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Digital twin for human-robot collaboration enhancement in manufacturing systems: Literature review and direction for future developments

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ABSTRACT

The integration of robots in manufacturing systems known as Human Robot Collaboration (HRC) can provide relevant opportunities in terms of productivity, safety and quality control although there are still many challenges such as integration costs, complexity, safety and workforce concerns, skills gaps and regulatory compliance. Digital Twins (DTs), which are virtual replicas of physical systems, are being explored as a promising solution to address these challenges. Therefore, this paper delves into the potential DTs-based approaches for HRC in manufacturing systems with a focus on their ability to provide a realistic simulation environment for testing and optimizing collaboration strategies. The first part of the study involves a comprehensive literature review devoted to understand how the scientific community perceives the application of DTs for HRC in manufacturing systems and the main trends of this research area are identified. The second part of the study presents a detailed analysis of the currently available commercial simulation software solutions for developing DT models in manufacturing systems for HRC scenarios. The analysis encompassed various aspects such as: the software's capabilities in human and robot simulation, ergonomic and time measurements analysis, data exchange and interoperability with the physical world as well as with other software. The results of the analysis are meant to provide practical insights to researchers and practitioners interested in implementing DTs to enhance HRC in manufacturing systems.

1. Introduction

Industry 4.0 has facilitated the development of smart factories through the integration of various technologies such as robotics, artificial intelligence, and the Internet of Things, which has led to highly optimized, automated and interconnected manufacturing processes (Lu, 2017). The integration of these technologies in Industry 4.0 has led to the creation of highly efficient, agile, and adaptable manufacturing environments. Smart factories can respond quickly to changing market demands, reduce waste, improve product quality, and enhance overall productivity, making them a key driver of innovation and competitiveness in modern manufacturing industries. However, with the increased level of automation, the risk of neglecting human-related factors in manufacturing processes arises (Selvaggio et al., 2021). In this framework, HRC has become even more necessary as it involves the interaction between humans and robots working together in a shared workspace to complete a task (Huang et al., 2021; Boschetti et al., 2023). By integrating human-robot collaboration into smart factories, manufacturers can achieve a balance between automation and the human workforce, taking advantage of the strengths of both. This approach not only mitigates the risk of neglecting human factors but also leverages human skills, creativity, and problem-solving abilities to optimize manufacturing processes and drive innovation. HRC represents a subset of the broader concept of Human-Robot Interaction (HRI) but with a higher level of integration between the human operator and the robot (Müller et al., 2017). As previously described by Hoffman and Breazeal (2004), the main features that define HRC include: shared activity (Searle, 1990; Bratman, 1992), joint intention (Cohen and Levesque, 1991), common ground (Clark, 1996), and goal-oriented action (Hoffman and Breazeal, 2004; Bratman, 1992; Cohen and Levesque, 1991). In HRC, the human operator and the robot agent are in close contact, and a leader–follower relationship may naturally occur, with the leader taking responsibility for executing a given task (Wang et al., 2019; Wang et al., 2017). Moreover, HRC is often expressed in the form of a complex

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system in which the job can consist of a set of repetitive tasks (as can happen in assembly scenarios) and high responsiveness is needed to ensure human operator's safety. Here, Iterative Learning Control (ILC) algorithm optimization, can enhance robots performances in tasks that require precision and repeatability when collaborating with humans (Zhou et al., 2022; Zhuang et al., 2023). In addition, robots may need adaptive control in response to changing environments or human actions. It can be achieved by neural networks and adaptive control methods that can help robots to adjust their behavior and interactions with humans, making the collaboration safer and more efficient (Song et al., 2023). In this framework, the feasibility of supporting HRC through the use of digital twins has shown relevant potential benefits. Recalling that a digital twin is a virtual representation or digital counterpart of a physical object, system, or process (Tao et al., 2019), DTs enable dynamic, real-time simulation of physical entities and this allows monitoring, analysis, and optimization. The pivotal importance of DT has been so widely recognized to the extent that the need for a standard definition of the DT concept has emerged to lay the foundation upon which the digital twin ecosystem can grow, evolve, and mature while ensuring consistency and alignment across different sectors and applications (Coelho et al., 2021). Thus, DT may be defined as "a virtual representation of manufacturing elements such as personnel, products, assets and process definitions, a living model that continuously updates and changes as the physical counterpart changes to represent status, working conditions, product geometries and resource states in a synchronous manner" (ISO 23247, 2021). (Lu et al., 2020). When it comes to HRC-based DTs, virtual models of human operators are used to analyze their interaction with robots in a virtual environment (Lu, 2017) considering ergonomic aspects of the workspace and how to optimize HRC scenarios. As a matter of facts, ergonomics is crucial in HRC scenarios (Gualtieri et al., 2021) where the workspace design should reduce the physical and mental workload of the human operator as much as possible and avoid any physical strain or injury. Here, DTs allow for planning, simulating, monitoring, and optimizing human-robot collaboration (Wang et al., 2024). Besides, in conjunction with sensory data, big data analytics, AI and machine learning, Digital Twins can support diagnostics, prognostics, and reducing accidents and injuries (Zaccaria et al., 2018; Cai et al., 2017).

Several literature reviews investigating the use of DTs in manufacturing systems have been carried out as summarized in Table 1.

