Digital Twins in Architecture

An ecology of practices and understandings

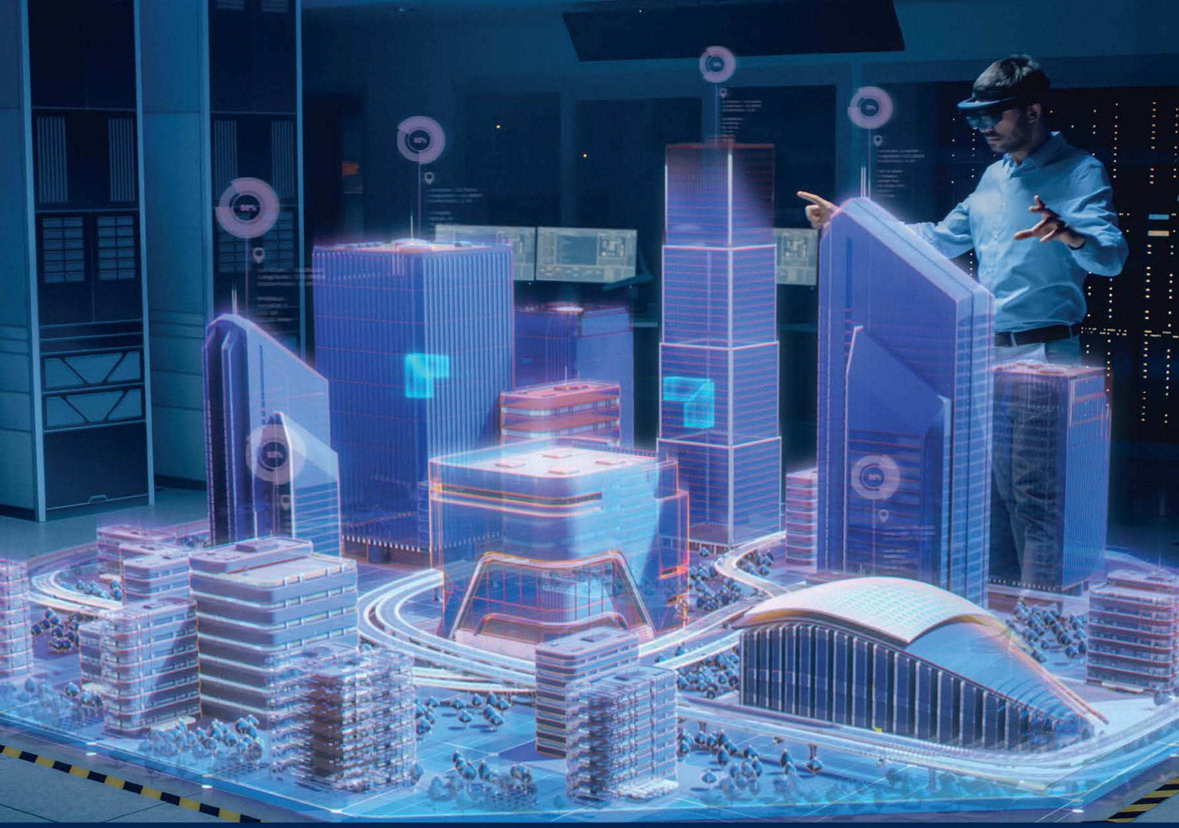
Horvath, Anca-Simona; Pouliou, Panagiota

Published in:
Handbook of Digital Twins

DOI (link to publication from Publisher):
10.1201/9781003425724-46

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record



HANDBOOK OF DIGITAL TWINS

Edited by

Zhihan Lyu

CRC Press
Taylor & Francis Group

Handbook of Digital Twins

Over the last two decades, Digital Twins (DTs) have become the intelligent representation of future development in industrial production and daily life. Consisting of over 50 chapters by more than 100 contributors, this comprehensive handbook explains the concept, architecture, design specification and application scenarios of DTs.

As a virtual model of a process, product or service to pair the virtual and physical worlds, DTs allow data analysis and system monitoring by using simulations. The fast-growing technology has been widely studied and developed in recent years. Featured with centralization, integrity and dynamics, it is cost-effective to drive innovation and performance. Many fields saw the adaptation and implementation across industrial production, healthcare, smart city, transportation and logistics. World-famous enterprises such as Siemens, Tesla, ANSYS and General Electric have built smart factories and pioneered digital production, heading towards Industry 4.0.

