. Some additional aspects have also emerged, such as Digital Twin-based prognostic and diagnostic activities [30-31], as well as Digital Twin-based real-time optimization [32].

Current Digital Twin applications span from automotive [33], avionics [34], aerospace [25], energy [35] to manufacturing [26], healthcare [36] and services [37]. Industrial applications of Digital Twins include controlling the predictive maintenance of equipment, improving assets safety and reliability, and optimizing process operation and product design. In healthcare, the Digital Twin approach holds the promise of designing personal and completely tailor-made treatments/surgeries for diseases, in contrast with traditional approaches that are based on what is best on average for a large group of patients. Digital Twins also allows servitization by supporting companies in monitoring their products while they are in customers' hands. Therefore, when interacting with stakeholders in different communities, the use of the term Digital Twin raises the question of its formal definition in a way akin to the metaphor of a group of blind men who have never encountered an elephant before and who conceptualize what it is by touching it. Each blind man feels a different and unique part of the elephant's body. They then describe the elephant based on this sole experience and their views differ radically. Nonetheless, the numerous Digital Twin viewpoints [19-44] fall under one common umbrella, that can be expressed as follows [5-6].

A numerical model of a system of interest, that we call the Twin of Interest (TOI), becomes its Digital Twin when there is a synchronization between the TOI and the Digital Twin, based on data tracked in the TOI. The term TOI is preferred to terms such as "physical twin" or "real twin", as it can be a product system, a service system, a process, or even a software (therefore an immaterial/virtual entity). The Digital Twin, as a model, is a digital abstraction that may reflect one or multiple perspectives (static, dynamic, functional, etc.) of the TOI. The synchronization between the TOI and the Digital Twin is either clock-based (ranging from real-time synchronization to low-frequency synchronization) or event-based (ranging from cyclic synchronization, to on-demand synchronization). The synchronization between the TOI and the Digital Twin can be a one-way/two-way process. While there is always a strict requirement for data to be sensed at the TOI side and sent to the Digital Twin without any other intermediary except the communication middleware, there might be or not a human third party to derive decision for the TOI from the information derived at the Digital Twin side. Therefore, the twinning loop can either be closed (in which case, the Digital

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 October 2023 doi:10.20944/preprints202310.0659.v1

Twin not only monitors the TOI but also controls it) or open (in which case a third party makes and applies the control decision).

4. Digital Twin for Smart City

Figure 1 summarizes the value chain of a Smart City Digital Twin. Smart Cities increasingly operate on large, time-varying, heterogeneous data, including raw data, information models and business knowledge. Such systems are referenced under the umbrella of Cyber Physical and Human Systems (CPHS). Their proper instrumentation, through distributed sensors and actuators connected in real environments via the IoT (Internet of Things), produce Big Data in records of processes and human interventions, which can be saved in large repositories referred to as Data Lake. The data-driven knowledge is used to reflect on the structure and behavior of the system under consideration, through the mining of digital models that are amenable to simulation-based prediction and the exploration of what-if scenarios, as well as multi-objective/criteria optimizations, analytics-based system diagnosis, and real-time monitoring and control. Integrating these models and regularly updating them with new data collected result in the Digital Twin of the smart city. Such an infrastructure is necessarily distributed across a cluster of computational nodes, therefore calling for High Performance Computation support. Since the purpose of the Digital Twin is to support the smart city's stakeholders to decision-making, visualizations and human-digital interactions through a Metaverse technology (i.e., a collective, virtual, open space developed by integrating virtually enhanced digital, as well as physical, reality, known for offering immersive experiences to users) allow human-centric immersive experience, improved engagement and better perception and understanding of the smart city and its issues. This implies, not only focusing on the technological solution, but also engaging researchers in social and human sciences, as well as business players, with willingness to consider the multi-sectoral effects of public policies on the territory and populations. Note that we introduce here the concept of CityVerse (a contraction of Smart City and Metaverse), as the Smart City's Digital Twin immersed in the Metaverse.

