Digital Twin Collaborative Platforms: Applications to Humans-in-the-loop Crafting of Urban Areas

Published Version:
Bononi L., Donatiello L., Longo D., Massari M., Montori F., Stacchio L., et al. (2022). Digital Twin Collaborative Platforms: Applications to Humans-in-the-loop Crafting of Urban Areas. IEEE CONSUMER ELECTRONICS MAGAZINE, 1, 1-8 [10.1109/MCE.2022.3214944].

Availability:
This version is available at: https://hdl.handle.net/11585/918292 since: 2023-02-27

Published:
DOI: http://doi.org/10.1109/MCE.2022.3214944

(Article begins on next page)

Digital Twin Collaborative Platforms: Applications to Humans-in-the-loop Crafting of Urban Areas

Luciano Bononi
Dept. of Computer Science and Engineering, University of Bologna

Lorenzo Donatiello
Dept. of Computer Science and Engineering, University of Bologna

Danila Longo
Dept. of Architecture, University of Bologna

Martina Massari
Dept. of Architecture, University of Bologna

Federico Montori
Dept. of Computer Science and Engineering, University of Bologna

Lorenzo Stacchio
Dept. for Life Quality Studies,University of Bologna

Gustavo Marfia
Dept. of the Arts, University of Bologna

***Abstract*—The opportunity to foresee how a physical system might work in advance, resorting to its digital model, explains the general attractiveness of digital twins. The use of digital twins, especially in the manufacturing context, encourages the investigation of the benefits they may bring in many circumstances, ranging from medical to commercial applications. In this work, however, we do not introduce yet another field where digital twins may be applied but, instead, propose digital twins as part of a convergence of technologies that may be put to good use to foster advanced distributed collaboration platforms to support humans in the loop. To clarify our proposal, we contextualize the proposed methodology by providing a conceptual framework related to a Virtual Hackable City, where we explain the advantages of such an approach.**

INTRODUCTION The over thirty months elapsed since the beginning of the pandemic have emphasized the role of digital technologies, as lifelines capable of supporting and governing global logistic and communication networks when social distancing is needed. Whether the new paradigms based on the use of digital media will linger or not beyond the end of the emergency depends on the services that these will offer. Regardless, the carbon footprint concerns posed by Vardi in [1] remain uncomfortably valid and may sustain the continuation of given practices online rather than in person. Among such practices, many have benefited from vertical collaboration software platforms, which have become essential to carrying on social and economic activities. However, despite the current popularity and economic value of such systems (e.g., Slack has recently bought by Salesforce

Digital Object Identifier 10.1109/MCE.2022.Doi Number
Date of publication 00 xxxx 0000; date of current version 00 xxxx 0000

This article has been accepted for publication in IEEE Consumer Electronics Magazine. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/MCE.2022.3214944

for 24B$), and the interest devoted by academia to the implementation of hybrid workplace models in a number of different settings (manufacturing, education, etc.) [2], [3], [4], [5], they still present technical barriers which hinder their full potential. Most implement basic communication paradigms such as video calls, screen-sharing, and instant messaging but lack interoperability and integration with professional platforms which exceed the classic office ones (e.g., spreadsheets, word processors, etc.). None, to the best of our knowledge, have so far defined a standard method to incorporate and manipulate complex graphical content. No widespread solution, in addition, can present and support collaborative manipulations of models and data within Extended Reality (XR) environments. In essence, the full potential in terms of collaboration and productivity obtainable through the integration of multiple technologies is still far beyond the horizon. This contribution aims to provide a holistic approach to designing collaboration platforms that may at once foster multiple communication patterns and workplace productivity. To this aim, we present a scheme for a collaborative open design platform, describing how this may apply to the context of the design and management of urban spaces.