The background summarized in Table 1 shows that DTs have been widely investigated in terms of applications, technologies and data integration but there is a lack of research in the area of DTs for HRC enhancement. In fact, the state-of-the-art shows that a proper consideration of human-related factors is a compelling research issue DTs design (Lu et al., 2020). Given that, the proposed research is aimed at investigating the potential for digital twin technology to enhance human-robot collaboration. While detecting and analyzing meaningful applications of DTs for HRC enhancement and future research directions, a particular attention is paid on the latest tools and best practices for successful implementation of DT in HRC scenarios. These considerations following research questions (RQs):

- RQ1: What are the most recent and impactful applications of Digital Twins in enhancing Human-Robot Collaboration across different industries?
- RQ2: What are the essential factors that must be considered when developing Digital Twins for enhancing Human-Robot Collaboration in manufacturing systems?
- RQ3: Which solutions and tools are appropriate for developing and deploying Digital Twins specifically designed for Human-Robot Collaboration in the context of manufacturing systems?
- RQ4: Which constraints and obstacles are to be considered when implementing Digital Twins in manufacturing systems to enhance Human-Robot Collaboration (HRC)?

Table 1
Comparison between our paper and other literature reviews.

Reference	Reviewed topics
Grieves (2014)	Early perspective on digital twins and their applications in manufacturing
Saddik (2018)	The role of multimedia technologies in the development and use of digital twins
Huang et al. (2021)	AI-driven DTs in smart manufacturing and advanced robotics
Leng et al. (2021)	Digital twin-based smart manufacturing
Rathore et al. (2021)	Overview of digital twins and their integration with big data analytics
Wilhelm et al. (2021)	Main applications of DT-based HMI in manufacturing and definition of roles which both humans and DTs adopt in manufacturing systems
García et al. (2022)	DT learning applications in manufacturing systems
Liang et al. (2022)	DT enabling technologies for manufacturing and robotics
Sharma et al. (2022)	Overview of the state-of-the-art in digital twin technology, applications, challenges, and future directions
Ramasubramanian et al. (2022)	Approaches used to create DTs for HRC in manufacturing
Stavropoulos and Mourtzis (2022)	Role of digital twins in Industry 4.0 and their applications across various domains
Correia et al. (2023)	Data integration aspects of digital twins and how data from various sources are used to create and maintain digital twins
Our contribution	DTs for HRC enhancement in manufacturing systems: main trends, key requirements and commercial software benchmark

The reminder of the paper is organized as follows: Section 2 provides an overview of the materials and methodologies employed in the study; Section 3 offers the primary findings, encompassing the results of the systematic literature review and the identification of key prerequisites, tools, and limitations for improving Human-Robot Collaboration through Digital Twins in manufacturing systems; Section 4 e delves into the importance and implications of the proposed research while the last section draws conclusions and future research directions.

2. Materials and methods

The study includes two complementary research streams. The first involves a systematic exploration of the scientific literature related to the implementation of Digital Twins for Human-Robot Collaboration in manufacturing systems (RQ1, RQ2). The second entails an analysis of the most frequently used solutions, tools and approaches for simulation models within a Digital Twin framework including both human and robotic models (RQ3, RQ4).

The literature review has been carried out using the PRISMA methodology (Moher et al., 2009; Page et al., 2021), as depicted in Fig. 1 and summarized hereafter:

(1) **Identification**: Carry out a detailed search for scientific documents in databases like Scopus and PubMed, based on research questions set out in Section 1. The process includes selecting databases, developing search queries with relevant keywords, executing searches, and finding additional documents from various sources.
(2) **Screening**: Filter the documents to get those pertinent to the research questions. This involves applying predefined inclusion and exclusion criteria, screening titles and abstracts first, and keeping records of the screening process.
(3) **Eligibility and Inclusion**: Evaluate the filtered documents for quality, remove duplicates, and screen full texts to select final documents for data extraction and analysis.

For software analysis, a technical approach was used to evaluate

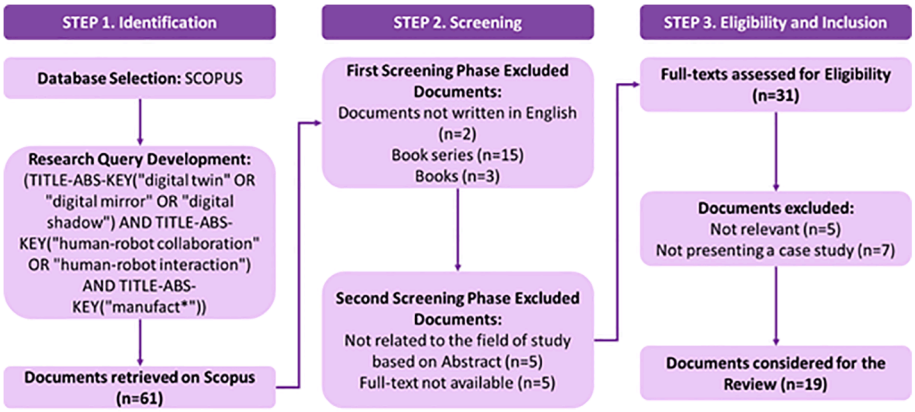


Fig. 1. Literature Review Methodology.

different tools' abilities to integrate simulation models for HRC contexts (see Fig. 2). The analysis included structured testing, reviewing support documentation, and engaging in community forums. The goal was to identify and document each tool's features, advantages, and limitations without ranking them, providing an impartial assessment of the available options.

