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EDITORIAL

Special issue on 'digital twins for smart production and logistics'

Industry 4.0 has been a revolutionizing concept that for more than 10 years has been inspiring, guiding and challenging many information technology – and engineering-related research fields. The many technologies that are involved in this novel picture of a 'digitally enhanced' world are at different maturity stages, and, often, the maturity of a single technology also depends on the application area. The common feature that can be found everywhere in Industry 4.0 approaches, technologies, methods, applications, and strategies is that digitization is accompanying the real 'physical' world applications and decision-making.

Traditionally, we consider the digital world as a small protrusion of the physical world into the virtual one, where things happen/are decided/are experienced anchored in the physical world, and the digital one is used to simplify or quicken some tasks in the physical one (think of trivial examples such as 'I get help in making calculations with an electronic calculator'), this is the 'old generation's perspective' even of advanced technologies. However, the digitization vision can develop in the direction of realizing that the unbalance between the importance of the physical world and the digital world is not necessarily shifted towards the physical world. In reality, it could be stated that there are situations in which the digital and the physical worlds are both at the same importance level, and other situations, more extreme, where the digital world is more important than the physical one (think of the metaverse experiences, where people can get married and lead a full 'parallel' life without having any counterpart in the physical world, but no one can argue with the 'real existence' of such human experiences and interactions in this scenario, despite their being purely virtual).

This digitization vision sometimes refers to the traditionally physical objects as evolving to 'Cyber-Physical Systems' (CPS), which is an object of extensive and interesting investigation in literature (Lee, Bagheri, and Kao 2015). Digital twins are part of this Industry 4.0 and CPS wave, where the digital aspect is at least as important as the physical one. The digital twins, in this respect, are part of the CPS paradigm as a technological basis that grants a real-time simulated replica in the virtual world of what is happening in the physical world, thus allowing many important functionalities, such as monitoring, control, optimization, and prediction of physical systems (Macchi, Ragazzini, and Negri 2023). This allows us to make more precise, accurate, timely, and efficient decisions at different levels.

Initially, the digital twin concept was born to accompany complex products and systems from their design phase throughout the whole lifecycle (Grieves and Vickers 2016), with a particular emphasis on aerospace systems, such as flying vehicles, as demonstrated by the NASA Roadmap (Shafto et al. 2012). This concept was then successfully adapted and adopted across several different fields and applications of various nature, such as agriculture, medicine, transportation, and smart manufacturing and logistics, to name a few (Singh et al. 2022). The adoption of digital twins in the different sectors is not homogeneously distributed in the sectors, for example, applications in agriculture and retail are relatively new compared to other sectors, such as aerospace and healthcare, and, within the industry, manufacturing applications of digital twins are more mature than logistics ones, suggesting a need to explore the latter field more extensively.

Being the digital twin, a technological concept still under evolution, many are developments, open challenges and discussion points that are waiting to be addressed by the scientific and industrial community. Open aspects to be investigated range from the technological development of the digital twin itself – e.g. in terms of system modelling and simulation – of data formats and sources to integrate information from the physical world, of interface with other software systems and with the human decision-makers, of development of advanced statistics or machine learning algorithms to be integrated in the digital twin to empower the potentialities of data elaboration in real time, of development of information system architectures to find the best way for the digital twins of the various systems to interact with one another, of solution of standardization and interoperability issues of the digital twin components and systems to allow easier applicability and adoptability in industry, and, finally, of demonstration of the effective efficacy on the field, evaluating the impacts on the physical systems, on the companies, and on the supply chains.

This Special Issue contributes to the discussion on these open points and challenges for the manufacturing industry, with a focus on production and logistics activities/sectors: to this aim the title of the Special Issue is 'Digital Twins for Smart Production and Logistics' and proposes 15 reference research works that provide a wide overview on various directions of investigation that are currently active on the topic and that reflect the open points above mentioned.

In particular, the first paper starts the topic of digital twins for smart production and logistics by defining the state of the art of the still open challenges path; papers 2 to 5 propose modelling advancements to improve the current technological development at the basis of the current digital twins for industry; papers 6 to 8 propose ameliorated functionalities of digital twins through new models or through the fusion of existing models; papers 9 to 12 focus on industrial logistics at large (from Autonomous Mobile Robots – AMR – to warehousing systems), proposing specific digital twin-based functionalities or efficiency improvements; finally, papers 13 to 15 explore industrial implications on the adoption of digital-twin based solutions.

In the following, the reader may find a brief description of the papers present in the Special Issue:

The first paper entitled 'Production digital twin: a systematic literature review of challenges' by Kerrouchi et al. presents a systematic literature review on the state of the art of the challenges related to the implementation in the field of digital twins for manufacturing. The contribution fills the gap of a more comprehensive, clear, and consistent understanding of the underlying definitions and concepts and provides a framework of the challenge paths, connecting them with their causes and consequences. In particular, the paper identifies the manufacturing-related digital twin challenges; it categorizes them based on components and criteria and analyzes their presence over time; it develops an innovative framework to identify the relationships/paths between the challenges of the manufacturing digital twins and their related causes and consequences; and it maps the interconnected challenges to the different digital twin components.

