Towards Developing Federated Digital Twins for Society 5.0

Elena Navarro, Pascual González, Jose Luis de la Vara*, Francisco Montero, María T. López, Víctor López-Jaquero, Elena Pretel and Clara Ayora

Albacete Research Institute of Informatics, Universidad de Castilla-La Mancha, C/ Investigación 2, 02071 Albacete, Spain

Abstract

Society 5.0 is emerging as an evolution of the Information Society, shifting the focus from information and its management to people. Society 5.0 will enable a high degree of fusion between cyberspace and physical space, balancing economic advancement with the resolution of social problems. To achieve this, Digital Twins (DTs) are one of the essential enabling technologies, as they establish a connection between the digital and the physical worlds. Most of the proposals present DTs as monolithic, individual applications that offer bidirectional communication with its associated physical entity. However, there is a need to go further by considering DTs as autonomous entities capable of cooperating, collaborating, and coordinating with other DTs to achieve goals that they could not achieve alone. We present our vision to fill this gap in a new research project: FDT4S. This project focuses on enabling an evolution of DTs by embracing the concept of Federated Digital Twins (FDTs). The aim is to facilitate the design and development of DTs that can be operated and managed independently, but jointly contribute to some objective, also simplifying their maintenance and evolution. Our ultimate goal is to provide a holistic framework for the development of FDTs, considering the needs of both developers and end-users in the context of Society 5.0.

Keywords

Digital Twin, DT, Society 5.0, Federated Digital Twins, FDT, FDT4S

1. Introduction

Society is constantly evolving because of advances in technology. Following the Information Society, a new concept is emerging: Society 5.0. First coined by the Japanese government [1], it corresponds to a society that places people at the heart of technological development, integrating both physical and virtual worlds. Through a high degree of fusion between cyberspace and physical space, Society 5.0 can balance economic progress with the resolution of social problems by providing goods and services that address multiple latent needs regardless of location, age, gender, or language [2]. The key to the success of this social evolution lies in maintaining a people-centred approach, using technology as a tool to improve everyone's lives and to create a more sustainable and inclusive future.

Society 5.0 proposes an iterative cycle where data is collected from the real world, analysed, and transformed into meaningful information that is then applied in the real world, and where different systems do not act in isolation but are coordinated. To achieve this vision, Digital Twins (DTs) is an essential enabling technology, as they connect cyberspace and the physical world [3]. A DT receives real-time data from sensors and other sources, analyses the behaviour of its physical counterpart, and predicts potential outcomes. In the context of Society 5.0, DTs can be used to optimize the management of cities, infrastructure, industrial processes, and healthcare.

RCIS 2026: Companion Proceedings of the 20th Conference on Research Challenges in Information Science: RCIS Research Projects and Workshops, May 26-29, 2026, Toulouse, France

* Corresponding author.

elena.navarro@uclm.es (E. Navarro); pascual.gonzalez@uclm.es (P. González); joseluis.delavara@uclm.es (J.L. de la Vara); francisco.msimarro@uclm.es (F. Montero); maria.lbonal@uclm.es (M.T. López); victormanuel.lopez@uclm.es (V. López-Jaquero); mariaelena.pretel@uclm.es (E. Pretel); clara.ayora@uclm.es (C. Ayora)

0000-0001-9496-6890 (E. Navarro); 0000-0003-3549-5712 (P. González); 0000-0003-1813-398X (J.L. de la Vara); 0000-0002-0902-9681 (F. Montero); 0000-0002-2846-3483 (M.T. López); 0000-0003-2093-4065 (V. López-Jaquero); 0000-0002-7703-9558 (E. Pretel); 0009-0002-8265-6531 (C. Ayora)

The concept of DT was originally coined by Grieves and Vickers [4], who identified three main elements: i) a real space, ii) a virtual space, and iii) a link between both spaces for bidirectional flow of data to offer the convergence of the spaces. At a high level, a DT is a digital representation of an element, process or system of the physical space (physical object, PO). A DT continuously interacts with its PO, sharing data in real time and synchronizing the physical and cyber worlds. DTs use simulation, machine learning, and reasoning to assist in decision-making. The distinguishing properties [3] of DTs can be divided into essential properties (representativeness and contextualization, reflection, and entanglement) and added-value ones (replication, persistency, memorization, composability, manageability, augmentation, and predictability).