This book aims to provide an in-depth understanding and reference of DTs to technical personnel in the field, students and scholars of related majors, and general readers interested in intelligent industrial manufacturing.

Dr Zhihan Lyu is an Associate Professor at the Department of Game Design, Uppsala University, Sweden. He is also IEEE Senior Member, British Computer Society Fellow, ACM Distinguished Speaker, Career-Long Scientific Influence Rankings of Stanford's Top 2% Scientists, Marie Skłodowska-Curie Fellow, Clarivate Highly Cited Researcher and Elsevier Highly Cited Chinese Researcher. He has contributed 300 papers including more than 90 papers on IEEE/ACM Transactions. He is the Editor-in-Chief of Internet of Things and Cyber-Physical Systems (KeAi), an Associate Editor of a few journals including *ACM TOMM*, *IEEE TITS*, *IEEE TNSM*, *IEEE TCSS*, *IEEE TNSE* and *IEEE CEM*. He has reviewed 400 papers. He has received more than 20 awards from China, Europe and IEEE. He has given more than 80 invited talks for universities and companies in Europe and China. He has given 20 keynote speeches at international conferences.

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

Front cover image: Gorodenkoff/Shutterstock

First edition published 2024
by CRC Press
2385 NW Executive Center Drive, Suite 320, Boca Raton FL 33431

and by CRC Press
4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

CRC Press is an imprint of Taylor & Francis Group, LLC

ISBN: 978-1-032-54607-0 (hbk)
ISBN: 978-1-032-54608-7 (pbk)
ISBN: 978-1-003-42572-4 (ebk)

DOI: 10.1201/9781003425724

Typeset in Palatino
by codeMantra

Contents

Part 5 Digital Twins in Management

Part 6 Digital Twins in Industry

Part 10 Digital Twins in Medicine and Life

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Part 1

Introduction

1

Overview of Digital Twins

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1.1 Introduction

This book consists of 50 chapters contributed by 129 authors. This chapter is a general introduction to each chapter of the book. From the second chapter, the concept of digital twinning, architecture description, design specification, and application scenarios are introduced. Section 2 introduces the concept and development of digital twins. Section 3 introduces the key technologies to promote the development of digital twins. Section 4 introduces some general frameworks and construction methods of digital twins. Section 5 introduces the application of digital twins in management and operation. Section 6 introduces the application of digital twins in industry. Section 7 introduces the application of digital twins in building construction. Section 8 introduces the application of digital twins in transportation. Section 9 introduces the application of digital twins in the energy industry. Section 10 introduces the application of digital twins in health and life.

1.2 Thinking about Digital Twins

Ashwin Agrawal and Martin Fischer designed a framework to enable users to find suitable Digital Twins applications, to help practitioners systematically think about the basic factors that affect successful Digital Twins deployment in Chapter 2. Realizing these factors in practice can improve the probability of success and accelerate the application of Digital Twins in the industry.

Pedro Henrique Diniz examines the application of the Digital Twins paradigm to the field of computer networks in Chapter 3. At present,

DOI: 10.1201/9781003425724-2

only industrial tools that deal with life-cycle network management through intention-based network automation and closed-loop automation can be effectively classified as Network Digital Twins, mainly because they maintain two-way communication between physical and virtual environments.

Xiaochen Zheng et al. introduced the concept of cognitive Digital Twins, which reveals a promising development of the current twins paradigm toward a more intelligent, comprehensive, and full life-cycle representation of complex systems in Chapter 4. Compared with the current Digital Twins concept, cognitive Digital Twins enhances cognitive ability and autonomy. This chapter first introduces the evolution process of cognitive Digital Twins concept.

Marco Francesco Funari et al. outline the concept of Digital Twins in the Architecture, Engineering, Construction, and Operation domain in Chapter 5. Then, some applications in the integrity protection of architectural heritage structures are critically discussed. The Digital Twins concept prototype of heritage building structural integrity protection is proposed.

