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Digital Twin and Human Factors in manufacturing and logistics systems: state of the art and future research directions

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Abstract: Nowadays, Digital Twin (DT) represents an emerging topic in Manufacturing and Logistics (M&L) systems due to its role as an enabler of digital transformation in the so-called Smart Factories. Since 2017 it has been widely integrated into maintenance, production planning and control or layout planning decisions. Several frameworks and surveys have been proposed to provide guidelines, managerial insights, limitations and future research perspectives on this emerging topic. However, just a few works focus the attention on DT and its role in quantifying, evaluating and providing ergonomics, mental or physical workload, posture feedback or warnings to workers, aiming to improve their safety conditions. For this reason, this study investigates the current state of the art about the DT and its application as a tool to evaluate and integrate ergonomic aspects, or additional human factors, in M&L systems. Moreover, future research directions are provided.

Keywords: Digital Twin; Human Factors; ergonomic risk assessment; feedback; manufacturing systems; logistics systems; literature review

1. INTRODUCTION

Industry 4.0 paradigm has triggered the process of enterprise digitalization in various working sectors. However, there is still little knowledge on the benefits that the adoption of new technologies has had on business performance (Semeraro et al., 2021). Big data, Internet of things, cloud computing, Augmented Reality (AG), Virtual Reality (VR) and wireless sensor networks are only a few examples of technologies that recently started to spread in manufacturing industries, enabling data collection in real-time (Liu et al., 2021). The concept of DT arises from the opportunity to exploit a huge amount of precise information to recreate the digital equivalent of the manufacturing working process, aiming to monitor and control complex systems from their digital counterparts (Uhlemann et al., 2017). The aerospace industry pioneered DT first real applications for NASA and U.S. Air Force vehicles design (Glaessgen and Stargel, 2012). Ultra-realistic flying twins of aircraft were created with DT technology to monitor mission parameters in near-real-time and provide recommendations to real physical models, aiming to increase the probability of mission success. According to the most cited literature review provided by Kritzinger et al. (2018), the relation between one physical object and its digital representation can have three levels of integration, depending on the nature of data flow. Manual data exchange between one physical object and its digital version characterizes Digital Models, while Digital Shadow takes place only whenever a change in the state of the physical object automatically leads to a change on its digital counterpart. Finally, DT refers to the models characterized by fully automated data flow between the physical object and its digital version, and vice versa. In a continuous cycle of automatic and synchronized exchange of data, DT models monitor and control physical entities through their digital representations, while physical objects constantly update the virtual DT model with real-time data (Leng et al., 2019).

The fourth industrial revolution has fostered manufacturing enterprises digitalization, and in particular, the creation of DT models for several industrial applications, such as construction sectors, maintenance and healthcare facilities (Semeraro et al., 2021). Recent literature reviews investigate the use of DT in manufacturing (e.g., production planning and control, maintenance, layout design) (Jones et al., 2020; Liu et al., 2021). However, the integration between DT models and Human Factors (HF) is often neglected even if, according to Sgarbossa et al. (2020), humans still represent the core of all M&L processes that will never be performed by robots due to the complexity required in carrying out the task. For this reason, in this work, we aim to investigate the current state of the art about the integration and application of DT technologies as a tool to quantify, improve and provide feedback from an ergonomics and worker's safety perspective. In particular, all the DT contributions that aim to improve workers' well-being will be investigated, as well as the hardware and software tools developed to achieve this goal.

The remainder of this paper is structured as follows. Section 2 provides the methodology we have conducted for the literature review. Section 3 discusses the outcome of the literature classification. Section 4 presents the future research directions and conclusions.

2. REVIEW METHODOLOGY

To identify relevant works, we conduct a literature search using Scopus database. Three sets of keywords have been used to identify studies that use DT in M&L systems by considering human factors, ergonomics, or humans' (resp. workers' or operators') safety.