The second paper entitled 'An AutomationML extension towards interoperability of 3D virtual commissioning software applications' by Zhao et al. offers a way to make digital twins for 3D virtual commissioning applications more interoperable by extending the AutomationML standard to include a full-scope 3D-based virtual commissioning data exchange. The approach is to standardize attributes and modelling methods related to sensors, actuators, and signal connections. The paper methodology is case-driven and iterative, and the AutomationML extension is evaluated by exchanging data between two 3D virtual commissioning tools. The paper demonstrates that the methodology converts considerably more attributes than the traditional AutomationML.

The third paper entitled 'Extending factory digital Twins through human characterization in Asset Administration Shell' by Cutrona et al. incorporates the human characterization into Asset Administration Shell (AAS) to offer a more realistic Human Digital Twin (HDT), i.e. a digital twin that is able to mimic the behavior of human beings, such as workers' skills and status (position, tasks, physiological state, psychological state and so on). AAS is a common modeling approach to define common semantics for intra-company information (Tantik and Anderl 2017) that could be used as data model for digital twins. In this work, the authors propose various sub-models to use AAS to facilitate the transition towards Industry 5.0 and the inclusion of the human-in-the-loop. The proposed sub-models are demonstrated in two laboratory scenarios: one related to worker's fatigue estimation, where the digital twin monitors the worker's well-being; the other related to the collaboration between humans and robots, where the digital twin goal is to optimize the task allocation between humans and robots.

The fourth paper entitled 'Scalable and efficient digital twins for model-based design of cyber-physical systems' by Cimino et al. develops a framework for a more efficient and scalable simulation modelling in digital twins, based on object-oriented modelling and IEC industrial standards. In particular, the paper fills the technological gap of the inherent difference between the representations of the physical world, which are typically time-based and relying on DAE (Differential and Algebraic Equations), and the representations of the virtual world – among which the digital twin lies -, which are typically event-based and related to FSM (Finite State Machine) modelling. The effort of the authors is to be able to simulate the cyber and the physical part of the CPS within a single model. Practical examples and a case study are provided to demonstrate the industrial benefits and viability of the proposed framework.

The fifth paper entitled 'Synthetic data generation for digital twins: enabling production systems analysis in the absence of data' by Lopes et al. investigates the generation of synthetic data, and in particular of fictional production lines, to simulate their behaviour without the need for real datasets to conduct experiments. This is in line with the necessity to elaborate new data-driven strategies that can fully exploit the potential of digital technologies, in the absence of open or precise manufacturing data (Li et al. 2009). The authors propose a twofold approach to solve the gap in benchmarking of manufacturing systems' open datasets. On the one side, an algorithm capable of generating random networks representing a range of manufacturing systems is proposed; on the other side, a simulation strategy to simulate the generated complex networks. The demonstration offers three application use cases of the proposed approach.

The sixth paper entitled 'A digital twin-driven part spatio-temporal quality prediction framework integrated with equipment degradation state analysis' by Wang et al. develops a novel framework for quality prediction of manufactured products that takes into account the spatial and the time dimensions contribution to quality. In particular, by considering the fact that part quality is an accumulated result of many stations (spatial dimension) and of machine degradation in time (temporal dimension), the framework relies on the digital twin to manage data and provide simulation functions to support quality prediction (Liu et al. 2021); and on a module with the Relationship Graph Analysis (RGA) to classify continuous equipment degradation into discrete states to build the multi-stage machining process. The framework and related models are validated in a production line with positive results on the part quality prediction accuracy.

The seventh paper entitled 'An application-oriented digital twin framework and the multi-model fusion mechanism' by Zheng et al. proposes a unified and application-oriented framework for the fusion of different models of the Digital Twin. The contribution of the paper offers a progress in the solution of the challenge of needing different models, when virtualizing the system, such as information models, principle models and field models. The paper also offers the unified application procedures of the developed framework and demonstrates the feasibility of the approach with two case study scenarios where the framework is used for three applications: evaluation-oriented, prediction-oriented, and optimization-oriented.

The eighth paper entitled 'Digital twin-driven parameter change propagation path optimization for production line variant design' by Yan et al. offers a contribution in the light of the ever-increasing degree of customization of products in specific sectors, such as the electronics sector, which leads to shorter product lifecycles and to the need to adapt or modify the production lines. Being the latter complex systems, these changes are not simple and stand-alone but are often concurrent, intricate, and coming from multiple sources. The contribution of the paper is in the optimal path of change propagation through a digital twin-driven framework, by keeping the cost of trial and error limited thanks to the high-fidelity simulation capability of digital twins. The demonstration takes place in the context of assembly lines for mobile phone welding.