1.3 Digital Twins Technology

Serge P. Kovalyov provides an overview of Digital Twins model–specific technology in Chapter 6. Integrated physical models and simulations, statistical machine learning models, and knowledge-based models play a central role.

Mohammed Hamzaoui and Nathalie Julien aim to introduce the general deployment method of Digital Twins in Chapter 7. Considering the position that Digital Twins may occupy in various fields as key technologies of digital transformation, we emphasized the key requirements of this method.

Istvan David and Eugene Syriani outlined how to use machine learning to automatically build simulators in Digital Twins in Chapter 8. The methods discussed in this chapter are particularly useful in systems that are difficult to model because of their complexity.

Dan Wang et al. introduced how to apply the Digital Twins technology to simulate physical/end side with limited resources and use rich resources on virtual/computing side in Chapter 9. The concept of Digital Twins is applied to the federal distribution analysis problem, and the global data distribution is obtained by aggregating partial observation data of different users.

Esra Kumaş et al. proposed a model that combines blockchain technology with Digital Twins in Chapter 10, because it provides benefits for decentralized data storage, data invariance, and data security. The integration of Digital Twins and blockchain ensures the security and integrity of data accumulation generated by the Internet of Things from relevant stakeholders of the system by verifying transactions in the blockchain ledger.

Emil Kurvinen et al. believe that real-time physics can accurately study the machine operated by humans in Chapter 11, so that human actions can be better integrated into the machine. For high-tech products, the use of physical-based Digital Twins can explore design options and their impact on the overall performance, such as the dynamic behavior of machines.

1.4 Digital Twins Design and Standard

Andreas Pester et al. provide the classification and analysis of Digital Twins types based on recent research in this scientific area in Chapter 12.

Richard Heininger et al. designed and ran the abstraction layer required by Digital Twins as part of the Cyber-Physics System in Chapter 13. A layered Digital Twins modeling method is proposed, which promotes the use of coarse granularity abstraction in the composition of Cyber-Physics System, while retaining the controllability of Cyber-Physics System for operational purposes.

In Chapter 14, Vivek Kant and Jayasurya Salem Sudakaran believe that the human-centered design of Digital Twins and their interfaces is crucial to ensure the effective use of this technology and provide the highest possible benefits for human users. It solves all kinds of problems, from the larger theme designed for human beings to the specific details of Human Machine Interaction design, to achieve interactivity and visualization.

Chiara Cimino et al. propose the specification of a tool that can help ensure consistency among such a heterogeneous set of Digital Twins in Chapter 15, making consistent the set of models and data that are processed during the design phase. The aim is to create a knowledge base of the system, which will serve the design and be useful to analyze the system throughout its life cycle.

Shaun West et al. introduced a human-centered approach to developing Digital Twins in Chapter 16, which can create new value propositions in intelligent service systems. When creating and designing Digital Twins, a people-centered, system-based design lens can support value co-creation and gain multiple perspectives of value within the system.

In Chapter 17, Abdeljalil Beniiche and Martin Maier first introduced the evolution of mobile networks and the Internet, then briefly discussed 6G vision, and elaborated various blockchain technologies. They borrow ideas from the biological superorganism with brain-like cognitive abilities observed in colonies of social insects for realizing internal communications via feedback loops, whose integrity is essential to the welfare of Society 5.0, the next evolutionary step of Industry 4.0.

Timo Ruohomäki and others distinguish urban Digital Twins from industrial Digital Twins in Chapter 18. Urban Digital Twins should be based on complex and scalable information models to maintain the key artifacts of social structure. The urban Digital Twins is about a large organism of a city, a complex urban system.

In Chapter 19, Tobias Osterloh et al. believe that the combination of Digital Twins and modern simulation technology provides significant benefits for the development and operation of robot systems in challenging environments. In the future, integrating big data into concepts will provide new possibilities for predictive maintenance and further match simulation data with available operational data.

1.5 Digital Twins in Management

Vladimir Shvedenko et al. considered managing complex systems through interactive Digital Twins, and described the realization of the principle of process function management of multi-structure system elements in Chapter 20. The main advantage of the proposed method is that the management system is built as open to its improvement, function expansion, and interaction with other systems.

