

Advances in Smart Environments and Digital Twin: Current Trends and Future Directions

Mariusz Żytniewski ^{1,*} , Małgorzata Pańkowska ¹, Mariia Rizun ¹  and Francesca Fallucchi ² 

¹ Department of Informatics, University of Economics in Katowice, 40-287 Katowice, Poland; malgorzata.pankowska@ue.katowice.pl (M.P.); mariia.rizun@ue.katowice.pl (M.R.)

² Department of Engineering Sciences, Guglielmo Marconi University, 00193 Roma, Italy; f.fallucchi@unimarconi.it

* Correspondence: mariusz.zytniewski@ue.katowice.pl

1. Introduction

Ubiquitous miniaturisation and increasing computer performance allow technical solutions to be used more often in everyday life to support end users. Two concepts related to the use of information technologies are smart ecosystems and digital twins. Smart ecosystems are commonly understood as a network of Internet of Things (IoT) devices, computers, software, and services that communicate, collaborate efficiently, manage resources, and adapt their behaviour to environmental changes. Such systems promote sustainable practices, increase quality of life, enhance safety, and generate large amounts of valuable data.

In a broader interpretation, smart ecosystems encompass not only technology but also people, organisations, and business processes. As a result, smart solutions become part of the activities undertaken by organisations and carried out by the participants in these processes. On this basis, IoT-based solutions can be perceived as organisational components and may be monitored and managed similarly to enterprise information systems, contributing to the creation of specialised smart environments.

A smart environment, understood as either a physical or virtual space, enables the monitoring, analysis, and automation of tasks and activities in areas such as smart buildings, smart campuses, smart factories, smart homes, and smart hospitals. From the perspective of virtual spaces, smart environments are closely related to the concept of the digital twin, in which physical objects and processes are represented in a virtual environment. Such representations allow the simulation of behaviours, processes, and interactions without incurring unnecessary risks or costs associated with real-world experimentation.

The data collected through these systems, combined with digital twin approaches, may support the monitoring, simulating, optimising, and predicting the behaviour of users as well as entire sociotechnical systems. These processes have led to the emergence of a broad and highly interdisciplinary research area encompassing data privacy, cybersecurity, the resilience of cyber-physical systems to cyberattacks, the modelling of complex interactions, and issues related to user acceptance and societal adoption of smart technologies. Three key future perspectives can be identified: the integration of intelligent agents, the emergence of new technological and societal challenges, and the transition from reactive to proactive smart ecosystems.

The development of these concepts was the primary motivation for launching this Special Issue, entitled “Advances in Smart Environments and Digital Twin Technologies”. The aim of this Special Issue was to disseminate recent research findings in these areas to a broad scientific audience.



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2. Overview of Special Issue

One of the key research areas addressed in this Special Issue is digital twins for smart physical environments. The included studies in this area sought to determine how digital twin technologies can support and enhance urban infrastructure, agricultural systems, forest ecosystems, and transportation assets through monitoring, prediction, optimisation, and data-driven decision-making [1–4].

Barrile et al. [1] present an urban digital twin that can be used to examine and simulate real-world scenarios. The authors focused on two different scenarios: the first concerns the assessment of hydrogeological risk, and the second involves the evaluation of light pollution due to public lighting. The analyses are based on topographic, meteorological, and infrastructure data and may provide valuable support for risk management and urban decision-making in smart city environments.

Fernández et al. [2] focused on an AI-driven digital twin architecture for hydroponic greenhouse horticulture and proposed DigiHortiRobot, a system designed to support monitoring, data acquisition, decision-making, and virtual simulations for scenario analysis and intervention planning. The proposed solution also allows autonomous task execution with feedback-based model refinement. To implement the system, the authors developed a layered architecture consisting of a physical layer, a virtual layer, and an implementation framework. In addition, the authors specified a robot task assignment algorithm for greenhouse operations, demonstrating how digital twin technologies can support sustainable and semi-autonomous smart agriculture.

Sasaki and Abe [3] propose a digital twin architecture for forest restoration. Their main objective was to explain the capability of digital twin technology to facilitate environmental monitoring, transparent data governance, climate-related decision-making, and sustainable restoration practices, highlighting the potential of digital twin technology for addressing complex ecological challenges. From the technological aspect, the article addresses the integration of artificial intelligence, the IoT, blockchain technology and smart ecosystem management to create a comprehensive framework supporting environmental restoration. Gurrola-Mijares et al. [4] evaluated pavement condition using digital twin technology and deep learning techniques applied to IMU signals. One of the main objectives of the study was developing a three-layer architecture consisting of a physical space, a virtual space, and a data interconnection layer to support real-time data acquisition and processing. In addition, the authors conducted a case study on road anomaly detection and indicated how the proposed approach can support pavement condition assessment and predictive maintenance in smart transportation systems.

Another research area addresses data-driven and human-centred smart service ecosystems, in which user-generated data, digital interactions, and user acceptance are key factors in the development of intelligent services. In this context, smart ecosystems are not limited to physical infrastructures or automated environments but also include digital platforms, service users, behavioural patterns, trust mechanisms, and decision-making processes. The presented studies in this area explore how digital technologies can support the collection, interpretation, and use of data generated through interactions between users and smart services.