The rest of this paper is organized as follows. We first introduce the problem of interest in the section that follows, while we then introduce the component that may serve as a pillar of the proposed solution in section **Digital Twins**. A review of works that fall close to the proposed vision is described in section **Human-Cyber-Physical Systems**. Our proposal, the key ingredients necessary for its implementation and an application of such a conceptual framework are provided in sections **DT-Empowered Collaboration**, **Implementation Strategy** and **Applying the Conceptual Framework**, respectively. This paper ends with the **Conclusion** section.

Product Driven Collaboration

As highlighted in a recent article by Paul Marks, *Videoconferencing apps took off during the COVID-19 lockdowns, but more efficient ways to collaborate virtually are waiting in the wings [6]*. In particular, in his contribution, Marks states that technologies such as drones, robots, and virtual reality may be the next game-changers in online collaboration. It is interesting to observe, though, that such a vision puts the location where collaboration occurs at the center of the stage [7].

This contribution approaches the problem from a different perspective, putting content and scope at the center of a collaboration platform. Following such a vision, collaboration platforms should amount to ecosystems that do not only foster human-to-human communications but also seamlessly exchange technical information and data, are interoperable, offer complex visualizations, and use what-if analyses. In essence, collaboration platforms should become an integral part of those processes which lead to the design, implementation, and deployment of a product: they may bring into such workflows the feedback of the stakeholders, enriching them with all the possible dimensions of information of the final collaboration goal.

The present amounts, therefore, to a unique opportunity to rethink the dynamics involved in digital collaborations and the digital workplace in general. To this date, digital collaboration has mainly meant communication. The question is whether digital collaboration may go beyond such a pattern, also including, for example, design, prognostics, maintenance, verification, prediction, and awareness.

Computing models that are increasingly employed to represent a physical product and to perform all of such tasks are Digital Twins (DTs). DTs offer a digital representation of a system and are meant to mimic the behavior of their original counterparts for specific sets of physical inputs. DTs represent a pillar technology of Industry 4.0 as they realize the convergence between simulation techniques and Internet of Things (IoT) solutions [8]. In brief, they extend computer simulation practices and emerge following the falling costs of networking resources and the advances in computing and technological innovations and tools. In the following, we present a few of their main characteristics before moving on to how a DT may become a driver for collaboration by providing a practical proposal related to urban spaces.

Digital Twins

DTs have been seriously researched in the past decade, in the context of industrial processes and beyond. In [9] Kshetri cites different examples, ranging from company assets protection (the DT deployed by Shell for the Bonga oilfield's floating production, storage, and offloading facility) to medical applications (the Living Heart Project, which employs Dassault

Systems' 3DExperience platform). From a methodological point of view, Qinglin et al. [10] critically compared Big Data and DTs in industry, concluding that their convergence could speed product development and verification. This convergence also appears in Cantamessa et al. [11] where the authors analyze the specific case of Tesla, which monitors and verifies the real-time use of its products through DT instances (each car constantly communicates with its DT instance running on a Tesla server, for timely prognostics and maintenance).

The benefit of involving the use of DTs in all of the steps composing the life-cycle of a product has been recognized in Tao et al. [12], where the authors exhibited the advantages of adding the design (starting from the conceptual design to the detailed design and virtual verification) and the manufacturing phases to the service one. Along the same path, Barricelli et al. [13] presented DT applications to optimize several design processes, including manufacturing to healthcare. In essence, we can expect a growing demand for large-scale simulations through the recombination and interaction of many and varied DTs beyond those conventionally used in industry. As stated in [14], *digital twins may be created for all types of things in the real world*, so they could reproduce an entire city by recombining buildings, roads, automobiles, residents, etc. As a thought-provoking example, consider the recent proposal of human Digital Twins Computing (DTC), whose contribution would be to expand the range of human activities from the real world to cyberspace. To this aim, Thosima et al. [15] proposed DTC to digitally represent a person's outer self in terms of physical and physiological characteristics, as well as the person's inner self, as personality and thoughts. A human DTC model reproducing the individuality and characteristics of humans defines the behavior of a DT. By reacting to other people's actions in cyberspace as if they were our real-world selves and by making them behave autonomously in a virtual society, human DTs could engage with others as our real-life selves [16], [17].