Despite the development and use of the DTs in different contexts [5], the characteristics of Society 5.0 require an evolution of the concept. DTs cannot be considered isolated but rather interconnected to respond to this social environment. For example, several DTs are needed to represent and analyse different aspects of a smart city in a cost-effective way, including human aspects. DTs need to be designed as autonomous entities capable of cooperating, collaborating, and coordinating with other DTs in order to achieve goals that they would not be able to achieve in isolation. However, most of the proposals present DTs as monolithic, individual applications focused on offering bidirectional communication between the PO and the DT. These proposals do not meet the major requirements of Society 5.0.

We aim to fill this gap by providing a DT development framework that considers that the level of DT autonomy will need to increase for Society 5.0, as DTs will need to interact as autonomous agents in cyberspace, expanding from local to global data analysis. The framework will need to support the design and implementation of different DTs that can be operated and managed independently and can act together, simplifying not only their development but also their maintainability and evolution. There is also a need to adopt a different approach to DT development, leveraging their composability. DTs must offer mechanisms for integration with other DTs to provide new functionalities that no single DT could support independently. This represents a paradigm shift, moving from developing monolithic DTs to developing Federated Digital Twins (FDTs) [6] instead. The framework will be applied in the scope of social interaction for Society 5.0.

Our vision is being enacted in the FDT4S project (A Framework for developing Federated Digital Twins to pursue the Society 5.0; https://www.i3a.uclm.es/louise_w/?project=a-framework-for-developing-federated-digital-twins-to-pursue-the-society-5-0). The project started in November 2025 and will end in October 2028, and is funded by the government of the Castilla-La Mancha region in Spain. FDT4S deals with research challenges in information science related to information systems and their engineering, user-oriented approaches, data and information management, and domain-specific information system engineering, among other areas.

The rest of the paper presents the background, objectives, expected results, and current results of FDT4S, and our main conclusions.

2. Background

Different needs, gaps and challenges must be tackled so that DTs in general and FDTs in particular can effectively contribute to Society 5.0. Progress is necessary in several research areas to characterize, understand, and effectively support the overall model and the technological requirements underlying Society 5.0.

FDTs consist of a composition of autonomous DTs [7]. An autonomous DT is one that satisfies the distinguishing properties of a DT and can also communicate, collaborate, and coordinate with other autonomous DTs in the virtual space in order to, e.g., improve predictions, optimize processes, and adapt more effectively to dynamic environments. Autonomous DTs can be composed in such a way that the resulting federation can be homogeneous or heterogeneous from two different dimensions: information and functionality. In essence, FDTs may be understood as socio-technical distributed systems in which multiple autonomous and potentially heterogeneous DTs interoperate and coordinate through federation mechanisms, enabling data and model integration as well as collaborative decision-making in complex and dynamic environments. The development of FDTs require the identification of: *interconnection patterns that optimise the communication process between the physical entity and the DT*, minimising various aspects such as latency, while also considering the need to use or share information between different autonomous DTs; *patterns for information storage considering the constraints imposed by FDTs*, and; *architectural styles that enable autonomous DTs to act as a federation*. It is also necessary to provide *mechanisms to aggregate knowledge from different autonomous DTs* following a decentralised model, as well as to adapt its processing through the interaction with the federation. Related results can be found for DTs (e.g., [8][9]), but not FDTs.

In the scope of **quality assurance**, it is necessary to provide confidence that FDTs are dependable (safe, secure, reliable...). In critical domains [10], this typically involves the consideration and management of compliance with applicable standards, dependability justifications, and assurance evidence. Although some progress has started to be made in these aspects for DTs (e.g., [11]), the available means need to be adapted to FDT characteristics and do not consider the assurance needs related to the joint use of DTs and other technologies such as AI (Artificial Intelligence) and XR (Extended Reality). Therefore, no *general quality assurance framework for FDT* exists. In addition, the quality of the interaction between and with DTs needs to be considered, including human interaction. A *design framework that facilitates interaction between POs and FDTs* is needed as well.