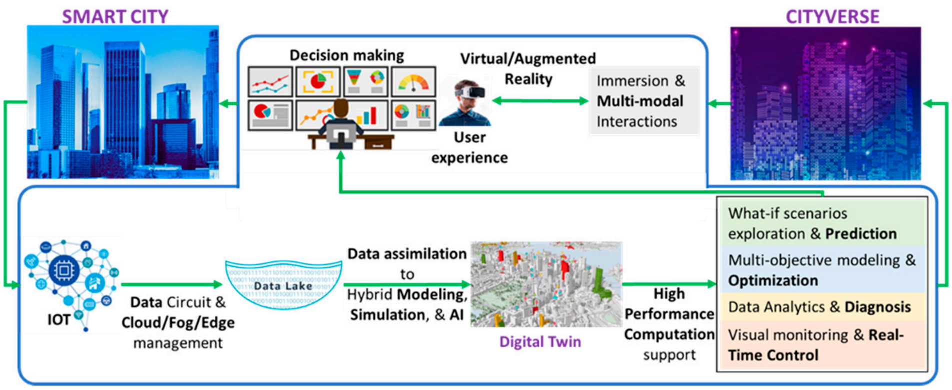

Figure 1. Value chain of a Smart City Digital Twin.

5. High-level Architecture for a Smart City's Digital Twin

Figure 2 captures a high-level view of this value chain, while highlighting in blue what has to be designed for deploying an effective Digital Twin for Smart City. Three main stakeholders form this triangle: The Physical (i.e., the Smart City), the Digital (i.e., the core Digital Twin), and the Human (i.e., users and managers of the Smart City). At the Physical side, which in reality is necessarily a cyber-physical system [45], i.e., an integration of cyber and physical components where system's operations may be partly or entirely executed by actuators, and data related to these operations are collected by sensors and transmitted through a network. At the Digital side is the Digital Twin of the system, where data are received, translated to models, which in turn allow making decisions to be either directly sent back to the system, or used by the governance body of the system to elaborate further management decisions. At the Human side, major stakeholders, like citizens, specialized bodies (e.g., students, healthcare workers, disable persons, etc.), communities, enterprises, and

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 October 2023 doi:10.20944/preprints202310.0659.v1

governmental agencies, are allowed to use the Digital Twin and explore their own use case scenarios in order to build their own economic/social strategies.

The Digital-Physical interactions focus on the symbiotic relation between the Smart City and the Digital Twin infrastructure, and thus address related scientific and technological issues and challenges, including: (1) the design of the end-to-end data circuit, from the conceptualization and assessment of data needs to the integration of heterogeneous data sources, and the requirements for IoT liability and efficiency; and (2) the use of edge computing for faster computations related to the real-time data streams, e.g., algorithms to transform raw data for use by the Digital Twin. The Digital-Human interactions focus on the application of advanced technologies such as Virtual/Augmented Reality and Web/Mobile approaches to bridge the reality gap in interfacing human with the Digital Twin, and addresses related scientific and technological issues, including: (1) the use of Metaverse-type technologies as the Digital Twin last miles to end-users for better and more informed decision-making; and (2) social interactions to formalize the so-called "cognitive interoperability" in the Metaverse. The Digital-based Human-Physical interactions focus on how the Digital Twin models and services impact on the relation between the Smart City and its decision-makers (such as holistic urban decision-making) or its users (such as change of behavior).

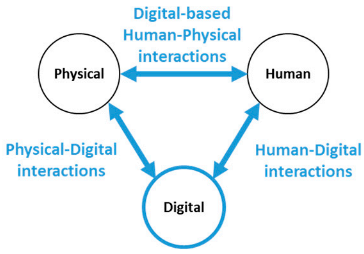

Figure 2. High-level view of Digital Twin-based Smart City management.