No limits in terms of publication year have been applied since DT is an emerging topic of the last few years. Both journal and

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conference proceedings papers have been selected with the requirements to be written in the English language. The remaining articles were carefully read by the authors, and out-of-scope articles were excluded from the final analysis. Finally, a "snowball" approach was applied to include additional papers that provide useful insights and outcomes in the discussion. Table 1 summarizes the overall procedure. In conclusion, 35 are included in the literature review.

Table 1. Selection steps adopted for the literature review

Step	Process	#Papers
1.Database	Scopus	
2.Keywords	**Keywords Category A:** "Digital twin*" OR "Digital-twin*" **Keywords Category B:** "Human Factor*" OR "Human-factor*" OR "Human safety" OR "Worker* safety" OR "operator* safety" OR "Ergonomic*" **Keywords Category C:** "Production" OR "Manufacturing" OR "Warehous*" OR "logistic*" OR "assembly"	36
3.Selection criteria	Document type: Journal article or Conference article Language: English	31
4.Content analysis	Paper analysis and classification Application of the snowball approach	35

3. CLASSIFICATION & DISCUSSION

In this section, the 35 selected papers are classified according to the methodology adopted to implement the DT. Moreover, the enabling technologies are discussed. Figure 1 represents the distribution of the 35 selected papers over the years. As one can see, the adoption of DT technologies in M&L systems for ergonomics, safety or other human factors has begun to be investigated since 2015, but it is only since 2019 that there has been an increase in work on this topic. Case et al. (2015) and Arisoy et al. (2016) can be considered pioneer studies in this field. Among the 35 papers, 60% have been published in journals, while the remaining 40% have been published in conference proceedings. Moreover, 30 papers include a case study or a practical application to demonstrate how the developed method, approach, platform or framework can be integrated in the manufacturing context.

Table 2 reports the categorization of papers according to the area of interest, in terms of which type of activities workers are asked to carry out. There are three main categories these works can be classified, which are: manual assembly, material handling and Human-Robot Collaboration (HRC) assembly. Moreover, 5 papers do not report any case study neither focus the attention on layout plant design to ensure better workers' well-being, while performing tasks or general working activities. Concerning the industrial sector investigated by previous works, 7 papers have been developed for the automotive sector, 3 for the warehousing and logistics field, 3 to produce and assembly furniture and general medium-small items, 2 for the aerospace industry, 2 for the production of large products, parts and components, while the remaining papers do not report any specific sector. Thus, a first consideration can be derived: more than half of the papers included in the literature review investigate, analyze or use DT technology considering one or more human factors by focusing on assembly tasks.

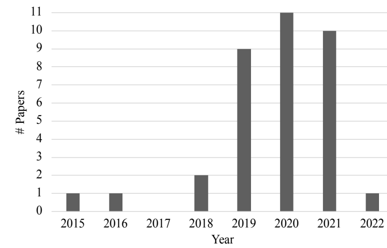

Fig. 1. Publications over the years

Table 2. Focused area categorization

Focused Area	# Papers	%
Manual assembly	14	40,00%
Material Handling	9	25,71%
HRC Assembly	7	20,00%
Other	5	14,29%
	35	100,00%

This observation can be related to the fact that the assembly process requires high expertise levels and, just for some tasks, workers can be entirely replaced by robots. Consequently, both researchers and practitioners are continuously working to improve both workplace design and workers' conditions through assistive devices (e.g., exoskeleton, cobots, AR, VR). In Table 3, papers are classified according to the methodology adopted to include DT technology and the HF investigated. Three are the main categories on which the HF can be classified:

- Ergonomics risk assessment: we group all papers that quantify ergonomic index, postures, vibration level, lighting, noise, force, joint angles.
- Worker's safety: human-robot interaction, warnings to assure workers' safety.
- Mental/physical workload: quantification of human capabilities, cognitive effects, mental or physical stress detection, physiological implications in using smart devices and high-tech tools.

Based on to the methodology adopted for the proposed classification, we now cluster and discuss the selected papers.