Another important area is the use of **multi-agent systems (MAS) for FDT development**. A MAS comprises numerous interconnected computing elements known as agents. These agents can make autonomous decisions and communicate with each other not only by exchanging data but also by engaging in social activities such as association and coordination. Previous work has explored how distributed computing systems exhibit significant synergies with MAS [12] and has highlighted the opportunities that MAS offer for the development of human-centred systems that can address complex social problems and improve the quality of life [13]. MAS also have characteristics that make them a natural alternative for defining the architecture and development of DTs. However, creating FDTs presents additional challenges compared to isolated DTs, and it is necessary to identify *theoretical proposals that provide a solid foundation for the development of FDT using MAS*. It is especially important that the proposals are domain independent.

Finally, **DTs for social interaction management** are very relevant for Society 5.0, as social relationships are expected to be more complex. Although in our society communication between individuals has broken down the physical barriers of sharing the same physical space and the same moment in time, social interaction is more than this. In Society 5.0, many of these social interactions will take place using the virtual environments proposed by the metaverse and embedding FDT components whose PO will correspond to people. As a consequence, it is necessary to study *social interaction based on concepts such as social presence, sociability, and social space* [14], understand *how the combined use of different technological platforms (XR, tablets, smartwatches, etc.) affects social interactions* [15], and create *human-like emotional behaviour by equipping DTs with basic principles of social behaviour*, such as the application of Theory of Mind [16]. Furthermore, achieving effective social interaction in Society 5.0 requires moving beyond subjective assessments toward *objective, non-intrusive emotional monitoring*. Recent advances suggest that integrating portable neurophysiological technologies within a structured methodological framework can foster emotional self-awareness in everyday contexts [17].

3. Objectives

The main goal of FDT4S is to **design a holistic framework for the development of FDTs**, considering both the needs of developers and end-users in the context of Society 5.0. Its specific objectives are as follows.

O1. Analyse existing interconnection patterns to facilitate interconnection between POs and their DTs with regard to characteristics such as latency and information homogeneity.

O2. Analyse the information storage patterns available for FDT development with regard to characteristics such as privacy and information homogeneity.

O3. Analyse existing architectural styles to facilitate the development of autonomous DTs, bearing in mind that these must have communication, collaboration and cooperation capabilities.
O4. Analyse the alternatives existing in the literature that enable the design of FDT architectures in order to support cognitive diversity and distributed problem solving.
O5. Define a quality assurance framework for FDTs, tailored to their distinctive characteristics and taking into account other technologies that will be used in conjunction with them.
O6. Analyse which User Experience (UX) factors are applicable in the interaction between DTs and their physical counterparts.
O7. Define a proposal for the specification and design of FDTs based on MAS, providing them with communication, collaboration and cooperation capabilities and integrating the different patterns and styles analysed.
O8. Analyse, through the development of prototypes, how FDTs facilitate social interaction based on concepts such as social presence, sociability and social space.
O9. Analyse, through the development of prototypes, how the combined use of different technological platforms affects social interactions through FDTs.
O10. Analyse, through the development of prototypes, how FDTs can maintain emotional behaviour similar to humans.

Reaching these objectives will allow FDT4S to tackle the needs, gaps and challenges discussed in Section 2, complementing other work on, e.g., model-driven and knowledge-based DTs [18][19].

4. Expected Results

The expected project results can be divided into three areas. Each area corresponds to a technical work package of FDT4S (WP1, WP2 and WP3, respectively)

FDT requirements and quality assurance (O5, O6 and O7). The first result needed in FDT4S is the characterization of FDTs and their requirements in the scope of Society 5.0, as well as of associated quality assurance aspects. This area will be materialized in:

- A literature review on approaches for DT requirements specification, including an analysis of the requirement types and quality requirements that are currently addressed.
- A metamodel for FDT requirements specification, so that FDT characteristics can be suitably defined in relation to both DT autonomy and DT federations.
- An analysis and comparison of standards for FDTs, from the latest developments on standardization for DTs and for related technologies such as AI and XR.
- A quality assurance framework for FDTs, which will indicate assurance requirements to meet, activities to perform, techniques to use, artifacts to manage, and roles to involve.
- An UX model for interaction with FDTs, with global UX factors applied to FDT development and with specific metrics for their evaluation.

