Digital Twin for Smart Cities: An Enabler for Large-Scale Enterprise Interoperability

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Abstract

In a context of increasingly connected production systems and ambient intelligence, the digital twin is an approach that is becoming increasingly popular to help control and pilot such systems. The interest for the digital twin is to be able to meet a need for modeling and piloting as close as possible to the physical system and a better anticipation of behavior. How, in this context, the question of the composition of digital twins to model a system of systems, where each system already has its own digital twin? This paper examines such a question from the perspective of digital twin for smart cities. The position adopted here is the concept of Digital Industrial Territories, a middleware for large scale interoperability between digital twins of enterprises involved in multiple supply chains (energy, transport, health, etc.).

Keywords

Digital Twin, Industry 4.0, smart city, interoperability.

1. Introduction

The development of Industry 4.0 in the last years has focused on the development of higher level of digitization. In that context, advanced manufacturing technologies and systems are oriented towards the deployment and use of Digital Twin (DT), a building block of digital transformation, in order to address the need for agility in production and/or predictive quality of products and processes. Indeed, as current industries are increasingly faced with the challenge of delivering more customized products in shorter production times, they need to respond by having agile production systems, which can be efficiently reconfigured as needed. With shortening lifecycles and increasing market demands, a constant improvement of current systems is taking place.

In such a context, a DT of a manufacturing system can address the challenge of making systems easily and quickly reconfigurable by applying it for realizing and testing reconfiguration scenarios in a simulative environment.

Intelligent manufacturing involves integrating detection, computing and communication capabilities with traditional physical infrastructures to increase efficiency, resilience and security. In other words, a digital double is expected for almost each constituent element. Therefore, the existence of a "digital model" coupled with the object it copies is implied. The objects concerned can be a product, a machine, a production line, a process, or a supply chain. Depending on the system concerned and the desired use, it can be a geometric, multi-physical, functional, behavioral model, which must evolve over time like its real twin, while providing means for diagnosis, prognosis, and decision-making. For example, each turbine of a power plant comprises thousands of components, each of which is subject to failure based on metallurgy, load, environment, and other factors. By building a DT for every critical turbine assembly, enriching it with situational data such as system load, ambient temperature, and air quality, and continuously analyzing it using advanced statistical tools, plant operators can bring turbines down for maintenance predictively, eliminating the costs of

Proceedings of the Workshop of I-ESA'22, March 23–24, 2022, Valencia, Spain
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unnecessary downtime and mitigating the risks of unplanned outages. The individual DTs can also be leveraged in the whole supply chain of the plant, such that the behavior of the supply chain can be simulated based on energy consumption of the plant's customers. How can such a digital supply chain be efficiently built? This paper examines the potential of smart cities digital twin to achieve this goal.

The remaining of the paper is organized as follows: Section 2 gives a unifying view of the DT concept that subsumes the numerous viewpoints available in the literature. Section 3 presents the architecture and key components of smart cities' DTs. Section 4 discusses how such DTs can provide the large-scale interoperability middleware for enterprises' DTs. Section 5 concludes the paper.

2. Digital twin concept

When interacting with stakeholders in different communities, the use of the term Digital Twin raises the question of its formal definition. Nonetheless, the various DT viewpoints [1-14] fall under one common umbrella, that can be expressed by an invariant characteristic.

A numerical model of a system of interest, that we call the Twin of Interest (TOI), becomes its DT when there is a synchronization between the TOI and the DT, 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 DT, 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 DT is either clock-based (ranging from real-time/near real-time synchronization to low-frequency synchronization) or event-based (ranging from on-condition/cyclic synchronization, to on-demand synchronization).

The synchronization between the TOI and the DT 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 DT 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 DT side. Therefore, the twinning loop can either be closed (in which case, the DT not only monitors the TOI but also controls it) or open (in which case a third party makes and applies the control decision).

3. Digital twin for smart cities

The digital twin of a city is of high strategic importance to public decision-makers, as urban metropolitan areas are facing new challenges of sustainable development due to increasing digitization of their production and service systems. Examples include the expansion of public transport networks, mechanisms to address global warming, measures to preserve air quality and their impact on public health, and infrastructures to favor energy transition. In such a context, the concept of smart city is central, as it relates to intelligent transport, energy, climate, and health challenges. 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. 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, these 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.

A snapshot of state-of-the-art smart city initiatives shows that, even if the focus is on the use of IoT in an urban planning context across a large spectrum of applications (https://www.nominet.uk/list-smart-city-projects/), few of the projects scale to the building of a digital twin of the city, due to most of them facing the challenge of being flooded by data and details. Significant visible initiatives include: (i) Mini Tokyo (https://minitokyo3d.com), the DT of the city of Tokyo (Japan), which aims at providing a real-time 3D map of Tokyo's urban public transport; (ii) the Singapore city's DT (https://www.nrf.gov.sg/programmes/virtual-singapore), which aims at providing a 3D model of the city, as well as a data platform open to the public and private sectors, and researchers and civil society for developing applications and performing holistic urban development tests; (iii) the Rennes city's DT, which aims at having a virtual territory fed with data from the Rennes metropolis and its partners to simulate and predict the future (https://metropole.rennes.fr/rennes-metropole-smart-city).

