Digital Twins Approach for Sustainable Industry

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Abstract. Sustainable industry is a part of The European Green Deal, which aims to achieve the EU's climate and environmental goals based on the circular economy. Digital twins are important technologies for realizing industry 4.0 and related sectors. In this paper, we looked at building the DTs for manufacturing, healthcare and construction industrial sectors in Industry 4.0 architecture to realize a sustainable industry.

Keywords: Digital Twins, Sustainable Industry, Industry 4.0.

1 Introduction

Industry 4.0 brings the potential for increased flexibility and efficiency, cost reduction, and increased competitive advantage. Current trends towards Industry 5.0 [1] introduce a complementary view, targeting a sustainable, human-centric, and resilient industry. The notion of Industry 5.0 represents an even more comprehensive strategy on science, technology and innovation aiming for all industries more sustainable while providing effective responses to the economic, technological, and societal rising challenges.

Digital Twins (DTs) describe the effortless integration of data between a physical and virtual object in either direction [2]. Digital Twin is at the forefront of the Industry 4.0/5.0 revolution facilitated through advanced data analytics and the Internet of Things (IoT) connectivity. IoT's data rich environment, coupled with data analytics, provides an essential resource for various problems on the digital-physical interface including but not limited to predictive maintenance and fault detection. In the paper, the initial focus is on manufacturing, healthcare, and construction (addressing e.g., sustainable manufacturing and anomaly detection in patient care) and to look at a potential Industry 4.0 architecture to support sustainable industry through DT technologies.

Manufacturers track, monitor and simulate manufacturing and related processes to save time, reduce costs, become disruption resilient and environmentally friendly [3]. Digital Twins, providing these capabilities, thus have a significant potential for impact within this field [4].

In healthcare and wellbeing (wearable) IoT devices are cheaper and easier to implement than ever before. Based upon this Digital twins of a human, giving real-time analysis of vital signs are now possible. A Digital Twin is used for monitoring and planning treatment and follow up after surgery [5, 6].

The construction industry can benefit from Digital Twins by applying them in the development of smart buildings/shopfloors or structures but also as an ongoing real-time prediction and monitoring tool [7, 8]. The use of the Digital Twins and data analytics provides greater quality of Building Information Modelling and predictive maintenance.

A decentralized network comprised of a multitude of ecosystems still yet to be connected and integrated to enable a wide range of applications that contribute to sustainable industry. Building DTs for smart manufacturing, healthcare, and intelligent construction is a necessary step for realizing such sustainable industry. In this paper, we review related DT technologies in manufacturing, healthcare and construction industry in Section 2. Section 3 discusses the sustainable industry's objectives and requirements. Section 4 details the architectural solution combining existing implementational architecture. At last, Section 5 rounds up the paper with the conclusions.

2 Digital Twins in Manufacturing, Healthcare, and Construction Industry

Nowadays, the DT paradigm is becoming more and more permeating in many research domains such as manufacturing, healthcare and construction industry. Since DT concept was proposed, manufacturing has stood out as one of the most promising application fields, attracting substantial attention from both academia and industry. Although there is no unified definition of DT yet, it is well-accept that a DT has to be made by three components: physical entity, virtual entity and their connections [9, 10]. As counterpart of a physical entity, a virtual entity could receive real-time running data of physical entity, analyze it and provide predictive results through simulation that can support decision making. Accordingly, the performance of physical entity could be improved or optimized.

It is clear that bidirectional communication between physical entity and virtual entity is essential to implement a real DT [9]. As a result, Tao et al. proposed that a complete DT should be defined in five dimensions: physical part, virtual part, connection, data, and service [11]. Meanwhile, they listed 9 types of services provided by DT in another work [12]. The researches on DT in manufacturing could be exemplified in different scales, such as equipment [13, 14], workstation [15, 16], production line [17] and production system [18], in terms of these five dimensions as well.