Figure 3 presents the high-level architecture we propose for the core Digital Twin, as a 3-nodes graph that translates our definition of a Digital Twin, i.e., as a symbiotic association of data, models and services. Data in the Digital Twin are not only those collected in real-time from sensors deployed on ground, but legacy data sources can also be aggregated to provide what is necessary for feeding and updating the Digital Twin, including historical data, users' equipment (such as smartphones, embedded/fixed cameras, etc.), open data and Internet-based APIS (e.g., Google map). Models in the Digital Twin are related to modules, each focusing on specific objectives and therefore designed to answer to specific questions (such as, how will the city evolve in its environment under given circumstances? What is the impact of adding/modifying given infrastructures? What are the upcoming on-site security holes? Etc.). Modules are developed in transport, energy, waste, health, security, education, communication and governance domains, and not all modules are present in each Digital Twin. Services provided in the Digital Twin are considered in each of these domains. They broadly fall in the following three categories: (1) predictive maintenance, e.g., continuous diagnostic of infrastructures (material fatigue, wear of covers, etc.), and savings on regular maintenance costs (through diagnostic-based maintenance and anticipation of pre-maintenance failures); (2) safety, e.g., monitoring of the condition and operation of infrastructures if there is a risk of intentional or natural damage, on-site intrusion detection, disaster forecasting (flood, fire, etc.), and automated alert (air quality, noise pollution, well-being at work, traffic congestion, smart bins, etc.); and (3) optimization, e.g., remote control of the shutdown or operation of equipment (lighting, barriers, heating, traffic lights, etc.), simulation-based exploration of the best use case scenarios (buildings, traffic, roads, rental vehicles, eco-circular circuits, etc.), improvement of the installation or configuration of new infrastructures (solar panels, 4G/5G coverage, buildings, etc.), and à la carte treatment (digital patient, administrative procedures, academic monitoring, employment, etc.). Data-Model integration addresses what is referred to as probably the most outstanding challenge for the Digital Twin technology, i.e., how data can be dynamically assimilated to detect changes of the real system and reflect them by updating on-the-fly the corresponding models. Model-Service integration focuses on how models are used and possibly combined to provide the expected services. Data-

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 October 2023 doi:10.20944/preprints202310.0659.v1

Service integration focuses on services that can provided directly from data (i.e., without the need for a model), such as the organized access to historical data for monitoring purposes.

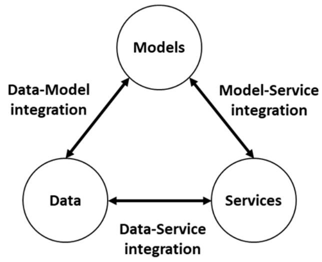

Figure 3. High-level architecture for Digital Twin.

Figure 4 is a synthesis from combining Figure 2 and Figure 3, where a distinction is made at the Human side between the urban decision-maker (i.e., the Smart City manager) and the citizen (i.e., all other users of the Smart City).

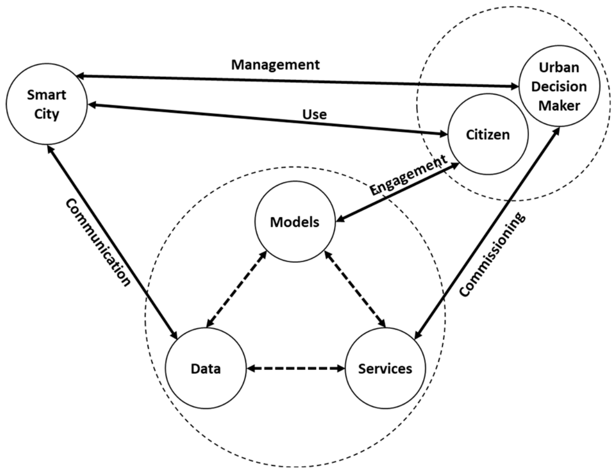

Figure 4. Digital, Physical and Human interoperations.