In Chapter 21, Gozde Basak OZTURK and Busra OZEN introduce the integration of artificial intelligence and building information modeling to create a Digital Twins that improves the knowledge management process in the architectural, engineering, operation, and facility management. The progress of information and communication technologies and AI technology has improved the ability of building information modeling to transform static BIM model into dynamic Digital Twins.

Frits van Rooij and Phil Scarf discussed the application of Digital Twins in the context of engineering asset management in Chapter 22. Special attention is paid to the design principles of the maintenance plan Digital Twins. These principles are introduced as a framework, and a real case is used to illustrate how to use this framework to design Digital Twins.

In Chapter 23, Päivi Aaltonen et al. believe that the organizational barriers and facilitation factors to achieve Digital Twins maturity have not been widely discussed, but they are similar to the barriers and facilitation factors to achieve AI maturity. The author discusses the concept of AI and Digital Twins maturity and their relationship.

Petra Müller-Csernetzky and others described the innovation process, prototype stages, and relevant business models of five selected intelligent service projects and tried to apply Digital Twins to these links in Chapter 24. It can be learned from practice that when designing Digital Twins, it is important to be able to scale up and down in the time dimension, because doing so will outline the system dynamics and the main inputs and outputs.

Sofia Agostinelli summarizes the existing definition and specific use, complexity level, and system architecture of Digital Twins in Chapter 25. Lessons can be learned and applied to architecture, engineering, construction, and operation.

1.6 Digital Twins in Industry

Seppo Sierla analyzed recent work on Digital Twins in the process industry in Chapter 26. It shows different types of processes and different use cases of Digital Twins.

In Chapter 27, Dayalan R. Gunasegaram points out that Digital Twins offers an ideal method by which operations can be autonomously controlled and optimized in the highly connected smart factories of the Industry 4.0 era. Digital Twins can also optimize the various operations within factories for improved profitability, sustainability, and safety.

Jože Martin Rožanec et al. shared their experience in the methods we followed when implementing and deploying cognitive Digital Twins in Chapter 28. This concludes by describing how specific components address specific challenges involving three use cases that correspond to crude oil distillation, metal forming processes, and the textile industry.

In Chapter 29, Ning Gou et al. 's innovative concept of ultra-precision machining based on digital twin and its realization and application prospects are proposed. It may provide new insights for the future development of ultraprecision machining tools or processing systems in the Industry 4.0 era.

Giulia Marcon and Giuseppe Aiello research and solve the conceptualization, design and development of the Digital Twins of the logistics system in the shipbuilding industry in Chapter 30, in which the material handling operation is planned and managed in the space of the virtual shipyard, and the autonomous mobile robot and cooperative robot technology are used to improve the safety and efficiency of the operation.

George Falekas et al. introduce the concept of Digital Twins under the scope of electrical machine diagnostics and provide a Digital Twins framework of electrical machine predictive maintenance in Chapter 31.

In Chapter 32, Ahsan Muneer and Jyrki Savolainen discuss the applicability of Digital Twins in the board industry, and identified several practical problems in model building, data availability, and the use of unstructured data. The key issues of building and implementing Digital Twins are related to data availability and how to effectively use data, especially in the case of unstructured datasets that are traditionally utilized only by the human operators for high-level decisions.

Jascha Grübel believes that Digital Twins have a lot of untapped potential in Chapter 33, especially when they are combined with rigorous practices from experiments. The author shows the possibility of the combination of Digital Twins and disease algorithm codes.

Jairo Viola et al. proposed a new development framework in Chapter 34, which uses Digital Twins to make control and predictive maintenance intelligent. The case shows the ability of Digital Twins in the intelligent control of temperature uniformity control system and intelligent predictive maintenance of mechatronics test bench system.

1.7 Digital Twins in Building

In Chapter 35, Gabriele Garnero and Gloria Tarantino give a general overview of the current application fields of 3D urban models, to classify 3D data requirements into specific applications and clarify which types of 3D models with specific characteristics are suitable for this purpose. Then, a practical application example is shown in the Swedish environment, and a 3D building model was developed for Vaxholm City, Stockholm County.