In order to make the CNC machine tool intelligent, Luo et al. [13] applied DT on CNC machine tool to optimize its running mode, reduce its sudden failure probability and improve its stability. Liu et al. [14] investigated the connection modeling and data modeling of CNC machine tool in cyber-physical production system. Two popular information modeling and data exchanging standards for industrial equipment, OPC

UA and MTConnect, are successfully applied for digital twins of CNC machine tools. Havard et al. applied DT for the design of human robot collaborative assembly workstation [15].

The ergonomic assessment and safety issue simulation of DT are used to optimize workstation design and regularize the human workers' behavior. Söderberg et al. [16] did an attempt to develop the DT of a sheet metal part assembly line. Their DT can not only use data from individuals to perform real time in-line individual adjustments, but also use data from batches of parts to make adjustment batch wise.

Zhang et al. [17] used DT to optimize the design of hollow glass production line. Benefitting from the powerful simulation of DT, the running information of production line such as the order delivery time, production takt time and production load can be calculated for its iterative optimization.

Fan et al. emphasized the digital twin visualization of flexible manufacturing system [18]. The visualization method of high-value information, for instance, life cycle planning, design, debugging and service stages, was investigated to achieve a lightweight architecture without compromising its functions. As a large amount of work on DT applications in manufacturing exists, the review on the selected literature just provided a systematic view due to space limitation. More details can be found in Ref. [4, 19].

As part of a rise in use of personal health monitoring devices in the form of mobile applications or build-in sensors, which can actively monitor real-time user's vital health parameters, DT technology is being explored to develop fast, accurate and economical solutions to address the massive strain on existing healthcare resources caused by rapid population growth as well as aging populations. Croati et al. present a new healthcare system by integrating DTs with agents and Multi-Agent Systems (MAS) technologies [5]. A preliminary version of a system prototype was developed according to the designed conceptual model and a trauma management process was selected as a case study to evaluate the proposed model. Unfortunately, the paper does not present results that demonstrate the efficiency of the proposed model.

Liu et al. propose a cloud-based healthcare system based on the concept of DT [6]. The patient information, sensed data along with patient symptoms are described by the proposed DT framework to provide real-time monitoring and enabling a personalized healthcare plan with the overall goal of supporting self-management of elderly patients. The results show that a virtual replica of a patient could be an optimal solution for improving healthcare operations.

Rivera et al. present a DT driven model for personalized medical treatments [20], where machine learning and DT serve to track the health status of patients continuously and to allow for virtual evaluation of medical treatments. The definition of internal structures of DT to support precision medicine techniques were elaborated but the system work has not been evaluated in a real case scenario.

Elayan et al. present an intelligent context-aware healthcare system using a proposed (and implemented) DT and IoT framework was proposed to improve healthcare operations [21]. In this framework, a machine learning enabled electrocardiogram (ECG) heart rhythms classifier model was built to diagnose heart disease. The results show that the implemented DT framework with prediction model successfully detects a particular heart condition with quite high accuracy.

Digital twins are broadly applicable, not only in health, but in all kinds of application areas including the construction industry. In the construction industry DT technology has the potential to drive transformation and modernization leading to increased sustainability. Opoku et al. review 22 publications about DT application in the construction industry [7]. The paper provides an overview of the origin, evolution of the concept and industrial applications of DT in the construction industry. It shows that most of the investigated DT applications in the construction industry focused on the design and engineering phase while ignoring the demolition and recovery phases of projects.

Lin and Cheungh propose an advanced monitoring and control system using DT enabled Building Information Modelling (BIM) for underground garage environment management [22]. This paper establishes a real time active model using the combination of BIM and IoTs technologies to provide efficient information during the design of the project. The results show that the designers can make informed decisions by having a complete digital footprint of the project through DT.

Sacks et al. present a data-centric mode of construction management system built on existing concepts of AI and DT [8]. The paper extends the existing understanding of DTs in the construction industry by applying conceptual analysis to derive the four-core information and control concepts to define future development of DT construction systems for the design and construction phases of buildings and infrastructure facilities.