It conceptually captures the various levels of interoperations between the key stakeholders identified in the value chain of the Smart City Digital Twin. While the Data node of the Digital Twin is the communication gate with the Physical (i.e., the Smart City) is realized, the Services node is the gate enabling the commissioning of the Digital Twin by the urban decision maker, and citizen engagement is done through the Models node.

6. Levels of Digital Twins Interoperability

The molecular structure of the high-level architecture enables larger molecular constructions towards the integration of Digital Twins as System of Systems (SoS). The strength of the architecture is that it describes what has to be done and not how this has to be done, therefore giving flexibility in the choice of the technologies to be used and the way they will be. As several matured technologies already exist, they can be leveraged to serve this purpose. Figure 5 gives the various categories of such larger molecular constructions, which we call levels of Digital Twins interoperability, each of which refers to Digital Twins composition by an adapted mechanism of interoperability between two nodes of the architecture: (a) Data interoperability only involves Data nodes, thus dealing with data format conformance as well as semantic alignment; (b) Model interoperability only involves Models nodes, thus dealing with multiparadigm (i.e., multi-formalism, multiple temporal/spatial scales, multiple abstractions) integration; (c) Service interoperability only involves Services nodes, thus dealing with orchestration and choreography; (d) Data/Model reuse involves the Data node at one side and the Models node at the other side, thus addressing the question of data reuse (i.e., the use of data for models that are not the ones for which the data were initially collected and consolidated)

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 October 2023 doi:10.20944/preprints202310.0659.v1

and/or model reuse (i.e., the use of a model with other datasets than the ones the model use to be fed with) ; (e) Data/Service reuse involves the Data node at one side and the Services node at the other side, thus addressing similarly the question of data reuse and service reuse; and (f) Model/Service reuse involves the Models node at one side and the Services node at the other side, thus addressing similarly the question of model reuse and service reuse.