DTs could be key in the design stages of many types of projects, foreseeing any future outcomes resulting from their design choices, with no expenditures caused by unexpected disruptions. This flexibility of DTs is the main reason they may become game-changers for design: a DT platform may show how specific design choices would work in specific contexts of use. This flexibility also motivates why DTs may perfectly fit within collaborative design platforms (e.g., digital playgrounds created, modified, or even disrupted by multiple users as their constituent elements can be more simply installed, stretched, or broken, than their physical equivalent).

It is now interesting to observe that although the state-of-the-art DT research in the domain of computing is mainly focused on the production, management, and processing of data (i.e., Internet of Things, Cloud Computing, and Artificial Intelligence), also other directions are being sought [18]. In addition to the need for automation, also a need for human collaborations and direct interventions is emerging, as witnessed by the novel Human Cyber-Physical Systems paradigms at the base of future Industry 5.0 and Society 5.0.

Human-Cyber-Physical Systems

An interesting conceptual framework that aims at integrating human interventions with cyber and physical systems has been emerging in the manufacturing sector and amounts to the Industry 5.0 one, with the development of Human-Cyber-Physical Systems (HCPSs) [19]. According to [20], a HCPS *is a composite intelligent system comprising humans, cyber systems, and physical systems to achieve specific manufacturing goals at an optimized level*. At the peak of their development, HCPSs could learn from past experiences and implement analytical thinking using Artificial Intelligence, thus being able to augment the information available in the ecosystem and let humans focus on non-standard aspects of work. HCPSs may also play a role in future Society 5.0, i.e., a society that *through the high degree of merging between cyberspace and physical space, will be able to balance economic advancement with the resolution of social problems by providing goods and services that address manifold latent needs regardless of locale, age, sex, or language* [21], [22]. While our proposal fits within the field of view of such visionary paradigms, it concentrates on one specific aspect: the fostering of online and distributed collaborative environments through the integration of DT and immersive technologies. [23], [24], [25]. To this aim, in the following we introduce our vision regarding the setting-up of DT-empowered collaboration platforms.

DT-Empowered Collaboration

The challenge, concerning the state of the art, is to surpass the existing distances between mainstream

This article has been accepted for publication in IEEE Consumer Electronics Magazine. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/MCE.2022.3214944

collaboration platforms (e.g., forums, chats, instant messaging, shared screens, etc.) and DTs. To explain how we deem such a challenge may be approached, we resort to Figure 2, which reports the main constituent elements of what we here define as a DT-Empowered Collaboration Platform. In essence, a DT-Empowered Collaboration Platform may be seen as composed of a core simulation engine, integrated with software, data, and IoT components that support an active exchange of information in the two directions in addition to interoperability, both at a syntactic and semantic level. IoT components, in fact, feed in a bottom up fashion the simulation engines with their data (straight arrow in Figure 2), but may also benefit from and utilize the forecasting information and what if analyses returned by such engines (U arrow in Figure 2). Interoperability (represented with a two ended arrow in Figure 2), across tools and applications, as discussed in [26], is key to creating an ecosystem of models of real-world objects which may consistently and seamlessly work together, thus favoring the creation of collaborative environments. Artificial intelligence-powered interfaces, instead, are the components necessary to translate any natural means of communication of human beings in DT settings and vice versa (two ended arrow in Figure 2). Finally, extended reality visualizations may support an active exchange of information in the two directions with a given DT, to comprehend its behavior beyond the representations that may be provided by numbers and charts (straight arrow in Figure 2), including the responses to specific stimuli and manipulations of its state (U arrow in Figure 2). We aim at fostering an ecosystem supporting the exchange and enactment of the ideas originating from multiple players, participating through legacy open-source collaborative paradigms. Immersive visualizations, augmented interactions, and collaborations, along with artificial intelligence paradigms, are all ingredients that may promote a human-in-the-loop approach and empower the predictions of the proposed platform, to boost the design process convergence for human designers. Note that, what may appear as a pile-up of technologies, instead aims at putting human beings at the center of the design space, as with a collaborative immersive approach any innovations driven by DTs will be more strongly controlled and human-centric.