Lu et al. describe a semi-automatic geometric DT system they developed based on images and CAD drawings for facilitating building operation and maintenance management [23]. The paper elaborates on the methodological framework of the proposed semi-automatic geometric DT approach and an office building was employed as a case study to evaluate the proposed system. The results show that DT-assisted operations and maintenance are an effective approach in the operations phase of the building.

3 Sustainable Industry

Sustainable industry is a part of The European Green Deal, which aims to achieve the EU's climate and environmental goals based on the circular economy [25]. Sustainability and tackling energy and resource issues (from production to installation, from use and maintenance to disposal or recycling) should be placed at the heart of the combined digital and green transitions early on.

Digital twins are important technologies for realizing industry 4.0 and related sectors. Different DTs can be used for simulating products, materials, and production processes respectively. Another kind of Digital twin is a virtual model of the factory including all elements, i.e., machines, products, and humans, that can be used to simulate the plant operation for improvement or decision making.

Furthermore, the use of industrial data to establish data-based services has potential for further innovation. Digital twins enable sustainable industry where collected industrial data is expected to help improving productivity, flexibility, and resource efficiency through big data for predictive maintenance and fast production system reconfiguration [26].

When a digital twin is used as a virtual model of the factory, it is a model that transvers all parts of the production chain. Such a digital twin can be used to design for disassembly, remanufacturing, and recycling applied in the production life cycle management. In the production life cycle management, lean and green management for resource efficiency can be simulated by using digital twin technologies. A digital twin that connects with a supply chain management, reverse logistics can be designed and evaluated with key performance indicators for the circular economy.

3.1 Objectives and problem descriptions

In an increasingly digitized world, the physical and digital domains are increasingly intersecting. Digital Twins, originating in NASA, provide a powerful tool that captures this intersection by providing digital representations of physical objects or processes. Not only do Digital Twins provide an interface for the digital world to interact with the physical world, their nature as a digital model of the physical allows for the Digital Twins to be used in ways, for example for simulation, that the physical twin could not.

As the needs of the various cyber physical systems of our modern world are diverse, the form, shape and capabilities of Digital Twins are diverse too, but all are based upon common ingredients: Modeling the physical object to a required fidelity; mediate digital interactions with its physical counterpart; data analytics to maintain consistency with the real-world counterpart; statistics and AI to allow predictions to be made about the future or hidden properties of the physical twin; simulation technology to make predictions on constellations of twinned pairs.

The paper brings together four different types of DTs as well as the even broader application areas. Digital twins, in their nature interdisciplinary, combine various fields of understanding and research. Depending on the purpose of the Digital Twins, different aspects of domain knowledge as well as modeling and simulation approaches is needed.

Some examples of potential technical fields or strategic application domains [22, 27]:

- Digital twins for sustainable manufacturing simulation and real-time interaction with cyber-physical systems
- AI assisted training and assistance systems for optimal factory operation
- Management systems for lifecycle monitoring and operations
- ICT architectures, platforms and standards for industry and logistics 4.0
- High-performance manufacturing systems
- Sustainable, secure and resilient interconnection of all stakeholders and systems
- Cyber-physical production and logistics systems

In short, digital twins can support value creation in different sustainability dimensions. Using digital twins and industrial data generates new business models and new product-services for organizations. Digital twins can be used to improve resource efficiency in a sustainable-oriented decentralized organization through simulation and optimizations. Different digital twins for closed-loop product life cycles and industry symbiosis create value networks. Sustainable production process using digital twins can provide increased sustainability, flexibility, and resiliency. Finally, digital twins could also realize training and competence developments of sustainable industries' needs.