The methodology used for the software review was structured into three main steps:

1. **Selection**: In the initial step, we identified the most pertinent software tools based on the existing scientific literature. Our focus was on tools that had gained recognition within the academic community, which closely aligns with the literature review conducted in the first part of this study.
2. **Exploration**: This multifaceted phase consisted of three pivotal sub-phases. In the first sub-phase, named 'Testing,' we pinpointed and tested the core features of each chosen software to establish a foundational understanding of their capabilities and functionalities. The second sub-phase, 'Manufacturer Support Material,' involved the analysis of support materials offered by the software providers, including manuals, tutorials, and case studies. These resources provided valuable insights into the software's optimal usage and potential applications. The third sub-phase, 'Online Communities,' encompassed delving into various dedicated forums, YouTube channels, and discussions on third-party platforms. This exploration offered a broader perspective on the user community's perspectives, experiences, and challenges with the software, enriching our understanding of its practical implications and limitations.
3. **Evaluation**: It was carried out with a focus on the identified key requirements for designing and developing Digital Twins in Human-Robot Collaboration (HRC). These requirements encompassed areas such as Human Operator Simulation, Robotic Agent Simulation, Ergonomic Analysis, Time Measurement Analysis, and Data Exchange and Interoperability. The outcomes of this rigorous evaluation process were compiled into a report, which included a categorization and discussion of the discerned features and requirements of the selected software.

This methodological approach has supported a systematic assessment of software tools within the context of Digital Twins for collaborative human-robot scenarios. It provided valuable insights into their capabilities and areas for enhancement.

3. Results

Section 3.1 provides a systematic literature review of existing research on DTs for HRC enhancement in manufacturing systems. In Section 3.2, the key requirements for developing simulation models in a DT framework for HRC in manufacturing systems are highlighted. Section 3.3, explores the potentials of currently available tools for DTs aimed at HRC enhancement in manufacturing systems. Finally, section 3.4 presents a comparative analysis of software tools detected in Sections 3.3. based on the key requirements outlined in Section 3.2.

3.1. DT for HRC in manufacturing system – A literature review

As outlined in Section 2, the systematic literature review in this study adheres to the PRISMA methodology. The Scopus database was selected as the primary source for this review due to its comprehensive collection of peer-reviewed literature, including scientific journals, books, and conference proceedings, with a total of 87 million documents and 17 million authors (https://www.elsevier.com/solutions/scopus/how-scopus-works/content).

To analyze the relevant scientific literature, three major research

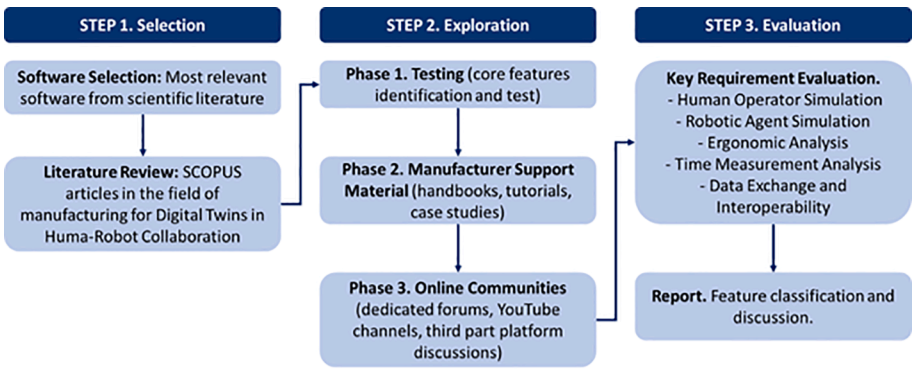


Fig. 2. Software Review Methodology.

areas, namely "Manufacturing Systems," "Human-Robot Collaboration," and "Digital Twin," were cross-referenced. This approach facilitated the identification and examination of relevant literature from diverse disciplines and sources, ensuring a comprehensive review.

Table 2 provides an overview of the scientific productivity of three areas of research both when searched independently and when cross-referenced. The results from the independent search revealed that each area of research generates a substantial number of publications, reflecting the high level of interest and research activity in these areas. However, when the three areas of research are combined, the number of publications decreases significantly, as evidenced by the mere 59 documents retrieved by the cross-referenced search. This suggests that there may be limited overlap between the three areas of research as well as the importance of using cross-disciplinary approaches to foster innovation and breakthroughs.

The query employed to cross-reference the three areas of research is provided below:

- (TITLE-ABS-KEY("digital twin" OR "digital mirror" OR "digital shadow") AND TITLE-ABS-KEY("human-robot collaboration" OR "human-robot interaction") AND TITLE-ABS-KEY("manufact*")) AND (LIMIT-TO(LANGUAGE,"English")).

It is noteworthy that the only exclusion criterion was language, with only English-language articles selected for the analysis.

By focusing on the 59 articles identified through the cross-referenced search, the authors have gained valuable insights into the current state of knowledge related to the use of DTs for HRC enhancement in manufacturing systems. The analysis has considered several key factors including publication frequency, global scale distribution, and source analysis. Additionally, an in-depth document analysis was carried out to examine the articles content and trends.

Publication frequency – it expresses the number of scientific studies published per year. Fig. 3 shows that the research topic under investigation is relatively new, with the first article published in 2017. However, there is a clear upward trend in the number of annual publications, indicating a growing interest in this area among the scientific community. It is important to specify that the discontinued line between years 2022 and 2023 means that data referring to 2023 are not definitive as the study was carried out at the beginning of this year.