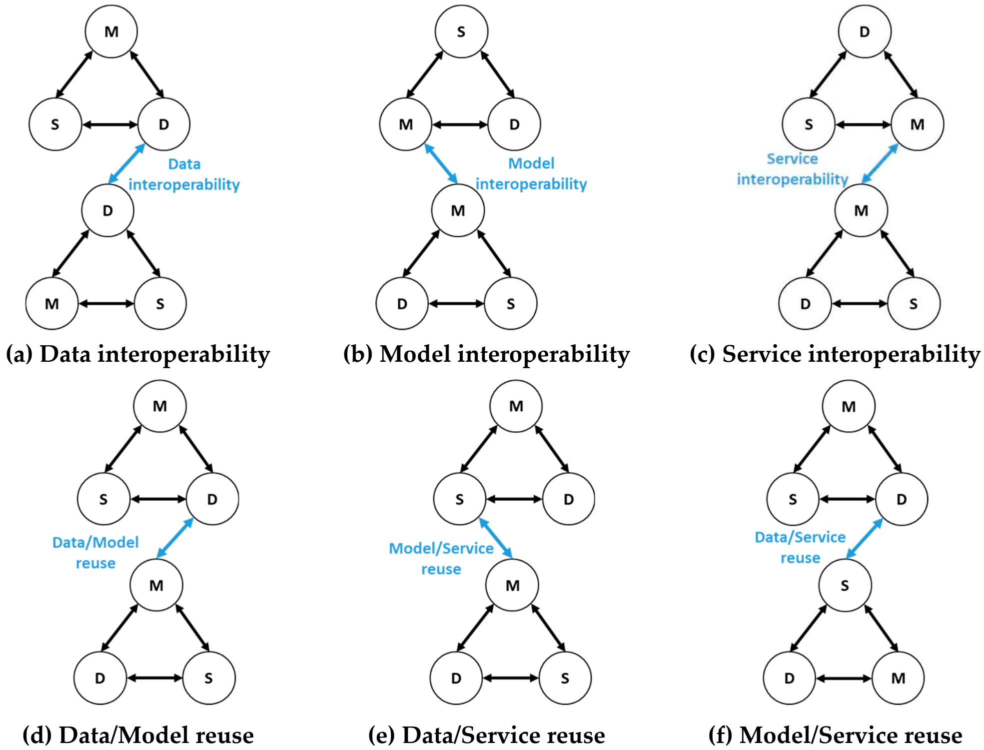

Figure 5. Levels of Digital Twins interoperability: (**a**) Data interoperability: composition by data-to-data interoperability; (**b**) Model interoperability: composition by model-to-model interoperability; (**c**) Service interoperability: composition by service-to-service interoperability; (**d**) Data/Model reuse: composition by reuse of one's data and the other's model; (**e**) Data/Service reuse: composition by reuse of one's data and the other's service; (**f**) Model/Service reuse: composition by reuse of one's model and the other's service.

7. Discussion

The technological ambition of a smart city's Digital Twin is to realize an effective vision of Digital Enterprises within Digital Supply Chains, as shown by Figure 6. Indeed, the Information Technology environments within industrial companies, ranging from embedded systems on shop floor level to operations and manufacturing execution systems or resource planning systems, form a basis for the vision of a digital management of the production plants. Each profile is a digital enterprise with Digital Twins that can be coupled with the Digital Twins of other profiles, leading to the digital supply chain of the network of enterprises then created. In that way, geographically distributed enterprises can form larger Digital Twin-driven consortia, abolishing spatial constraints on the monitoring and control actions, and the overall management of operations. For example, a garment retailer, using its fleet of trucks to support its logistics operations, will plug its digital twin to the one of the Smart City where it is located, and will consequently be part of several supply chains, including the one allowing the fleet of trucks to get fuel, the one allowing the company to receive goods from wholesalers and to deliver them to customers, etc. These supply chains will commission models within the digital twin of the smart city, such as the transport model, the energy model, etc. For this to materialize, two types of Digital Twins interoperability are necessary: (1) the vertical hierarchical composition of Digital Twins, where a set of component digital twins are hierarchically integrated into an asset digital twin, a set of assets digital twins are hierarchically integrated into a production line digital twin, etc.; and (2) the associative composition of Digital Twins (including peer-to-peer

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 October 2023 doi:10.20944/preprints202310.0659.v1

compositions), where Digital Twins of different enterprises are coupled together in a large-scale supply chain, and several such digital supply chains (possibly overlapping) are built and concurrently managed. This will give rise to the concept of "Digital Industrial Territories" (DITs). This is to be foreseen as the next step in the on-going industrial revolution. Current physical industrial territories (made of industrial companies in a given territory) will be mirrored in their digital counterparts, and management, control, monitoring and innovation will be carried out in the digital space before reflecting on the physical areas. Moreover, experimentations and explorations are more efficiently and less costly driven in the digital space. DITs will be composed of Digital Twins of industrial enterprises, and all the competitiveness initiatives and public/private decision-making processes will be rooted there.