4 Architecture

Digital twins are used in the context of a broader industrial ecosystem with supporting IT architecture. Such an architecture is ideally based upon a firm, existing basis, such as provided by FIWARE. FIWARE is an open-source framework for Industry 4.0 as well as a service ecosystem composed of various components, described as Generic Enablers (GEs) [28]. The GEs can range from different IoT/smart devices, components, and services to big data analysis components for the development of different application solutions. Interoperability and modularity are the key aspects that the FIWARE platform promotes and supports. This offers the industries the ability to easily develop and integrate smart solution for different needs and processes with GE components in a modular manner [28]. In this work, FIWARE is thus adopted for several reasons such as flexibility, interoperability, supporting big data analytics, and by supporting open and industrial standard data model allowing the ease integration of different IoT smart devices, systems.

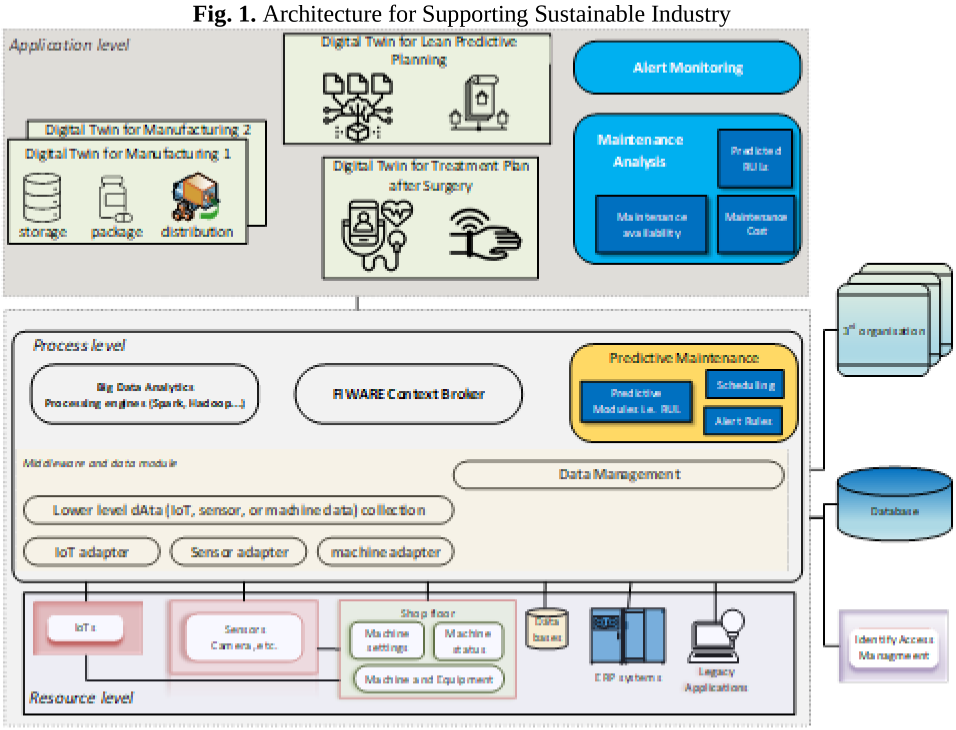
Based on the objectives identified in Section 3.1, digital twins can be implemented for single elements within an organization or multiple digital twins can work together within one organization for optimizing sustainable production processes. Moreover, different digital twins for closed-look product life cycles, and industry symbiosis enable the creation of value networks. Thus, based upon FIWARE, **Fig. 1** shows the architecture for DTs for sustainable industries. The proposed architecture can support digital twins within one organization with collected industrial data from different machines, IoTs, etc. as well as support digital twins of crossing different organizations for creating value networks from industry symbiosis.

On the basis of our previous work [29, 30], the architecture is organized in three levels: resource, process and application levels. Sensors, IoTs, items of shopfloor and legacy systems are located at the resource level. Different adapters for sensors, IoTs and machines are collected and managed at the middleware and data modules of the process level. The process level also includes big data analytics and processing engines as well as the FIWARE context broker. The FIWARE context broker provides the communication mechanism with different adapters and the related data sources and storage required for the platform. Our previous work on predictive maintenance provides predictive modules i.e., RUL, predicative maintenance scheduling module, and alert rules module are included at the process level as well. The application level, the predictive maintenance related analysis and monitoring services are supported.