Implementation Strategy

Expanding and including additional detail concerning the main constituent elements listed in the previous Section, it is now possible to provide a list of technologies, along with their characteristics, which may benefit from an exemplar DT-Empowered Collaboration platform:

- As anticipated, simulation platforms amount to the computational core, in charge of mirror physical assets acting as a single source of truth, as they may answer what-if questions originating from the modeling effort. Different approaches (e.g., discrete event, agent-based, cellular automata, etc.) and platforms (e.g., NetLogo, UrbanSim, Transims, etc.) may be exploited to such aim;
- IoT platforms act as generators of real-time data and actuators of real-world transformation. Some examples could include AWS IoT, Microsoft Azure IoT, Google Cloud IoT, IBM Watson IoT, Oracle IoT Cloud, etc. Some of the standard functions are connectivity (orchestration, management, services), device management (deployment and configuration, monitoring, command and control, update, edge application), IoT communications protocols and infrastructure (local hubs up to cloud backend and multiple protocols), IoT applications (from DT to rules and event management, app development);
- Big Data is the historical data related to an ecosystem of interest. It may be structured, semi-structured, or unstructured data and characterized in terms of Volume, Variety, Velocity, Variability, and Value (the Big Data 5Vs). Such data may help predict future behaviors of the system of interest. Different platforms are available, relevant examples are Microsoft Azure, and Amazon Web Services, which provide scalable, secure, and durable repositories for the storage and processing of big amounts of data.
- Artificial Intelligence (AI) paradigms amount to the keys required to interpret the inputs originating from collaborative platforms, as well as the information conserved within any available Big Data. To interpret the former, AI may be employed to interpret natural forms of human interactions (e.g., natural language processing and speech recognition). For what concerns the latter, regression and classification approaches based on deep learning, for example, will be used to leverage any available Big Data for the benefit of prediction tasks. In