Ramos and Ramos [5] examined the role of user-generated content in shaping purchase intentions for tourism products on TikTok, paying particular attention to differences between Millennials and Centennials. In this Special Issue, their study extends the discussion of smart ecosystems towards digitally mediated service environments, where social media platforms, user interactions, and data-driven content influence decision-making processes. The authors show that user-generated content can become an important component of

smart service ecosystems by supporting information exchange, user engagement, and consumer-oriented digital services.

This thematic area is further strengthened by Norbu et al. [6] through an analysis of consumer acceptance of blockchain-based digital payment systems in Bhutan. In the article, the authors emphasise the importance of user trust, perceived usefulness, perceived ease of use, and institutional conditions in the adoption of emerging digital services. In smart ecosystems, the authors demonstrate that the success of smart services depends not only on technological availability but also on user willingness to adopt secure, transparent, and reliable digital solutions.

Beyond the current applications, Calle-Heredia and Hesselbach [7] investigated federated extended reality (XR) network digital twins in AI-aware 6G environments. Their perspective extends the digital twin paradigm towards next-generation communication infrastructure and highly interconnected smart ecosystems. A novel performance evaluation approach for federated XR network digital twins was developed, and the authors argue that network digital twins, extended reality, and artificial intelligence can jointly support simulation, monitoring, and adaptive management in future communication environments.

3. Future Perspectives

The increasing availability of data and the adoption of digital twin technologies are transforming the monitoring, simulation, optimisation, and management of sociotechnical systems. By creating virtual representations of physical and social environments, digital twins support data-driven decision-making, opening new research opportunities across artificial intelligence, data science, systems engineering, and social sciences.

Some additional aspects of digital twin development and implementation concern the economics and management of financial and operational risks of the digital twin exploitation. Some challenges are connected with risk management during digital twin testing and refinement before the real-world rolled-out digital twin system. The economic development of digital twin systems as well as the measurement of their efficiency, reliability, and sustainability remain issues; therefore, managers need to identify specific key performance indicators for monitoring and control of digital twin systems.

3.1. Intelligent Agents Integration

A key future development is the integration of autonomous intelligent agents into digital twin environments. Advances in AI, including foundation models, large language models, and multi-agent systems, enable agents to autonomously perceive, reason, plan, and act. These agents can coordinate distributed resources such as energy, transportation, communication, and logistics networks while supporting decision-making processes.

These agents can also act as adaptive interfaces between users and complex technological ecosystems, providing personalised assistance and reducing cognitive workload. Integrated into digital twins, agent-based models can improve predictive simulations by reproducing realistic human and organisational behaviors, enhancing planning, optimisation, and resilience.

3.2. Emerging Challenges

The deployment of intelligent agents and autonomous Digital Twins faces important challenges related to accountability, governance, transparency, privacy, and cybersecurity. Assigning responsibility for autonomous decisions is difficult, especially in multi-agent environments.

Interactions among agents may generate unpredictable collective behaviors, requiring new approaches for verification, validation, monitoring, and control. Trust in these systems will depend on explainable AI, interpretable models, and human oversight.

Because digital twins rely on large volumes of potentially sensitive data, privacy-preserving techniques such as federated learning and differential privacy will be essential. Simultaneously, protecting critical infrastructure from cyberattacks will remain a major priority. Emerging technologies such as quantum computing and edge AI may further strengthen simulation and optimisation capabilities.

3.3. From Reactive to Proactive Ecosystems

Future sociotechnical systems will evolve from reactive infrastructure into proactive, adaptive, and cooperative ecosystems. Intelligent agents will anticipate changes, learn from experience, and continuously adapt to user and environmental needs. As a result, digital twins will evolve from monitoring tools into autonomous decision support systems capable of predicting future conditions, detecting anomalies, and recommending or implementing corrective actions. This transformation could significantly improve the management of smart cities, healthcare networks, industrial systems, and other critical infrastructure.

Ultimately, the convergence of digital twins, intelligent agents, advanced AI, and privacy-preserving technologies will reshape future smart ecosystems. The success of these smart ecosystems will depend on balancing autonomy, transparency, security, regulation, and human oversight to ensure resilient, sustainable, and human-centred systems.

4. Conclusions

The articles presented in this Special Issue cover a broad range of theories and implementations related to smart technologies and digital twin solutions in intelligent environments. The first group of contributions addresses application domains such as cities, agriculture, forest ecosystems, and transport infrastructure, confirming the diversity of digital twin applications in human-centred environments. The studies demonstrate that digital twins can support the monitoring, risk analysis, prediction, and optimisation of complex physical systems.

The second group of contributions focuses on intelligent services, data analysis, and decision support processes. These articles show that smart ecosystems are not limited to technology alone but are rather sociotechnical systems involving users, behaviours, processes, interactions, data, and services supported by artificial intelligence, especially digital twin technologies.

The papers collected in this Special Issue indicate that future smart ecosystems will increasingly depend on the effective connection between physical environments and their digital representations. Such integrations could help visualise complex processes and support the development of more sustainable, resilient, and adaptive solutions. These integrations could also enhance the importance of digital twins as practical tools for understanding changes in smart environments and supporting their more successful management. Future research should therefore continue to link technological development with practical needs and human-centred views.

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Conflicts of Interest: The authors declare no conflict of interest.

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