Figure 1, synthesizes the modular architecture of smart cities' DTs. At one side is the smart city, which is necessarily a cyber-physical system, 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 other side is the DT 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. Models in the DT 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 DT, but they are the building blocks that use to appear when the questions they allow to answer to are targeted by city planners.

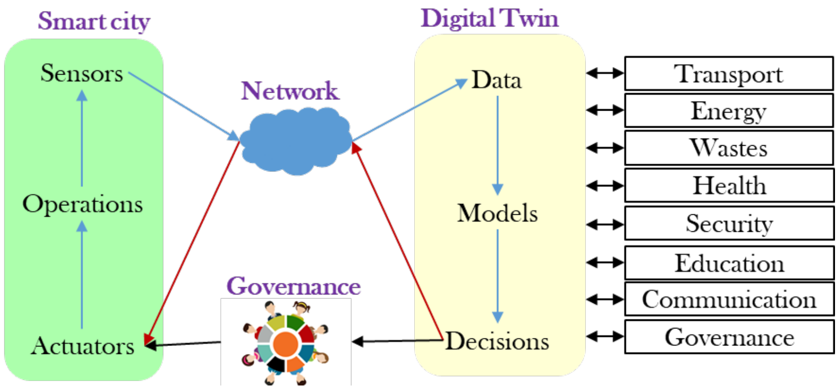

Figure 1: Smart city's DT architecture

The following three main objectives are considered in each of the domains:

1. Predictive maintenance, e.g., continuous diagnostic of infrastructures (material fatigue, wear of covers, etc.), savings on regular maintenance costs (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.), automated alert (air quality, noise pollution, well-being at work, traffic congestion, smart bins, etc.).
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.), à la carte treatment (digital patient, administrative procedures, academic monitoring, employment, etc.).

4. Digital twin-based large-scale interoperability

The technological ambition of a smart city's DT is to realize an effective vision of Digital Enterprises within Digital Supply Chains (Figure 2). Indeed, the Information Technology (IT) 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 DTs that can be coupled with the DTs 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 DT-driven consortia, abolishing spatial constraints on the monitoring and control actions, and the overall management of operations. For this to materialize, two types of DT interoperability are necessary (as shown by Figure 2):

(1) the vertical hierarchical composition of DTs, 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.

(2) the associative composition of DTs (including peer-to-peer 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 DTs of industrial enterprises, and all the competitiveness initiatives and public/private decision-making processes will be rooted there.

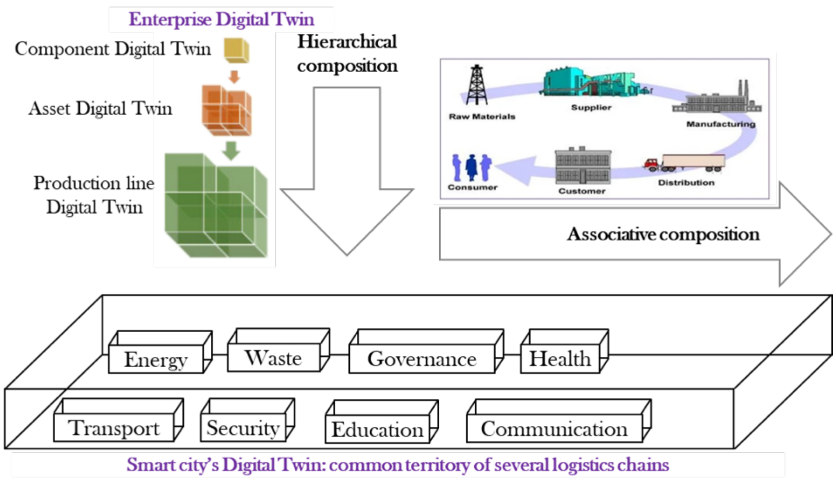

Figure 2: Smart city's Digital Twin-based large-scale interoperability

5. Conclusion

This position paper emphasizes on the potential of the DT 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. For example, a garment retailer, using its fleet of trucks to support its logistics operations, will plug its DT to the one of the smart city of its location, and will consequently be part of several supply chains, including the one allowing to get fuel, the one to receive goods from wholesalers and to deliver them to customers, etc. These supply chains will commission models within the DT of the smart city, such as the transport model, the energy model, etc. As part of our future work, we are focusing on smart city's DT servitization, (i.e., the DT used as a service). This entails the development of a DT-driven engineering methodology towards DT componentry. Related research issues to be addressed include coupling, interoperability, and reusability of DTs.

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