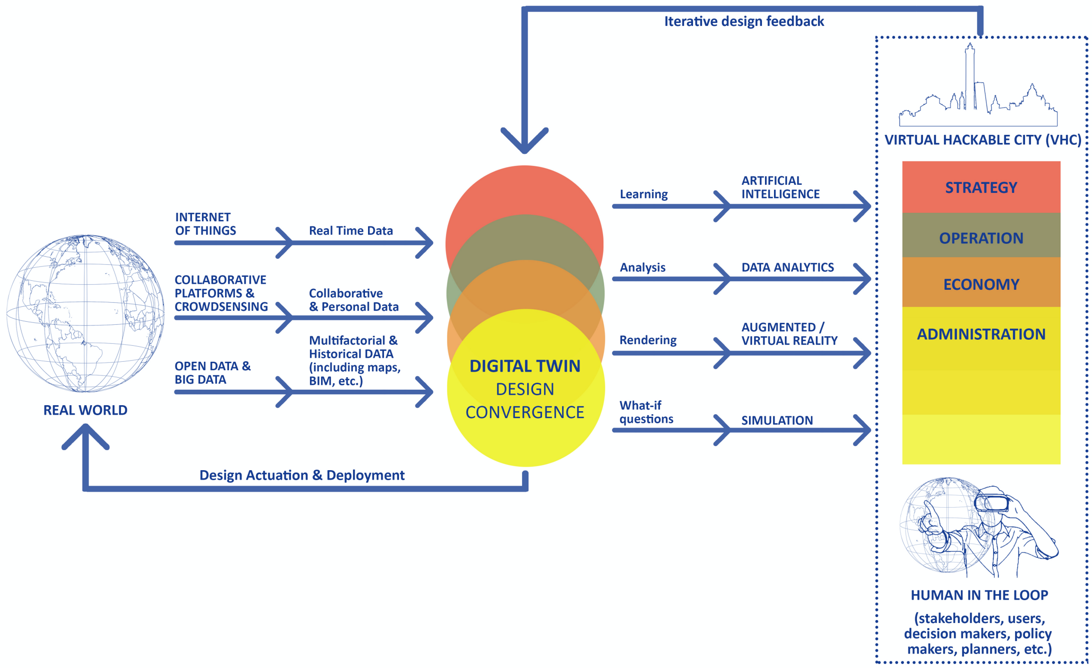

Figure 1. Open Collaborative Immersive Empowered Digital Twin-based Design platform.

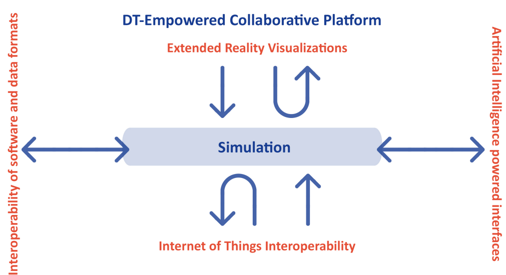

Figure 2. DT-Empowered Collaboration Platform.

addition, AI paradigms can analyze the outputs and behaviors of the DT, in a synergistic collaboration with simulation platforms. An excess of AI platforms are today available, Amazon Redshift and Microsoft AI are two relevant examples;

- Data Analytics platforms may return real-time insights regarding the execution of a DT. Normally employed for business intelligence purposes, several different platforms (e.g., Apache Spark, Microsoft Power BI, etc.) are available to implement such component category and may be easily integrated into the present proposal;
- Virtual and Augmented Reality (VR/AR) are enabling technologies supporting the human-centric aspect of the proposal. Immersive environments may be used to see, verify and interact with a DT. Many different platforms are available to create, build, publish and collaborate: Amazon Sumerian, Facebook Horizon, and Mozilla Hubs, to name a few. Of particular interest for the present proposal would also be the integration of the WebXR device API, a group of standards defined by W3C to support the rendering of 3D scenes to hardware designed for presenting virtual worlds (virtual reality, or VR), or for adding graphical imagery to the real world, (augmented reality, or AR);

In the next Section we discuss how such an approach may be put to good use to support a specific conceptual framework: a virtual hackable city.

Applying the Conceptual Framework

To assess the goodness of the proposed approach, we here consider a complex setting posed by city design maintenance and management (check Figure 1). A DT-Empowered Collaboration Platform of urban space may help to move along a path that aims at creating new participatory ways of governance and accountability in such shared environments.

The incoming flows of new cultural groups on one hand, and the changes affecting also conventional professions and enterprises on the other, emphasize the need for new practices and regulations, overcoming the rigid and functional rhythm of urban life designed upon a manufacturing paradigm. These issues generate frictions and conflicts, widening the inequalities and – from the public economic perspective – growing citizens', voters', and taxpayers' disaffection, with visible implications for public expenditure and the even diffusion and accessibility of urban services. Such tensions have exacerbated in the aftermath of the COVID-19 outbreak, calling for city preparedness and risk as a piece of overall city design and planning, incorporating the concept of widespread resilience. Preparedness, broadly including the treatment of uncertainty, requires rethinking not only operational aspects but also ways of producing knowledge to be prepared in the long term [27]. This objective needs a comprehensive method to intervene with out-of-the-box solutions in the short-term operative design and planning of urban public space, but at the same time propose scenarios for the longer-term future development. To this aim, digital human-in-the-loop and collaboration platforms have been used to exchange experiences and collaboratively seek solutions. The adoption of participative and collaborative approaches has produced methodological studies on common languages for the representation and accessibility of urban public space, by developing ontologies providing specialized and non-specialized information and visualization of local data. Vertical applications have been realized producing high value in separate sectors, but lacking the opportunity to synergistically adapt the digital model to urban complex systems [28], [29].