Global scale distribution – this refers to the number of published documents for each country where the study has been conducted. The results of the analysis indicate that, despite the increasing trend in publishing on this topic, only a few countries have dedicated efforts toward investigating the use of DTs for HRC enhancement in manufacturing systems. As illustrated in Fig. 4, the countries with the highest number of published papers in this area are China, Germany, Greece, and the United Kingdom. Italy, the United States, Denmark, and Sweden also have significant contributions. Several other countries have only one published paper in this field. These findings suggest that there is potential for increased research collaboration and knowledge exchange between countries to advance the understanding of this emerging field.

Source analysis – it is used to identify the number of published documents per research source. Table 3 presents the most prolific sources in the research area in terms of published documents. The results indicate that Computer & Industrial Engineering and the Journal of Manufacturing Systems are the most frequent sources for publications related to the use of DT for HRC enhancement in manufacturing systems. However, it should be noted that many sources have started to take an interest in this area by publishing papers on this topic. The authors have also included papers from conferences in their literature analysis due to the recent development of this research field. In fact, the contribution of preliminary studies on this topic is also relevant to understanding how this research trend is developing within the scientific community.

Table 2
Scientific productivity overview.

Keyword	Published documents
"Manufacturing Systems"	49.537
"Digital Twin"	12.112
"Human-Robot Collaboration"	2.947
"Cross-referenced search"	59

Document analysis – the authors utilized the initial pool of 59 articles as a starting point to conduct the document analysis. Each of these articles was thoroughly reviewed, and only 19 articles were deemed appropriate for this study, as they are aligned with the scope and requirements of this research. Specifically, the chosen articles examine HRC scenarios by utilizing DTs within manufacturing systems and by incorporating a case study. These articles have been classified in Table 4 based on the type of operations that the robot performs in collaboration with the operators, the simulation environment type which refers to the presence (controlled) or not (real) of approximations or assumptions in the development of the DT, the scope for conducting the simulations, and the software employed for the development of the DTs.

The document analysis reveals that HRC in manufacturing systems is primarily analyzed for assembly/disassembly, material handling, pick & place and welding operations. Fig. 5 shows exactly the distribution of operation Types within each simulation environment.

The analysis reveals that these studies are often carried out in controlled environments, which means that, even though the simulations are intended to capture real-world case studies, approximations are needed to make the experiments possible; in fact, very often, physical environments are either specially recreated in the laboratory or deliberately simplified to limit the number of variables to be handled for the scope of the research study. However, this practice should not be viewed as an absolute constraint on the application of this paradigm. This is supported by the growing research interest, particularly in recent years, and in response to the disruptions in real industrial operations caused by the Covid-19 pandemic.

As for the simulation scope of the studies being considered, particular attention has been paid on safety levels, production plans, ergonomics as well as on collaborative spaces management. Safety levels are identified as a top priority, as the potential risks associated with the interaction between human operators and robots in dynamic work environments cannot be underestimated. Production plans are evaluated based on task allocation between humans and robots, with a focus on optimizing efficiency and productivity. Ergonomics is also considered, to ensure that the work environment is conducive to human health and well-being. Finally, collaborative spaces are managed to promote effective communication and coordination between human operators and robots. Last but not least, the document analysis also reveals that the most prevalent software for developing the DTs is Unity 3D.

The synthesis of literature reveals a concerted progression in the field of HRC. Horváth & Erdős (2017) lay foundational work, introducing controls for Cyber-Physical Systems within collaborative environments, underpinning subsequent developments in virtual modeling and gesture recognition facilitated by Microsoft Kinect and Wolfram Mathematica. Malik & Bilberg (2018) underscore the indispensability of digital twins, proposing a framework notably illustrated through a case study involving Universal Robots UR-5 and UR-3 in assembly workstations.

This emphasis on virtual representations is further echoed by Oyecan et al. (2019), who not only delve into Virtual Reality (VR) digital twins but also introduce a Kinetic Energy Ratio metric, registering a noteworthy 73 % accuracy rate in classifying human reactions to robot motions. The narrative of virtual integration continues with Malik et al. (2019), who weave VR into human-robot simulations, utilizing a spectrum of technologies including AWS Sumerian and HTC Vive for varied applications such as assembly tasks and collision analysis.

In a similar way, Arnarson et al. (2021) explore VR's potential in robot programming and interaction, emphasizing simplified processes

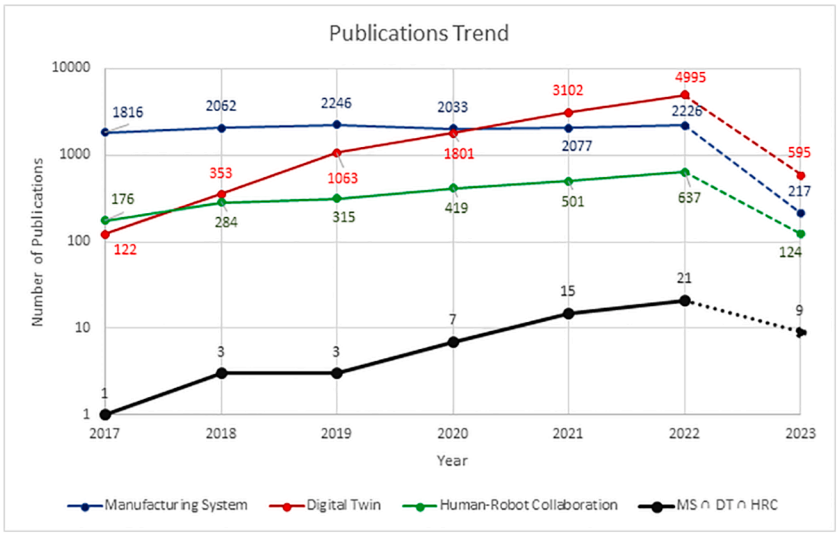


Fig. 3. Publication trends.