3.1. DT & HF frameworks

Among the revised papers, 13 works propose a methodological framework on which DT is implemented to collect real-time data and use them to provide analysis, feedback and warning to workers or safety managers. Tarallo et al. (2018) proposed a computer-aided production control framework based upon multimedia manuals and smart completeness control systems (Kinect 2, industrial tablet and a server workstation) aiming to reduce human errors and physiological effects while performing manual assembly tasks and provide an on-the-job training tool. The main limitation of the proposed architecture is related to its usability, since it was tested just for a simple laboratory assembly task.

Becue et al. (2020) proposed a holistic DT framework in which the factory is not represented by a set of separated DTs, but by a comprehensive modelling and simulation capacity

Table 3. Papers classification according to the adopted methodology and the investigated human factor

Methodology	Ergonomics risk assessment	Workers' safety	Mental/physical workload
AI and Data-driven models	Arisoy et al. (2016); Dimitropoulos et al. (2021)	Mourtzis et al. (2020)	
Coupling and process optimization model	Constantinescu et al. (2019); Ippolito et al. (2020)		
Digital integration model	Case et al. (2015); Caputo et al. (2019a); Rusu et al. (2021)		
Feasibility study model	Baskaran et al. (2019)		
Framework	Caputo et al. (2019b); Greco et al. (2020); Ognunseiju et al. (2021); Peruzzini et al. (2020); Sharotry et al. (2020)	Agnusdei et al. (2020); Arkouli et al. (2021); Bevilacqua et al. (2020); Franceschi et al. (2021); Malik & Bilberg (2018); Malik et al. (2020)	Becue et al. (2020); Tarallo et al. (2018)
Mathematical model & algorithms	Duplàková et al. (2019); Zhang et al. (2020)		
DT Platforms and systems	Bilberg et al. (2019); Havard et al. (2019); Battini et al. (2021); Maruyama et al. (2021)	Nagy et al. (2019); Fukushima et al. (2021); Malik & Brem (2021)	
Survey & Guidelines		Gualtieri et al. (2021); Kousi et al. (2022); Segura et al. (2020)	Push et al. (2019)

manufacturing process which include external network dependencies.

Moreover, they integrated some models to simulate human's behavior and capabilities. By focusing on ergonomic risk assessment, several frameworks have been proposed until now. In such a context, the first work refers to Caputo et al. (2019a) that implemented an inertial motion tracking system and simulation as DT enabling technologies to ergonomically design a new manufacturing line in a shorter amount of time. The authors quantified the ergonomic risk through the Ergonomic Assessment Work-Sheet (EWAS). Greco et al. (2020) adapted an existing DT framework based on six steps to quantify in real-time working time and workload balancing. In the new proposal, the authors evaluated workers' performances by investigating working postures, exerted forces and repetitive actions. All data required in the simulation process are collected through sensors and optical and non-optical motion-capture-based systems, while the simulation process is conducted via Tecnomatix by Siemens. No feedback is provided to workers involved in the assembly process, however, ergonomists can quickly evaluate the ergonomic design of existing workstations. Peruzzini et al. (2020) proposed a theoretical human-centered framework based on the concept of Operator 4.0. The framework is based on data collection through eye tracking and wearable biosensors. Then, data are used to assess the workers' ergonomics performance and perceived comfort and to build a proper knowledge about the human asset. Virtual prototypes are adopted to relate workers and digital factory to conveniently simulate the human–machine interaction, aiming to avoid bottlenecks at the shop floor, optimize the workflows, and improve the workstations' design and layout. Sharotry et al. (2020) proposed a simulation-based framework consisting of three modules (data collection, operator analysis and feedback and finally the DT module) to analyze worker's fatigue, through joint angles, and repetitive motions in lifting tasks. The authors adopted a motion capture system to collect data on body posture and joint angle values. Moreover, real-time audio-visual feedback is provided to the worker on the basis of the knee joint movement. Similarly, Ogunseiju et al. (2021) proposed a framework based on six tiers (sensing, data, communication, storage, computation and action tier) and three key elements (physical worker, virtual model and information flow) to improve the self-management ergonomic exposures. A wearable suit made of 19 IMUs was used to collect posture data while a long-short term memory network was employed to adapt the virtual feedback to the worker through HoloLens.