The ninth paper entitled 'Digital twin-based reinforcement learning framework: application to autonomous mobile robot dispatching' by Jaoua et al. integrates an intelligence layer within the Digital Twin, with the use of Reinforcement Learning (RL) and Deep Reinforcement Learning (DRL) algorithms. The basic idea is to overcome the intrinsic challenges of the simulation-based optimization, which was highly time-consuming, when a new optimization was needed, because in real time it has to run the simulation and the evaluation of different replicas and different alternative solutions. The RL and DRL, instead, allow to separate the training and execution phases: in particular, the proposed approach allows to train the Deep Q-network in advance and, at the time a new solution needs to be computed, the time to get it is extremely short. The validation of the approach has been carried out for laboratory-scale AMR dispatching decisions, demonstrating higher efficiency and robustness with respect to traditional dispatching rules.

The tenth paper entitled 'Goal-oriented clustering algorithm to monitor the efficiency of logistic processes through real-time locating systems' by Pilati et al. leverages on Industry 4.0 enabling technologies to provide a solution to the challenges posed by mass-customization (low-standardization, small-batches …) on the warehousing operations. In particular, the proposed architecture automatically and quantitatively assesses the performances of outbound and inbound logistic processes in low-standardized warehousing systems, with novelties in the goal-oriented algorithm in terms of time-oriented constraints and specific merging criteria. The digital architecture has been tested in a warehousing system to prove the improved efficiency.

The eleventh paper entitled 'Discrete event simulation and Digital Twins in warehouse logistics: a bibliometric and content analysis-based systematic literature review' by Aretoulaki et al. continues the investigation on warehouse logistics, by providing a broad overview of the adoption, implementation, and evaluation of Discrete Event Simulation and of digital twins in the warehousing context and discuss the related simulation approaches, modelling, technologies, algorithms and strategies. The paper also offers a conceptual framework to integrate various perspectives on the topics, that is a contribution to the systematization of the field and allows to show what are the future paths of research in this context.

The twelfth paper entitled 'A digital twin-based modularized design approach for smart warehouses' by Wu et al. still investigates the digitization related to warehouses, but with a focus on warehouse design. The authors propose a novel digital twin-based modular framework for smart warehouse design, where the digital replica of a virtual warehouse is created and simulated at the service of the warehouse design process. The case study is based on a semiconductor manufacturing plant and demonstrates the effectiveness of the innovative proposed framework.

The thirteenth paper entitled 'A framework to design smart manufacturing systems for Industry 5.0 based on the human-automation symbiosis' by Peruzzini et al. provides a framework that integrates all aspects of a manufacturing system into the digital twin modelling to design the manufacturing system, including the environment (e.g. presence of noise, light, pollution …), machines (e.g. set-up, performance, production costs, status, quality and maintenance plans …), humans (e.g. posture, anthropometry, eye tracking …) and human-Machine-Interfaces (HMI) (e.g. interaction type, click numbers, visualized pages …). The framework leverages on digital twin simulation and Artificial Intelligence to support the decision-making in the frame of the collaboration between human and machines. The framework is validated in four different application scenarios showing several benefits, such as impacts on the level of smartness, resilience, interaction, and health in the human-automation symbiosis.

The fourteenth paper entitled 'Digital twins in product-service lifecycles: a framework proposal for enhancing competitiveness and sustainability in manufacturing business' by Timperi et al. draws the attention of the readers to the contribution of digital twin-based product lifecycle solutions on the competitiveness and sustainability of manufacturing companies. In particular, the authors carried out semi-structured thematic interviews to manufacturing practitioners to understand the role of digital twins throughout the lifecycle of the product, from design, to use to renewal of solutions, until the end-of-life. The main contribution of the paper is a framework for product-service lifecycle management that helps companies identify business opportunities and ways to improve their competitiveness and sustainability levels.

The fifteenth paper entitled 'Unlocking factors of digital twins for smart manufacturing: a case of the emerging economy' by Gardas et al. continues the investigation on the adoption of digital twin technologies in manufacturing companies, by studying the Indian manufacturing sector. In particular, the study offers the results of an in-depth literature review and of experts' interviews, identifying 14 determinants affecting the adoption of digital twins in manufacturing companies. The determinants are posed into a multi-attribute decision-making approach that highlights the contextual relationships and the cause–effect relationships. The results of this study can benefit both companies willing to adopt digital twins and policymakers that can develop appropriate strategies.

The Guest Editors are aware that the intriguing topic of 'Digital Twins for Smart Production and Logistics' is receiving worldwide attention and continuous progress. They are conscious that a Special Issue provides only a necessarily limited view on the investigations of the topic, but for this reason, the selection has been strict, and the quality of the proposed reference papers is high. The Guest Editors invite the interested reader to delve into the interesting Special Issue papers and then to continue to stay updated on the topic. This is only one step in this exciting journey!

Finally, the Guest Editors would like to thank all the authors, who made the publication of this Special Issue possible, and all the referees, who provided precious comments and feedback for improvement. Also, special thanks to Prof. Stephen T. Newman, Editor-in-Chief of the International Journal of Computer Integrated Manufacturing, and Prof. Aydin Nassehi, Senior Editor, and to all the Editorial Board and reviewers who supported the publication of the Special Issue.

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