Software architecture for FDT development (O1, O2, O3, O4 and O7). This area can arguably be regarded as the main one of FDT4S, as it will integrate different results to design the holistic framework for the development of FDTs. The outcome of the area will consist of:

- A characterization and evaluation of architectural styles for FDTs, determining what styles are more suitable for FDT characteristics related to communication, collaboration and cooperation between autonomous DTs, and considering MAS frameworks.
- A characterization and evaluation of entanglement patterns, for both data fusion and filtering, and taking into account FDT constraints and needs and possible uses in different contexts.
- A metamodel for FDT design, considering the different DT properties to address in their design and the provision of a MAS-based approach.
- A framework for FDT development, integrating the metamodel, generation templates and a MAS framework, as well as the quality assurance framework, the UX model, and insights from the studies in the area below.

FDTs for study of social interaction in the scope of Society 5.0 (O8, O9 and O10). This area will focus on the development of specific FDTs and prototypes and on their application in different scenarios of social interaction, paying special attention to the interaction of humans with POs and with virtual entities and to situations in school environments (e.g., bullying situations). The deliverables of this area will be:

- Prototypes linked to social interaction enacted by FDTs, considering XR, different interaction modes, and novel ideas such as the use of DTs as virtual assistants and as interaction proxies.
- Prototypes linked to the integration of psychological theories in FDTs, focusing on possible social behaviours of FDTs and on human-FDT interaction.
- Prototypes linked to XR platforms in FDTs, building on the other prototypes and combining different XR environments and platforms to provide suitable DT interaction interfaces.
- Study of social interaction enacted by FDTs in Society 5.0, to determine, from different experiments, if FDTs are adequate for Society 5.0 systems that facilitate social interaction.

The combined delivery of these results will offer a holistic solution for the design of FDTs, effectively aligning technical excellence with the social values of Society 5.0. By synthesizing a quality assurance framework, a MAS-based architectural proposal, and prototypes for social interaction, FDT4S will lay the groundwork for a more inclusive and reliable digital future.

5. Current Results

FDT4S began less than six months ago and has only created preliminary results. The technical tasks have started to deal with: approaches for DT requirements specification, the quality assurance framework for FDTs, and UX factors applicable in the interaction between the DT and the PO, in WP1; architectural styles for the design of FDTs, in WP2, and; human-physical entity and human-virtual entity interactions, in WP3. Most of the work conducted corresponds to the analysis and definition of the project's baseline. Nonetheless, the following specific results are already available:

- A cross-domain analysis of requirements engineering for DT [20].
- A specification of how ontologies can be used in the engineering of critical systems [21].
- A characterization of how to deal with assurance of edge AI [22].
- An approach to combine model-based and knowledge-centred systems engineering [23].

6. Conclusion

Society 5.0 is envisioned as an evolution of Information Society focused on people and on the integration of the physical and digital worlds. These characteristics position DTs as a key enabling technology, as they can connect both worlds and consider human aspects. However, existing DT development approaches do not address Society 5.0-specific needs. The underlying development concepts and means need to progress towards FDTs: autonomous DTs that cooperate, collaborate, and coordinate with other DTs.

We have presented our plans to enact this vision in the FDT4S project. The project has started the work towards the design of a holistic framework for the development of FDTs for Society 5.0. The project is tackling needs, gaps, and challenges related to FDTs, quality assurance, the use of MAS for FDT development, and DTs for social interaction. Novel results will be provided in three areas: FDT requirements and quality assurance, Software architecture for FDT development, and FDTs for study of social interaction in the scope of Society 5.0. Although FDT4S has begun recently, specific results are already available, mainly in the first area.