Then, more generic reference methodologies have been proposed by Agnusdei et al. (2020) and Bevilacqua et al. (2020) who investigated the role of enabling technologies and DT tools from a worker's safety perspective (AR, smart devices, tablets). Bevilacqua et al. (2020) proposed a reference model based on four layers (Process industry physical space, Communication system, Digital Twin and User space) aiming to identify and collect all possible anomalies leading to workers' safety reduction.

By focusing on HRC and DT implementation, Malik & Bilberg (2018) investigated the HRC assembly through simulation, aiming to create a safe workplace and proper task scheduling between workers and robots. They provided a methodological framework to guide practitioners in evaluating the interaction between humans and robots. In the framework of Malik et al. (2020) VR is used to integrate human-robot collaboration in the simulation process to define the cycle time, the workers' safety conditions, the layout optimization and the robot control program. Arkouli et al. (2021) proposed a methodological approach based on the synergy between robotic resources, human workers, information and communication technology tools, aiming to ameliorate the interaction between workers and robots in shared workplaces. Moreover, exoskeleton, wearables sensors and VR tools are used for training and ergonomics optimization. Finally, Franceschi et al. (2021) suggested a framework in which DT is used to coordinate human workers and autonomous systems, sharing the same workplace for complex assembly environments, such as the aerospace ones.

3.2. DT & HF platforms & systems

Seven papers propose digital platforms and systems to quantify ergonomics risk assessment (Bilberg et al., 2019; Havard et al., 2019; Battini et al., 2021; Maruyama et al., 2021) or workers' safety (Nagy et al., 2019; Fukushima et al., 2021, Malik & Brem, 2021).

Bilberg et al. (2019) proposed a DT-driven HRC simulation environment to quantify ergonomic postures variation during task progressed in collaboration with robots. Maruyama et al. (2021) realized a real-time monitoring, predictive, and ergonomic assessment tool based on the full-body dynamics of workers, for an HRC environment. A highly accurate optical motion capture system is used to collect data.

Battini et al. (2021) proposed an in-house ergonomic platform, called WEM-platform, aiming to quantify heart rate, OWAS, RULA, REBA and PERA ergonomic index scores in real-time. The developed platform does not depend on the motion capture suit adopted to collect real-time data and provides real-time feedback to workers involved both in picking and assembly activities. Nagy et al. (2019) presented a cloud-based VR platform for HRC to prevent collisions while performing tasks jointly. Finally, Fukushima et al. (2021) presented Digimobot, a DT platform to simulate human behaviors and robots movements in an indoor environment (e.g. warehouse, production plant).

3.3. DT & HF surveys and guidelines

Some surveys and guidelines have been developed to help practitioners and managers in selecting the proper DT technology. Push et al. (2019) compared Microsoft HoloLens to small and large screen touch devices in industrial workplaces as a tool for training new and low-skilled workers. Several tests have been conducted, and according to workers' feedback, HoloLens appears to perform better than tablets, as the virtual and real environment interact together.

Gualtieri et al. (2021) provided guidelines for the design of safe HRC assembly system. They validate them with a virtual model demonstrating that they can be used in all HRC-based production environments.

Segura et al. (2020) demonstrated how visual computing technologies, as a field of DT, can play a key role in this empowering process, thus being essential in the realization of Operator 4.0. Moreover, with a practical example, they demonstrated that these technologies can be applied to provide direct feedback to workers as well training and general support in executing tasks.

Kousi et al. (2022) investigated existing approaches and methods for task planning in HRC environments analyzing workers' safety aspects and providing the requirements for implementing decision-making strategies about the shared workplace.