From a common basis and point of synergy, the four different digital twin application areas enhance and bring together our existing expertise [25]. The four digital twins will be developed in the applications level. One manufacturing digital twin will demonstrate improving resource efficiency in a sustainable-oriented decentralized organization. One manufacturing digital twin will extend value networks, i.e., horizontal logistic and production process integration. We explore the visualization and monitoring of manufacturing processes to enhance sustainability and resilience of production and supply chains through digital twin technologies.

One digital twin for lean predictive planning provides shopfloor construction planning capabilities. We explore Building Information Management, an enabler of information delivery and visualization platform that integrates the stakeholders in the supply chain. Given that it has the potential to provide a virtual replica of the physical facility and facilitate vital product information, it naturally serves as a Digital Twin platform, a vital source of information for the proposed project to improve the construction processes from the lean perspective. The digitization of the construction will make the process efficient and effective while retaining the flexibility inherent to this lean approach.

Fig. 1. Architecture for Supporting Sustainable Industry



The digital twin for treatment plan enables the improved provision of treatment plans after surgery. We will explore with a biotechnology Ltd. and an obstetrics and gynecology hospital the synergy effect of cutting-edge IT technologies, medical and human factors to create a customized treatment plan to improve patients' quality of life and recovery after surgery (through customized treatment plans and simulation of options). The four mentioned digital twins share some data collection, data management and some data analysis modules in the proposed architecture.

5 Conclusion

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Based upon cross-disciplines research carried on within the work, the individual DTs cross application domains will be implemented to provide a wide impact through:

- Providing demonstrations for Digital Twin technology for four areas, i.e. building plans, manufacturing, supply chain, and medical treatment.
- Working with real-world cases and individual organizations, sharing the technologies across and developing shared platforms.
- Disseminate to and extend our work with local authorities and businesses.
- Evaluate Digital Twin public health impact in working environments.
- Plans with local hospitals and a public health team providers to develop and evaluate Digital Twins for patient treatments and recovery.

References

1. EU Homepage, https://ec.europa.eu/info/research-and-innovation/research-area/industrial-research-and-innovation/industry-50_en, last accessed 2022/03/14.
2. Grieves, Michael, and John Vickers. "Digital Twin: Mitigating unpredictable, undesirable emergent behavior in complex systems." In Transdisciplinary perspectives on complex systems, pp. 85-113. Springer, Cham (2017).
3. Fuller, A., Fan, Z., Day, C., & Barlow, C. Digital twin: Enabling technologies, challenges and open research. IEEE access, 8, 108952-108971 (2020).
4. He, B., & Bai, K. J. Digital twin-based sustainable intelligent manufacturing: A review. Advances in Manufacturing, 9(1), 1-21 (2021).
5. Croatti, A., Gabellini, M., Montagna, S., & Ricci, A. On the integration of agents and digital twins in healthcare. Journal of Medical Systems, 44(9), 1-8, (2020).
6. YingLiu, Lin Zhang, Yuan Yang, Longfei Zhou, Lei Ren, Fei Wang, Rong Liu, Zhi bo Pang, and M.Jamal Deen.2019. A Novel Cloud-Based Framework for the Elderly Healthcare Services Using Digital Twin. IEEE Access 7(2019),49088–49101.