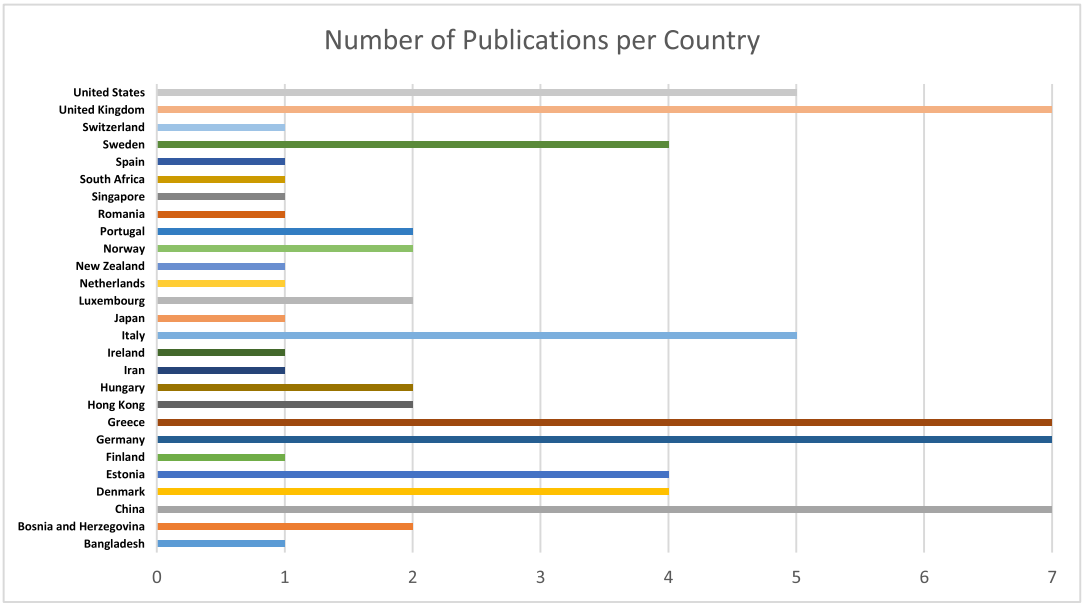


Fig. 4. Documents per country.

Table 3
Number of published documents per source.

Source name	Published documents
Computers & Industrial Engineering	4
Journal of Manufacturing Systems	4
ASME International Mechanical Engineering Congress And Exposition Proceedings Imece	3
International Journal Of Computer Integrated Manufacturing	3
Procedia CIRP	3
Robotics And Computer Integrated Manufacturing	3
Other journals	<3

and enhanced safety. Pisanelli et al. (2022) contribute to the discourse with the introduction of ROSIE Adapter, a pivotal tool facilitating the creation of digital twins, receiving accolades for user-friendliness and high satisfaction rates among users during a UK-based event.

Digital twins are integrated with AI systems, as seen in the work of Dimitropoulos et al. (2021), yielding improvements in cycle time (6 %), ergonomic factors, and operator satisfaction in industrial contexts. Safety remains paramount, with Douthwaite et al. (2021) introducing a framework dedicated to safety–critical digital twins in collaborative robotics, while Maruyama et al. (2021) provide a proof of concept for integrating Digital Humans (DH) into Digital Twin-driven HRC systems for enhanced ergonomic evaluations and efficiency.

The trajectory of development also witnesses the advent of Augmented Reality (AR) in the sector, as illustrated by Aivaliotis et al. (2023), who unveil an AR suite significantly optimizing operational and recovery tasks. In a methodological expansion, Gallala et al. (2022) outline a six-step framework for HRI, validated through use-case studies, whereas Gleirscher et al. (2022) spotlight a software approach increasing productivity by 40 % through optimal safety controller synthesis.

From architectural advancements showcased by Koukas et al. (2022) with the OpenFlow architecture, to comparative studies like those by Kuts et al. (2022) evaluating Digital Twin VR interfaces, the literature

Table 4
Document insights.