Muhammad Shoaib et al. proposed a green Digital Twins framework based on case studies in Chapter 36. It can be concluded that the process of sustainability assessment through Digital Twins is highly dependent on building information modeling and other input data. The sustainability parameters assessment is quite efficient, fast, and transparent through Digital Twins.

Bianca Weber Lewerenz believes that Digital Twins is the most effective method in Chapter 37, which can start to ride the waves in the wave of digital transformation of the construction industry, take advantage of various opportunities, master unique challenges, and set new standards in the digital era.

Marianna Crognale et al. implemented a general data platform for vibration data visualization in Chapter 38. The work develops an approach that integrates a 3D information model and IoT systems to generate a detailed BIM, which is then used for structural simulation via finite element analysis.

Anca-Simona Horvath and Panagiota Pouliou drew and summarized the current situation of Digital Twins art in architecture in Chapter 39. Digital Twins should take the data they use seriously and consider the need for data storage and processing infrastructure in their entire life cycle, because this ultimately constitutes a sustainability issue.

Chunli Ying et al. proposed a method based on Digital Twins in Chapter 40, which is used to control the processing accuracy and installation quality of structural steel rigid frame (SSRS) bridges. It can provide accurate three-dimensional dimensions, eliminate human interference to the measured data, and use more flexible and systematic data processing algorithms to greatly improve the speed and quality of data.

Marianna Charitonidou introduced how the digital twin of city size can promote the sustainable development goals in Chapter 41. In the context of the current data-driven society, urban digital twins are often used to test scenarios related to sustainable environmental design.

1.8 Digital Twins in Transportation

Mariusz Kostrzewski briefly summarized the application of most Digital Twins in the transportation branch in Chapter 42.

In Chapter 43, Yuan Zhou and Leiting Dong established a Digital Twins drive framework to realize damage diagnosis and predict fatigue crack growth. In the example of a cyclic helicopter component, the uncertainty of the Digital Twins is significantly reduced, and the evolution of structural damage can be well predicted. The proposed method, using the ability of Digital Twins, will help to achieve condition-based maintenance.

Antonio Bono et al. proposed an integrated strategy for managing and checking infrastructure using drones and Digital Twins in Chapter 44. This strategy can provide the real-time status of buildings and perfectly process location information.

1.9 Digital Twins in Energy

Nikolai Fomin and Roman V. Meshcheryakov discuss the Digital Twins security of network physical water supply systems in Chapter 45. By using the safety assessment method based on Digital Twins, the safety system of the water supply company is improved.

In Chapter 46, Dirk Westermann understands Digital Twins as a real-time digital representation of physical components based on measurement data and analysis knowledge. It enables power suppliers to transform their operations through actionable insight to achieve better business decisions. In other words, grid operators can improve operations, reduce unplanned outages, and manage fluctuations in market conditions, fuel costs, and weather conditions.

In Chapter 47, Elena F. Sheka believes that with the increasing amount of modeling data, it is inevitable that the concept of Digital Twins will change from ordinary modeling. This chapter takes the material science of high-tech graphene materials as an example to introduce an example of this concept reflection.

Triboelectric nanogenerator (TENG) is a technology that transforms the changes of the physical world into electrical signals. Jiayue Zhang and Jie Wang introduce the mechanism of common TENG, common self-powered sensors based on TENG, and various scenarios of TENG in Digital Twins applications in Chapter 48. In addition, this section also discusses the future application potential of TENG in Digital Twins.

1.10 Digital Twins in Medicine and Life

In Chapter 49, João A. M. Santos et al. introduced the current paradigm of Digital Twins applied in the pharmaceutical industry, studied the Digital

Twins applied in the pharmaceutical supply chain and pharmaceutical management more deeply, and proposed the future research direction.

Chenyu Tang et al. introduced the development status of human Digital Twins in Chapter 50. The success of Digital Twins technology in industrial application makes people more confident in building human Digital Twins models.

In Chapter 51, Sai Phanindra Venkatapurapu et al. describe the opportunities and challenges of Digital Twins for Proactive and Personalized Healthcare.

What Is Digital and What Are We Twinning?

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On the Design of a Digital Twin for Maintenance Planning

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Digital Twins for Proactive and Personalized Healthcare – Challenges and Opportunities

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