Leveraging on instances of the DT-Empowered Collaboration platform, effective and comprehensive solutions to such problems may be sought as the proposed platform may integrate:

1) Novel metrics apt to quantify urban gaps (identification and evaluation of the differences among different areas and between the city as the infrastructure on the one hand, and the citizen community on the other);
2) New means of participation of the community of stakeholders, fostering an easy and rapid collection of ideas and suggestions;
3) Methodologies suitable to translate community inputs into their most relevant implications and figures of merit;
4) Effective ways of visualizing and supporting the understanding of the implications and results, as well as of amending and adapting the contributions provided through the participatory step.

A Virtual Hackable City (VHC) hence amounts to a DT-Empowered Collaboration instance, enabling anyone to experiment with hacks in the urban space and eventually create value for the city, society, environment, and market (check Figure 1). Interestingly, the proposed paradigms appear suitable to implement the vision of De Waal et al [30]: create new participatory ways of governance which include advanced hacking, making, and prototyping skills, such as envisioning, translating, or orchestrating, and enable emerging, heterogeneous city-makers to participate actively in exploring the collaborative envisioned potential and constructive dialogue aiming for transformational change for the common good. Figure 3 reports the general VHC schema.

According to this vision, a VHC may be implemented to support co-design activities on the hybrid (physical/digital) model. The objective would be to verify, monitor, and anticipate the effects of the disruptive re-design of portions of public spaces of a given city (in a digital environment) while at the same time enlarging the participation to collaborate in co-design on a physical 3D model. The VHC would implement simulations of transformations of public spaces, allowing to overcome the barriers set by the physical environment, showing possible future arrangements in the light of alterations of some variable. Furthermore, the VHC would grant the space for experimentation both to policymakers and planners but also to citizens and less expert users. This provides the freedom to test and fail on a small controlled scale, before proceeding further with longer-term planning for a larger urban scale.

Conclusion and Future Works

This contribution is concerned with the design and development of a DT-Empowered Collaboration paradigm, applied to the context of a Virtual Hackable City (VHC), exploiting the most advanced technologies from Artificial Intelligence, Internet Of Things, Simulation, and Virtual and Augmented Reality fields. The proposed DT-Empowered Collaboration paradigm may be employed to manage and counter impor-

This article has been accepted for publication in IEEE Consumer Electronics Magazine. This is the author's version which has not been fully edited and
content may change prior to final publication. Citation information: DOI 10.1109/MCE.2022.3214944