Reference	Sector	Operation Type	Simulation environment	Simulation Scope	DT Development Software
Horváth & Erdős (2017)	Process	Not specified	Controlled	Gesture recognition	Wolfram Mathematica
Malik & Bilberg (2018)	Not specified	Assembly	Controlled	What-if analysis	Process Simulate
Malik et al. (2019)	Assembly	Assembly	Controlled	Workstation Layout design	Process Simulate
Oyecan et al. (2019)	Process	Not specified	Controlled	Safety assessment	Unity 3D
Arnarson et al. (2021)	Not specified	Not specified	Controlled	Robot Programming	Visual Components
Dimitropoulos et al. (2021)	Process	Material Handling	Real	Ergonomic assessment	Gazebo
Douthwaite et al. (2021)	Process	Welding	Controlled	Safety assessment	Unity 3D
Maruyama et al. (2021)	Not specified	Pick & Place	Controlled	Ergonomic assessment	DhaibaWorks(in-house software)
Gallala et al. (2022)	Not specified	Pick & Place	Controlled	Communication enhancement	Unity 3D
Gleirscher et al. (2022)	Process	Not specified	Controlled	Safety	Unity 3D
Koukas et al. (2022)	White Goods	Assembly	Controlled	Task Planning	OpenFlow(in-house software)
Kuts et al. (2022)	Not specified	Material Handling	Controlled	Safety assessment	Unity 3D
Lu et al. (2022)	Food	Packaging	Controlled	Task Allocation	Not Specified
Pisanelli et al. (2022)	Not specified	Not specified	Controlled	Path Movement	Unity 3D
Schmidt et al. (2022)	Not specified	Material Handling	Controlled	Cognitive Ergonomic assessment	Unity 3D
Yi et al. (2022)	Not specified	Not specified	Controlled	Safety assessment	Visual Components
Zhu et al. (2022)	Not specified	Not specified	Controlled	Task Allocation	–
Aivaliotis et al. (2023)	Automotive	Assembly	Controlled	Safety assessment	Unity 3D
Li et al. (2023)	Not specified	Disassembly	Controlled	Safety assessment	Unity 3D

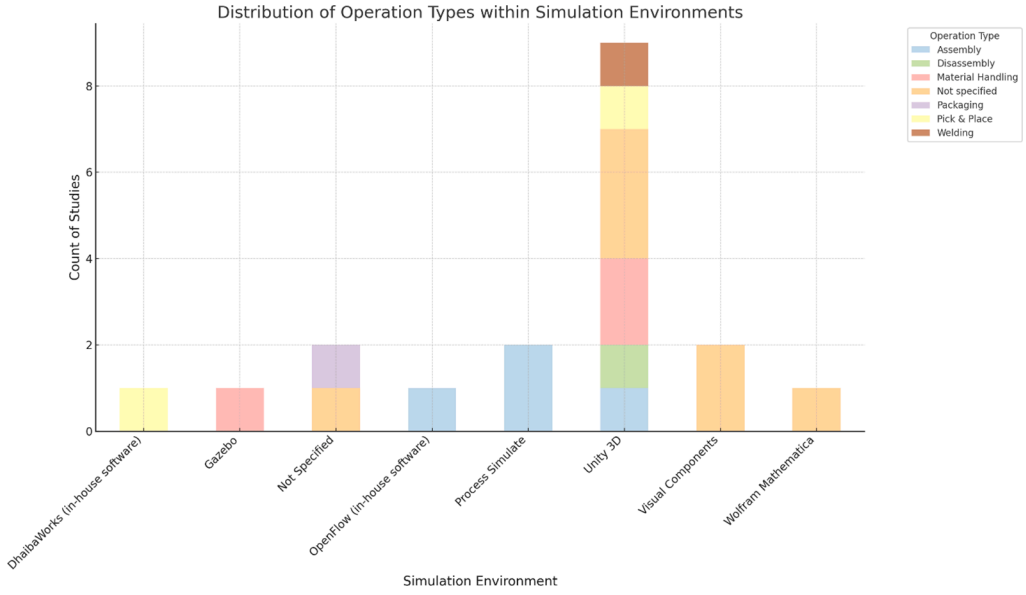


Fig. 5. Distribution of Operation Types within Simulation Environment.

captures a field in dynamic evolution. Notably, the works of Lu et al. (2022), Schmidt et al. (2022), and Yi et al. (2022) respectively offer modularized HRC frameworks, visualization tools for robotic cell optimization, and depth camera-based human recognition systems for efficient collaboration.

Zhu et al. (2022) add to this rich tapestry with their dynamic reconfiguration optimization method, whereas Li et al. (2023) introduce an innovative Human-Robot Interaction framework with AR devices, with a validation experiment noting a 93 % success rate in collision detection. Together, these studies coalesce into a multifaceted understanding of the ongoing innovations and challenges within HRC, each contributing a unique perspective and empirical finding to the burgeoning field.

Table 4 also suggests several limitations in the current research on DTs in HRC. Firstly, many studies do not specify the sector and operation type investigated, which significantly hampers the understanding and applicability of the research to real-world scenarios. This lack of specificity limits the transferability of the findings across different industrial sectors and operation types. The simulation environment in the majority of the studies is controlled, which may not accurately reflect the complexities and unpredictabilities of real-world operational environments. This limitation in the simulation environment restricts the external validity of these studies, as the findings may not be generalizable to actual industrial settings with dynamic and unpredictable elements. Additionally, there is a wide range of DT development software used across the studies, with Unity 3D being the most commonly used. However, the use of different software tools, including in-house developed solutions, might hinder the interoperability and integration of DTs across different systems and platforms. The inconsistency in the software tools used also makes it challenging to compare and consolidate findings across different studies. Furthermore, the simulation scope varies across studies, ranging from safety assessment to ergonomic assessment, to task planning and allocation, without a clear focus or prioritization of research efforts in addressing the critical challenges and needs in the application of DTs in HRC.

On the other hand, considering Table 5, there's a noticeable lack of standardization across studies in both the types of robots and sensors employed, which hinders the comparability and generalizability of the

Table 5
Documents comparative analysis.