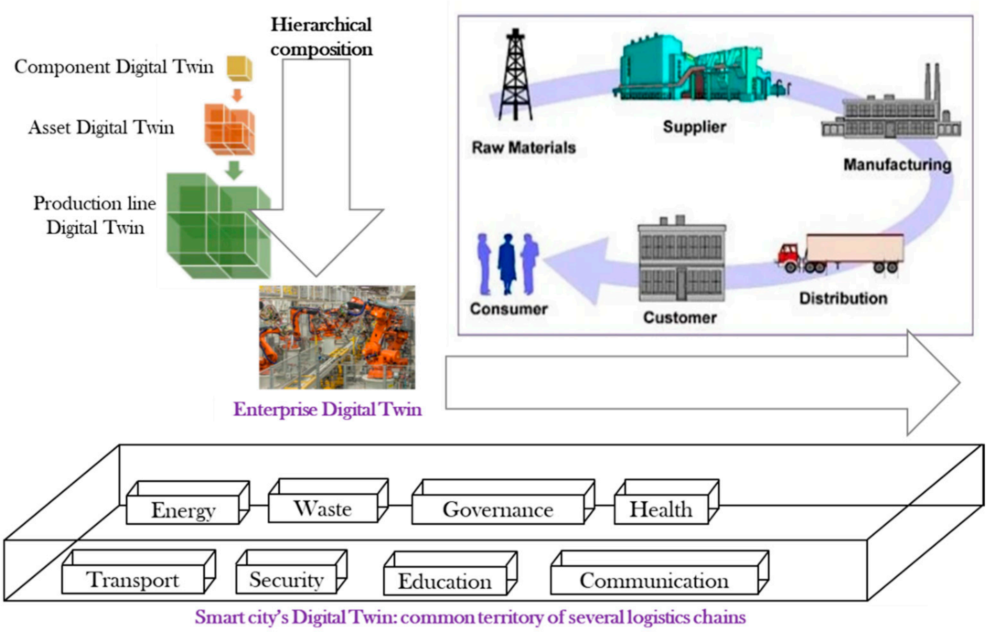

Figure 6. Smart city's Digital Twin-based large-scale interoperability.

8. Conclusions

At the heart of our contribution is a high-level architecture to model Digital Twins in a generic way, enabling their interoperability as well as with physical and human stakeholders. This technology-agnostic architecture shows what has to be implemented and not how this should be done. This paper emphasizes on the potential of the Digital Twin of a Smart City to be a middleware for large-scale interoperability of enterprises, towards the concept of Digital Industrial Territory. Multiple supply chains are then integrated, and a given enterprise will be involved in various supply chains (e.g., energy supply chain, health supply chain, or education supply chain), as an end-user in some cases, and in other cases as an initial supplier, or an intermediary supplier/consumer. As part of our future work, we are focusing on smart city's Digital Twin servitization, (i.e., the Digital Twin used as a service). This entails the development of a Digital Twin-driven engineering methodology towards Off-the-shelf Digital Twins. Related research issues to be addressed include reusability, adaptation and validation of Digital Twins.

References

1. Goldstone, J. A. (2010). The new population bomb: the four megatrends that will change the world. Foreign Aff., 89, 31.
2. Hallegatte, S., Rogelj, J., Allen, M., Clarke, L., Edenhofer, O., Field, C. B., Friedlingstein P., Van Kesteren L., Knutti R., Mach K.J., Mastrandrea M., Michel A., Minx J., Oppenheimer M., Plattner G-K., Riahi K., Schaeffer M., Stocker T.F., Van Vuuren, D. P. (2016). Mapping the climate change challenge. Nature Climate Change, 6(7), 663-668.