FDT4S tackles research challenges in information science related to software engineering, model-driven engineering, quality assurance, user-centred design, human factors in information systems, databases and information, conceptual modelling and ontologies, digital twins, and virtual worlds, among other topics. We are not aware of any other initiative that focuses on better supporting FDT development for Society 5.0.

Acknowledgements

The work leading to this paper has received funding from the FDT4S (JCCM INNOCAM ref. SBPLY/24/180225/000020; ERDF) and "Una propuesta integral para el desarrollo independiente de dominio de gemelos digitales" (UCLM ref. 2025-GRIN-38441; ERDF) projects.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

References

[1] Cabinet Office, Report on The 5th Science and Technology Basic Plan, 2015.
[2] Hitachi-UTokyo Laboratory (Ed.), Society 5.0, Springer, 2020.
[3] R. Minerva, et al., Digital Twin in the IoT Context: A Survey on Technical Features, Scenarios, and Architectural Models, Proceedings of IEEE, 108(10) (2020): 1785–1824.
[4] M., Grieves, J. Vickers, Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems, in: Transdisciplinary Perspectives on Complex Systems, Springer, 2017.
[5] N. Crespi, et al. (Eds.), The Digital Twin, Springer, 2023.
[6] C. Vergara, et al., Federated Digital Twin, DS-RT 2023.
[7] E. Pretel, et al., Digital Twins and Artificial Collective Intelligence, Synergies for the Future, IEEE Internet Comp. 29(1) (2025): 75-85.
[8] R. Casadei, Artificial Collective Intelligence Engineering: a Survey of Concepts and Perspectives, Artif. Life 29(4) (2023): 433–467.
[9] A. Macías, et al., Data fabric and digital twins: An integrated approach for data fusion design and evaluation of pervasive systems, Inf. Fusion 103 (2024): 102139.
[10] J.L. de la Vara, et al., Assurance and certification of cyber-physical systems: The AMASS open source ecosystem, J. Syst. Softw., 171 (2021), 110812.
[11] DNV, DNV-RP-A204: Recommended practice for digital twin assurance, 2023.
[12] E. Pretel, et al. Analysing the synergies between Multi-agent Systems and Digital Twins: A systematic literature review. Inf. Softw. Technol. 174 (2024): 107503.
[13] S. Gupta, et al. (Eds.), Multi Agent Systems: Technologies and Applications Towards Human-Centered, Springer, 2022.
[14] K. Kreijns, et al., Social Presence: Conceptualization and Measurement, Educ. Psychol. Rev. 34(1) (2022): 139–170.
[15] C. Merz, et al., Universal Access for Social XR Across Devices: The Impact of Immersion on the Experience in Asymmetric Virtual Collaboration, VR 2024.
[16] L. Zhinin-Vera, et al, Mindful Human Digital Twins: Integrating Theory of Mind with multi-agent reinforcement learning, Appl. Soft Comput. 174 (2025): 112939
[17] M.A. Sánchez-Cifo, Increasing Emotional Intelligence Self-awareness using Low-cost Devices, PhD Thesis, Universidad de Castilla-La Mancha, 2026.
[18] Lehner, D., et al., Model-driven engineering for digital twins: a systematic mapping study, Softw. Syst. Model. 24 (2025): 1339–1377.
[19] Microsoft, Azure Digital Twins, 2025. URL: learn.microsoft.com/en-us/azure/digital-twins/
[20] A. Macías, et al., Requirements Engineering for Digital Twins: a Cross-Domain Systematic Literature Review, QUATIC 2025.
[21] J.L. de la Vara, et al., An Ontology Metamodel for Knowledge-Centric Systems Engineering in Practice, ER 2025.
[22] C. Ayora, et al., Edge AI Assurance: A Systematic Mapping Study, Inf. Softw. Technol. 189 (2026): 107908.
[23] J.M. Morote, et al., Combining Model-Based Systems Engineering and Knowledge-Centric Systems Engineering to Design Reliable Systems in Practice, Appl. Sci. 16(5) (2026): 2179.