Reference	Robot	Sensors	Algorithms	Standards
Horváth & Erdős (2017)	Not specified	Microsoft Kinect™	Proximity Query Package	Not specified
Malik & Bilberg (2018)	UR-5/UR-3	Microsoft Kinect™	Robotiq	Not specified
Malik et al. (2019)	UR-5	Microsoft Kinect™/ Photosensors	Amazon Sumerian	Not specified
Oyecan et al. (2019)	ABB IRB 2600 12–1.85	Microsoft Kinect™	Savitzky–Golay filtering method	Not specified
Arnarson et al. (2021)	SCARA Adept 604-S/ KUKA KR-30–3/ Nachi MZ07	Not specified	Not specified	IEC 62,541
Dimitropoulos et al. (2021)	COMAU AURA	Kinect Azure	Convolutional Neural Networks (Actions Perception Module)	Not specified
Douthwaite et al. (2021)	Not specified	LIDAR	Not specified	Not specified
Maruyama et al. (2021)	Not specified	OptiTrack	Optimization-based motion estimation	Not specified
Gallala et al. (2022)	KUKA IIWA	Microsoft Hololens 2	Deep Conventional Neural Network	Not specified
Gleirscher et al. (2022)	Not specified	Microsoft Kinect™/ LIDAR/Light barrier	Not specified	ISO 10,218/ ISO/TS 15,066
Koukas et al. (2022)	UR-10	Microsoft HoloLens 2	Not specified	Not specified
Kuts et al. (2022)	Not specified	Head-Mounted Display	Not specified	Not specified
Lu et al. (2022)	ABB IRB 2600–20 (12)/1.65	uEye XS Camera	Not specified	Not specified
Pisanelli et al. (2022)	KUKA LBR IIWA 14/ Iconsys iAM-R	Not specified	Google Assistant	Not specified
Schmidt et al. (2022)	ABB IRB 4600/ ABB IRB 2600	Microsoft HoloLens 2	NSGA-II	Not specified
Yi et al. (2022)	Not specified	ASUS Xtion Pro cameras/ Kinect v2.0	Not specified	IEC 61,499
Zhu et al. (2022)	Not specified	Not specified	NSGA-II	Not specified
Aivaliotis et al. (2023)	Mobile Robot Platform	SICK microScan3 /Microsoft HoloLens 2	Not specified	Not specified
Li et al. (2023)	UR-5	Microsoft HoloLens 2	Proximal Policy Optimization (PPO)	Not specified

findings. The utilization of various robots and sensors without consistent reference to specific standards suggests that the research landscape is fragmented (Fig. 6). Moreover, the standards referenced in the studies are few and inconsistently applied, pointing out a potential gap in the establishment of universal protocols and benchmarks for evaluating and deploying DTs in HRC contexts. There's also an evident lack of transparency and specificity regarding the algorithms deployed in some studies, making it challenging to reproduce and validate the research outcomes. The absence of algorithmic details may also hinder the development of integrated frameworks that seamlessly combine various algorithms for enhanced DT-HRC functionality. This variability in technological and methodological approaches across the literature necessitates a more coordinated and standardized research agenda to advance the field of DTs in HRC effectively.

3.2. DT design for HRC - software key requirements

Developing DTs for HRC enhancement in manufacturing systems requires careful consideration of the software key requirements. Simulation studies are essential for a variety of reasons, and the motivations for using DTs in HRC enhancement are many. Given the delicate nature of HRC, which involves the coexistence of human operators and robots in the same workplace, appropriate integration studies are necessary. DTs enable the verification of space management and interference, guaranteeing efficiency and safety in shared work environments. The ergonomics of human operators and the productivity of manufacturing systems are also critical factors that need to be considered when developing DTs for HRC. These factors enable the evaluation of task management and assignment between human operators and robots, the delegation of tasks to the robot, and the selection of the best HRC scenario based on predefined key performance indicators (i.e., ergonomic parameters, production time, etc.). Moreover, data exchange and interoperability between the DT and the physical manufacturing system are crucial for effective communication and coordination between the digital and real-world environments in HRC scenarios, thus enabling the two systems to influence each other, and allowing for adjustments and improvements to be made to the manufacturing system.

Following the systematic literature review presented in section 3.1 and considering the aforementioned factors, this study has identified the following five key requirements as essential for a software to be used to develop DTs for HRC enhancement in manufacturing systems:

1. *Human operator simulation*: the software should have the capability to accurately and reliably replicate the actions of a real operator, ensuring precision and accuracy in HRC scenarios. Developing a digital human model for HRC scenarios is a challenging task, as the human body consists of a complex system of approximately 230 degrees of freedom, controlled by about 630 muscles (https://www.ifittraining.co.uk/insights/movement-variability-degrees-freedom/#:~:text=In%20total%20therefore%2C%20we%20have,we%20each%20have%20inside%20us). Due to the vast range of movements and postures that a human operator can assume, it is crucial to accurately replicate the motions of the real human operator in the simulation. Customization of anthropometric parameters is also important to ensure that the digital human operator closely resembles the real operator involved in the case study, especially for highly specialized work (Chaffin, 2005).
2. *Robotic agent simulation*: the software should have the capability to accurately and reliably replicate the actions of a real robot, enabling efficient and effective collaboration between humans and robots. The implementation of robot models for HRC simulations is a complex task that requires specialized software tools. Some of these tools' features, which are particularly useful for the development of DTs for HRC enhancement, include the ability to import different types of CAD files without loss of information, to build kinematic chains from scratch, to create robot models using simple geometry modeling functions, to access a library of pre-packaged robots, and to implement the Robot Operating System (ROS) (https://wiki.ros.org/ROS/Introduction).
3. *Ergonomic analysis*: the software should be capable of performing ergonomic analysis which supports the assessment and optimization of human operators' ergonomics. Several ergonomics methods can also be integrated into the DT to analyze and optimize human operator's working conditions. These include the Ovako Working