3. Yin, C., Xiong, Z., Chen, H., Wang, J., Cooper, D., & David, B. (2015). A literature survey on smart cities. Sci. China Inf. Sci., 58(10), 1-18.
4. Farsi, M., Daneshkhah, A., Hosseinian-Far, A., & Jahankhani, H. (Eds.). (2020). Digital twin technologies and smart cities. Berlin/Heidelberg, Germany: Springer.
5. Traoré M.K. 2021. Unifying Digital Twin Framework: Simulation-Based Proof-of-Concept. In Proceedings of the 17th IFAC Symposium on Information Control Problems in Manufacturing (INCOM) – June 7-9, Budapest, Hungary, In Press. IFAC – PapersOnLine, pp 886-893.
6. Traoré M.K. and Ducq Y. 2022. Digital Twin for Smart Cities: An Enabler for Large-Scale Enterprise Interoperability. In Proceedings of the 11th International Conference on Interoperability for Enterprise Systems and Applications (IESA) – Enterprise Interoperability Through Connected Digital Twins. March 23-25, Valencia, Spain.
7. MacLeod, G. (2018). The Grenfell Tower atrocity: Exposing urban worlds of inequality, injustice, and an impaired democracy. City, 22(4), 460-489.
8. Dong, B., Xia, J., Li, Q., & Zhou, M. (2022). Risk assessment for people and vehicles in an extreme urban flood: Case study of the "7.20" flood event in Zhengzhou, China. International journal of disaster risk reduction, 80, 103205.
9. Ford, D. N., & Wolf, C. M. (2020). Smart cities with digital twin systems for disaster management. Journal of management in engineering, 36(4), 04020027.
10. McGrath J. 2018. Becoming a Smart City Takes more than Sensors and Buzzwords. Digital.
11. Deng, T., Zhang, K., & Shen, Z. J. M. (2021). A systematic review of a digital twin city: A new pattern of urban governance toward smart cities. Journal of Management Science and Engineering, 6(2), 125-134.
12. Deren L., Wenbo Y., & Zhenfeng, S. (2021). Smart city based on digital twins. Computational Urban Science, 1, 1-11.
13. Ruohomäki, T., Airaksinen, E., Huuska, P., Kesäniemi, O., Martikka, M., & Suomisto, J. (2018, September). Smart city platform enabling digital twin. In 2018 International Conference on Intelligent Systems (IS) (pp. 155-161). IEEE.
14. Xia, H., Liu, Z., Efremochkina, M., Liu, X., & Lin, C. (2022). Study on city digital twin technologies for sustainable smart city design: A review and bibliometric analysis of geographic information system and building information modeling integration. Sustainable Cities and Society, 84, 104009.
15. NOMINET. List of Smart City projects. https://www.nominet.uk/list-smart-city-projects/
16. M. Hung ed. 2017. Leading the IoT – Gartner Insights on How to Lead in a Connected World.
17. Digital Twins for low emission last miles logistics. https://www.leadproject.eu/
18. Living in EU. https://living-in.eu/
19. Piascik, R., et al., Technology Area 12: Materials, Structures, Mechanical Systems, and Manufacturing Road Map. 2010, NASA Office of Chief Technologist.
20. Gelernter, David Hillel (1991). Mirror Worlds: or the Day Software Puts the Universe in a Shoebox—How It Will Happen and What It Will Mean. Oxford University Press.
21. Grieves, M. (2005). Product Lifecycle Management: the new paradigm for enterprises. Int. J. Prod. Dev. 2: 71-84.
22. Grieves, M. (2006). Product Lifecycle Management: Driving the Next Generation of Lean Thinking. New York: McGraw-Hill.
23. Grieves, M. (2011). Virtually Perfect: Driving Innovative and Lean Products through Product Lifecycle Management. Cocoa Beach, FL: Space Coast Press.
24. Grieves M., Vickers J. 2016. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems, in Trans-Disciplinary Perspectives on System Complexity, F.-J. Kahlen, S. Flumerfelt, and A. Alves, Ed. Springer: Switzerland. p. 85-114.
25. Glaessgen E., Stargel D. 2012. "The digital twin paradigm for future NASA and US Air Force vehicles." 53rd AIAA/ASME/ASCE/AHS/ASC.
26. Rosen R., von Wichert G., Lo G., Bettenhausen K.D. 2015. About the Importance of Au-tonomy and Digital Twins for the Future of Manufacturing, IFAC 48(3): 567-572.
27. Grieves, M. (2019). Virtually Intelligent Product Systems: Digital and Physical Twins, in Complex Systems Engineering: Theory and Practice, S. Flumerfelt, et al., Editors. 2019, American Institute of Aeronautics and Astronautics. p. 175-200.
28. Schluse M., Rossmann J. 2016. From simulation to experimentable digital twins: simulation-based development and operation of complex technical systems. IEEE ISSE, pp. 1-6.
29. Negri, E., Fumagalli L., Macchi M. 2017. A Review of the Roles of Digital Twin in CPS-based Production Systems. In Procedia Manufacturing, 11, pp. 939–948.
30. Reifsnider K., P. Majumdar, Multiphysics Stimulated Simulation Digital Twin Methods for Fleet Management, in: 54th AIAA/ASME/ASCE/AHS/ASC, 2013: p. 1578.