3.4. DT & HF models

Some works developed a model aiming to include and evaluate HF in DT development. Constatinescu et al. (2019) developed an innovative coupling methodology. The prototype of the Digital Twins coupled with a commercial Exoskeleton was validated in automotive and logistics companies. Simulation was used as an enabling technology to quantify posture improvement while wearing an exoskeleton. Ippolito et al. (2020) proposed an innovative approach to plan and optimize intelligent working environments with integrated adaptive Exoskeletons. Through the planning and optimization model, they harmonized the planning of production processes, by including ergonomics and workers' safety through new wearable technologies like the exoskeleton. Baskaran et al. (2019) proposed a feasibility study model to deploy a smart collaborative solution to provide physical assistance to workers. They used simulation software and they investigated various human anthropomorphic models to discover the limitations in performing the assembly tasks based on gender, weight and height. Moreover, the robot behavior was simulated to define the assembly process time and the joint ergonomic impact. Duplàková et al. (2019) developed an ergonomic rationalization algorithm for the redesign of the lighting of the working environment by using simulation software and digital tool to capture the lighting values of a process production plant. Zhang et al. (2020) is the only work that proposes a mathematical model to evaluate ergonomics and dynamically optimize the assembly line. Finally, just two works, Arisoy et al. (2016) and Dimitropoulos et al. (2021), used artificial intelligence and a data-driven approach to quantify and provide ergonomic feedback to workers or ergonomists. Arisoy et al. (2016) used Bayesian network classifier to learn a mapping between object geometry and natural grasping locations using a set of geometrical features. In such a way, they created a list of candidate grasping positions and selected a subset of these possible locations as natural grasping contacts using the machine learning model. Dimitropoulos et al. (2021) developed AI-based model consisting of three modules that can capture the operator status, the environment status and process status to identify the tasks that are performed by the operator using vision-based machine learning and provide customized operator support the robot for shared tasks, automatically adapting the behavior of the robot to operator's needs, postures and preferences.

Finally, Case et al. (2015), Caputo et al. (2019a) and Rusu et al. (2021) proposed a digital human model aiming to quantify respectively the ageing effect, the postures and benefits for exoskeleton adoption in automotive assembly tasks.

4. FUTURE RESEARCH DIRECTIONS & CONCLUSIONS

DT technology is increasingly penetrating the M&L systems due to the digitalization phenomenon in the so-called Smart Factories. It has been estimated that by the end of 2025 the 70% of M&L systems will use DT technology to improve production efficiency (Sharotry et al., 2020). However, according to the literature review here conducted, more research and study about how DT can improve and promote workers' well-being in M&L systems need to be done in the future. In fact, just 35 papers, of which 14 papers conference proceedings, have been found, analyzed and discussed in this literature review. Several works present conceptual or methodological frameworks, or even digital platforms to provide real-time feedback to workers for ergonomic risk assessment during the design or redesign phase of new or existing workstations. Moreover, several works tested the proposed framework through laboratory case studies, which have limitations despite real working environments.

Based on the findings of the literature review, the following future research directions can be derived:

-Economic quantification of DT implementation for workers' safety and ergonomics daily performance monitoring. To the best of the authors' knowledge, there are no papers that quantify the return of investment in implementing a DT technology. However, sensors, motion capture systems, activity trackers and software represent a huge cost for companies. Furthermore, the integration and the implementation procedure to obtain the digital platform requires a highly skilled workforce.

-Identification of the suitable technology to provide direct feedback to workers, according to their cognitive capabilities, their individual experience and the type of task they are asked to perform.

-Workers' real-time data integration in dynamic scheduling, rebalancing or task allocation decision problems aiming to continuously assure a balanced workload among workers involved in the production process. In fact, just Zhang et al. (2020) and Pabolu & Shrivastava (2021) proposed a mathematical model for dynamic scheduling by considering workers' real-time parameters. In such a context, both mental and physical fatigue, as well as ergonomic postures or task repetitiveness, should be integrated into real-time operational decision problems by following the methodological framework proposed by Berti et al. (2021).

-Predictive models, based on AI algorithms, to quantify and prevent workers' fatigue and ergonomic hazards during task progression.

-Identification and computation of risk in shared work environments between humans and robots. In such a context, some works investigated the worker's safety exposure in performing assembly tasks in collaboration with robots. However, even in warehousing and picking activities, robots are increasingly used and, for this reason, the collisions with humans should be further investigated (Fukushima et al., 2021).

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