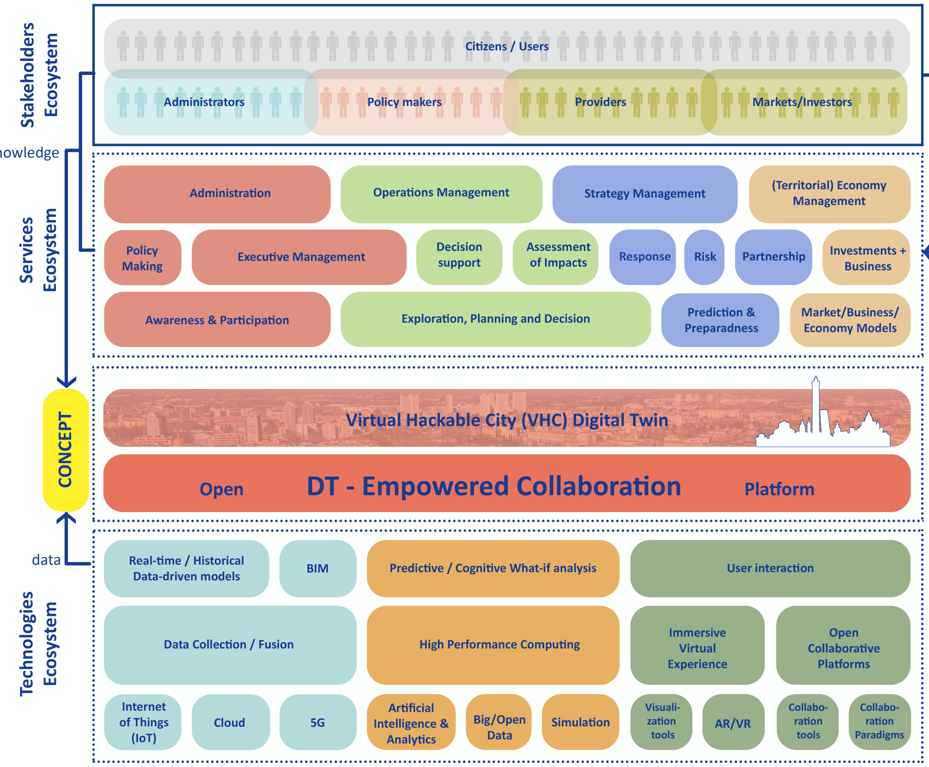

Figure 3. General Project Architecture.

tant issues of modern and crowded but also small and quiet cities, such as the flows of new cultural groups, changes in professions and enterprises, and the rigid rhythm of urban life. In essence, the proposed paradigm may be put to good use to assess the preparedness of a city to manage any kind of event. We idealize a digital world in which you can see the effects of changes in cities: what if we build a Mexican restaurant in a historic neighborhood? What happens to the traffic flows if we open a new road? Exploiting DT-Empowered Collaboration platforms, we advocate that we could quickly find convincing answers to all of these questions. Much work has to performed though. Data inconsistencies and shortcomings could jeopardize the final outcome of such initiatives. For this reason, a future direction of work will consider the issue of data availability to evaluate, under the current conditions, the real applicability of the proposed framework.

Acknowledgment

Thanks to the Italian Ministry of University and Research "PON Ricerca e Innovazione" funds 2014-2020, to Aeffe Spa and to e-Soft/Present Group Spa for supporting this research.

REFERENCES

1. M. Y. Vardi, "Publish and perish," 2019.
2. D. Mourtzis, N. Panopoulos, J. Angelopoulos, S. Zygomalas, G. Dimitrakopoulos, and P. Stavropoulos, "A hybrid teaching factory model for supporting the educational process in covid-19 era," *Procedia Cirp*, vol. 104, pp. 1626–1631, 2021.
3. D. Mourtzis, J. Angelopoulos, and N. Panopoulos, "A virtual collaborative platform for education in the design and simulation of aeronautics equipment: The teaching factory 5.0 paradigm," *Available at SSRN 4071869*, 2022.
4. M. Grzegorczyk, M. Mariniello, L. Nurski, and T. Schraepen, "Blending the physical and virtual: a hybrid model for the future of work," Bruegel Policy Contribution, Tech. Rep., 2021.
5. K. M. J. Iqbal, F. Khalid, and S. Y. Barykin, "Hybrid workplace: The future of work," in *Handbook of Research on Future Opportunities for Technology*

Management Education. IGI Global, 2021, pp. 28–48.