31. Tao F., Cheng J., Qi Q., Zhang M., Zhang H., Sui F. 2017. Digital twin-driven product de-sign, manufacturing and service with big data. In International Journal of Advanced Manu-facturing Technologies, 10 (4), p. 2233.
32. Zhang H., Liu Q., Chen X., Zhang D., Leng J. 2017. A digital twin-based approach for designing and multi-objective optimization of hollow glass production line. IEEE Access, n° 5, pp. 26901-26911.
33. Damjanovic-Behrendt V. 2018. A digital twin-based privacy enhancement mechanism for the automotive industry. Int. Conf. on Intell. Syst. (IS) (2018), pp. 272-279.
34. Tuegal E.J., Ingraffea A.R., Eason T.G., Spottswood S.M. 2011. 'Reengineering Aircraft Structural Life Prediction Using a Digital Twin', Int. J. of Aerospace Eng., Vol 2011.
35. Zhang M., Zuo Y., Tao F. 2018. Equipment energy consumption management in digital twin shop-floor: A framework and potential applications. IEEE 15th Int. Conf. on Net., Sensing and Control (ICNSC), pp. 1-5.
36. Bramlet, M., Wang, K., Clemons, A., Speidel, N.C., Lavalle, S.M., & Kesavadas, T. 2016. Virtual reality visualization of patient specific heart model. Journal of Cardiovascular Mag-netic Resonance, 18: T13.
37. Bolton R.N., McColl-Kennedy J.R., Cheung L., Gallan A., Orsingher C., Witell L., Zaki M. 2018. "Customer experience challenges: Bringing together digital, physical and social realms". J. of Service Management. 29 (5): 776–808.
38. Bailenson, J. N., Segovia, K. Y. 2010. "Virtual doppelgangers: psychological effects of avatars who ignore their owners," in Online Worlds: Convergence of the Real and the Virtual, ed. W. S. Bainbridge (London: Springer), 175–186.
39. Bauernhansl T., Hartleif S., Felix T. 2018. "The Digital Shadow of production – A concept for the effective and efficient information supply in dynamic industrial environments". 51st CIRP Conf. on Manuf. Syst., 69-74.
40. Ben Miled Z., and French, M.O. 2017. "Towards a reasoning framework for digital clones using the digital thread". 55th AIAA Aerospace Sciences Meeting, 0873.
41. Bramlet, M., Wang, K., Clemons, A., Speidel, N.C., Lavalle, S.M., & Kesavadas, T. 2016. Virtual reality visualization of patient specific heart model. J. of Cardiovascular Magnetic Resonance, 18: T13.
42. El Saddik, A. 2018. "Digital Twins: The Convergence of Multimedia Technologies". IEEE MultiMedia. 25 (2): 87–92. doi: 10.1109/MMUL.2018.023121167. ISSN 1070-986X.
43. Park H., Easwaran A., Andalam S. 2019. Challenges in Digital Twin Development for Cyber-Physical Production Systems. In: Chamberlain R., Taha W., Törngren M. (eds) Cyber Physical Systems. Model-Based Design. LN in CS, vol 11615. Springer, Cham.
44. Rios J., et al. 2015. "Product Avatar as Digital Counterpart of a Physical Individual Product: Literature Review and Implications in an Aircraft System." In Proc. of ISPE CE2015 2: 657–666, 2015.
45. Poursoltan M., Traoré M.K., Pinède N., VallespirB. 2020. A Digital Twin Model Driven Architecture for Cyber-Physical and Human Systems. In Proceedings of IESA. November 17-20, Tarbes, France. DOI: 10.1007/978-3-030-90387-9