7. Opoku, D. G. J., Perera, S., Osei-Kyei, R., & Rashidi, M. Digital twin application in the construction industry: A literature review. Journal of Building Engineering, 40, 102726, (2021).
8. Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. Construction with digital twin information systems. Data-Centric Engineering, 1 (2020).
9. Cimino, C., Negri, E., & Fumagalli, L. Review of digital twin applications in manufacturing. Computers in Industry, 113, 103130, (2019).
10. Tao, F., Zhang, H., Liu, A., & Nee, A. Y. Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4), 2405-2415, (2018).
11. Tao, F., Zhang, M., & Nee, A. Y. C. Digital twin driven smart manufacturing. Academic Press, (2019)
12. Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F. Digital twin-driven product design, manufacturing and service with big data. The International Journal of Advanced Manufacturing Technology, 94(9), 3563-3576, (2018).
13. Luo, W., Hu, T., Zhang, C., & Wei, Y. Digital twin for CNC machine tool: modeling and using strategy. Journal of Ambient Intelligence and Humanized Computing, 10(3), 1129-1140, (2019).
14. Liu, C., Vengayil, H., Lu, Y., & Xu, X. A cyber-physical machine tools platform using OPC UA and MTConnect. Journal of Manufacturing Systems, 51, 61-74, (2019).
15. Havard, V., Jeanne, B., Lacomblez, M., & Baudry, D. Digital twin and virtual reality: a co-simulation environment for design and assessment of industrial workstations. Production & Manufacturing Research, 7(1), 472-489, (2019).
16. Söderberg, R., Wärmefjord, K., Carlson, J. S., & Lindkvist, L. Toward a Digital Twin for real-time geometry assurance in individualized production. CIRP annals, 66(1), 137-140, (2017).
17. Zhang, H., Liu, Q., Chen, X., Zhang, D., & Leng, J. A digital twin-based approach for designing and multi-objective optimization of hollow glass production line. Ieee Access, 5, 26901-26911, (2017).
18. Fan, Y., Yang, J., Chen, J., Hu, P., Wang, X., Xu, J., & Zhou, B. A digital-twin visualized architecture for Flexible Manufacturing System. Journal of Manufacturing Systems, 60, 176-201, (2021).
19. Lu, Y., Liu, C., Kevin, I., Wang, K., Huang, H., & Xu, X. Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues. Robotics and Computer-Integrated Manufacturing, 61, 101837, (2020).
20. Rivera LF, Jiménez M, Angara P, Villegas NM, Tamura G, Müller HA. Towards continuous monitoring in personalized healthcare through digital twins. Proceedings of the 29th Annual International Conference on Computer Science and Software Engineering; 2019. p. 329-35.
21. Elayan, H., Aloqaily, M., & Guizani, M. Digital twin for intelligent context-aware iot healthcare systems. IEEE Internet of Things Journal, 8(23), 16749-16757, (2021).
22. Y.C.P. Lin, W.F. Cheung, Developing WSN/BIM-Based environmental monitoring management system for parking garages in smart cities, J. Manag. Eng. 36 (2020)
23. Q. Lu, L. Chen, S. Li, M. Pitt, Semi-automatic geometric digital twinning for existing buildings based on images and CAD drawings, Autom. ConStruct. 115 (2020)
24. Machado, C. G., Winroth, M. P., & Ribeiro da Silva, E. H. D. Sustainable manufacturing in Industry 4.0: an emerging research agenda. International Journal of Production Research, 58(5), 1462-1484, (2020).
25. CSREUROPE, https://www.csreurope.org/our-campaign), last accessed 2022/03/14.

26. Waibel, M. W., Steenkamp, L. P., Moloko, N., & Oosthuizen, G. A. Investigating the effects of smart production systems on sustainability elements. Procedia manufacturing, 8, 731-737, (2017).
27. Stock, T., & Seliger, G. Opportunities of sustainable manufacturing in industry 4.0. procedia CIRP, 40, 536-541, (2016).
28. FIWARE: FIWARE Components. https://www.fiware.org/developers/catalogue/ last accessed 2022/03/14
29. Sang, G. M., Xu, L., Vrieze, P. D., & Bai, Y. Towards predictive maintenance for flexible manufacturing using FIWARE. In International Conference on Advanced Information Systems Engineering (pp. 17-28). Springer, Cham, (2020).
30. Sang, G. M., Xu, L., & de Vrieze, P. A Predictive Maintenance Model for Flexible Manufacturing in the Context of Industry 4.0. Frontiers in big Data, 4, (2021).