6. P. Marks, "Virtual collaboration in the age of the coronavirus," *Communications of the ACM*, vol. 63, no. 9, pp. 21–23, 2020.
7. L. Ciolfi, G. Fitzpatrick, and L. Bannon, "Settings for collaboration: The role of place," *Computer Supported Cooperative Work (CSCW)*, vol. 17, no. 2, pp. 91–96, 2008.
8. D. Mourtzis, "Design and operation of production networks for mass personalization in the era of cloud technology," 2022.
9. N. Kshetri, "The economics of digital twins," *Computer*, vol. 54, no. 04, pp. 86–90, 2021.
10. Q. Qi and F. Tao, "Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison," *Ieee Access*, vol. 6, pp. 3585–3593, 2018.
11. M. Cantamessa, F. Montagna, S. Altavilla, and A. Casagrande-Seretti, "Data-driven design: the new challenges of digitalization on product design and development," *Design Science*, vol. 6, 2020.
12. F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, and F. Sui, "Digital twin-driven product design, manufacturing and service with big data," *The International Journal of Advanced Manufacturing Technology*, vol. 94, no. 9, pp. 3563–3576, 2018.
13. B. R. Barricelli, E. Casiraghi, and D. Fogli, "A survey on digital twin: Definitions, characteristics, applications, and design implications," *IEEE Access*, vol. 7, pp. 167 653–167 671, 2019.
14. T. Nakamura, "Digital twin computing initiative," *NTT Technical Review*, vol. 18, no. 9, pp. 13–18, 2020.
15. I. Toshima, S. Kobashikawa, T. K. H. Noto, K. Hirota, and S. Ozawa, "Challenges facing human digital twin computing and its future prospects," *NTT Technical Review*, vol. 18, no. 9, pp. 19–24, 2020.
16. L. Stacchio, M. Perlino, U. Vagnoni, F. Sasso, C. Scorolli, and G. Marfia, "Who will trust my digital twin? maybe a clerk in a brick and mortar fashion shop," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 2022, pp. 814–815.
17. L. Donatiello and G. Marfia, "Proposing the recursiverse overlay application for the metaverse," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 2022, pp. 844–845.
18. M. Farsi, A. Daneshkhah, A. Hosseinian-Far, and H. Jahankhani, *Digital twin technologies and smart cities*. Springer, 2020.
19. S. Huang, B. Wang, X. Li, P. Zheng, D. Mourtzis, and L. Wang, "Industry 5.0 and society 5.0—comparison, complementation and co-evolution," *Journal of Manufacturing Systems*, vol. 64, pp. 424–428, 2022.
20. J. Zhou, Y. Zhou, B. Wang, and J. Zang, "Human–cyber–physical systems (hcpss) in the context of new-generation intelligent manufacturing," *Engineering*, vol. 5, no. 4, pp. 624–636, 2019.
21. E. Flores, X. Xu, and Y. Lu, "Human cyber-physical systems: A skill-based correlation between humans and machines," in *2020 IEEE 16th International Conference on Automation Science and Engineering (CASE)*. IEEE, 2020, pp. 1313–1318.
22. A. Deguchi, C. Hirai, H. Matsuoka, T. Nakano, K. Oshima, M. Tai, and S. Tani, "What is society 5.0," *Society*, vol. 5, pp. 1–23, 2020.
23. L. Stacchio, A. Angeli, and G. Marfia, "Empowering digital twins with extended reality collaborations," *Virtual Reality Intelligent Hardware*, 2022.
24. J. Eyre and C. Freeman, "Immersive applications of industrial digital twins," *The Industrial Track of EuroVR 2018*, 2018.
25. J. Pang, J. Li, Z. Xie, Y. Huang, and Z. Cai, "Collaborative city digital twin for covid-19 pandemic: A federated learning solution," *arXiv preprint arXiv:2011.02883*, 2020.
26. V. Piroumian, "Digital twins: Universal interoperability for the digital age," *Computer*, vol. 54, no. 1, pp. 61–69, 2021.
27. A. Boeri, D. Longo, S. Orlandi, R. Roversi, and G. Turci, "Community engagement and greening strategies as enabling practices for inclusive and resilient cities," *International Journal of Environmental Impacts*, vol. 5, no. 1, pp. 1–14, 2022.
28. F. Montori, L. Bedogni, and L. Bononi, "A collaborative internet of things architecture for smart cities and environmental monitoring," *IEEE Internet of Things Journal*, vol. 5, no. 2, pp. 592–605, 2017.
29. F. Montori, L. Bedogni, C. Fiandrino, A. Capponi, and L. Bononi, "Performance evaluation of hybrid crowdsensing systems with stateful crowdsensim 2.0 simulator," *Computer Communications*, vol. 161, pp. 225–237, 2020.
30. M. De Waal, M. De Lange, and M. Bouw, "The hackable city: Citymaking in a platform society," *Architectural Design*, vol. 87, no. 1, pp. 50–57, 2017.