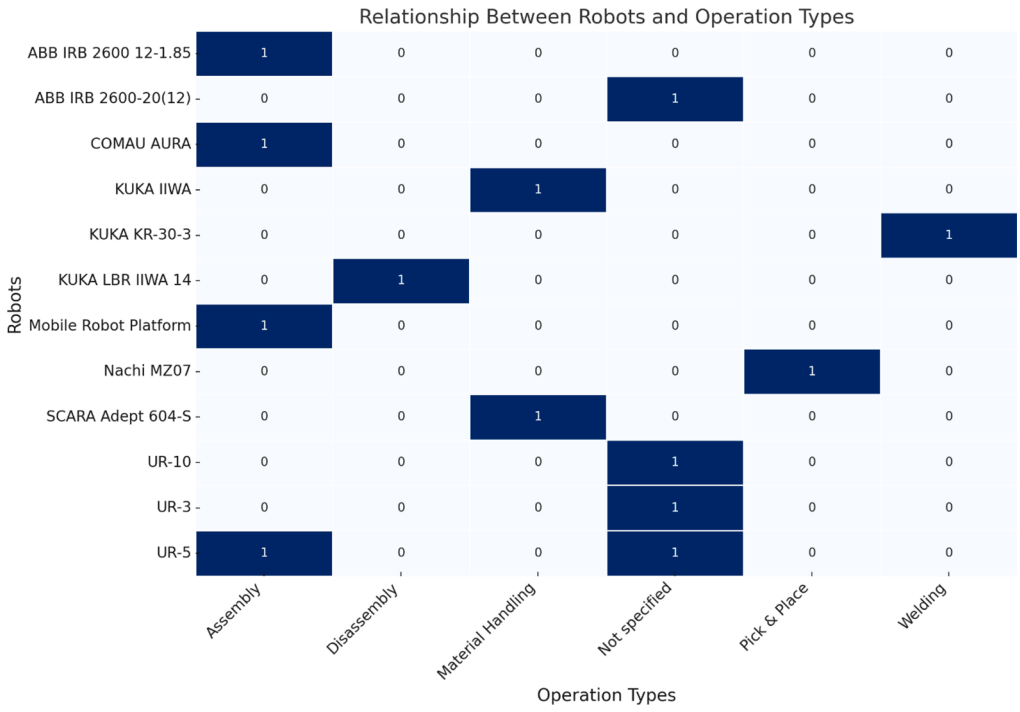


Fig. 6. Relationship between Robots and Operation Types.

Posture Analysis (OWAS) (Kharu et al., 1977; Kharu et al., 1981), the Static Strength Prediction Program (3D SSPP/SSP) (Chaffin et al., 2006), the Muscle Fatigue Analysis (MFA) (Rodgers and Suzanne, 1988; Rodgers and Suzanne, 1992), the Lower Back Analysis (LBA) (Herrin et al., 1986), the Cumulative Back Load analysis (CBL) (Coenen et al., 2012; Coenen et al., 2014), the Strain Indexes Analysis for Distal Upper Extremity Disorders (Moore and Garg, 1995), Rapid Upper Limb Assessment (RULA) (McAtamney and Corlett, 1993), the NIOSH 81 method (National Institute for Occupational Safety and Health, 1981), the NIOSH 91 method (Waters et al., 1994) and the GARG analysis (Garg, 1976). The presence of these methods within the DT enables the most accurate studies possible of HRC scenarios concerning the ergonomic conditions of the human operator.

4. *Time measurement analysis*: the software should be capable of performing time measurement analysis which plays a crucial role in optimizing the overall manufacturing system's productivity. Several time measurement methods can be integrated within a DT, such as the Methods-Time Measurement (MTM) (Maynard et al., 1948) and the Maynard Operation Sequence Technique (MOST) (Zandin, 2003). These methods allow for the accurate measurement and evaluation of the time required to complete a particular task, which can be used to identify inefficiencies in the manufacturing system and improve the productivity of human operators.
5. *Data Exchange and Interoperability*: the software should be able to exchange input and output data with the physical world as well as other software, facilitating efficient and effective communication and coordination between different components in the manufacturing system. The data exchange enables real-time monitoring, identification of issues, optimization of the manufacturing process, leading to improved productivity, reduction of waste, and increased efficiency. Additionally, it enhances better collaboration between humans and robots, improving manufacturing system safety as well as human operator's ergonomics.

3.3. DT development in HRC - commercial software overview

This section presents an overview of the commercial software that can be used to develop DTs for HRC enhancement in manufacturing systems. The software evaluated in this analysis were selected based on the document analysis conducted in section 3.1 (see last column in Table 3), with a focus solely on commercially available options, thus excluding In-house software. To ensure comprehensiveness, the authors further expanded the list of software by conducting additional searches through major search engines. Following a complete list of the software is reported, along with a concise description of each software's key features.

Wolfram Mathematica – it is a computational software program developed by Wolfram Research (https://www.wolfram.com/mathematica/). It provides a comprehensive set of tools for numerical and symbolic computations, visualization, and programming across a wide range of disciplines. Some of its key features include symbolic computation, numerical computation, data analysis and visualization, programming, integration with other technologies and access to curated data.

Process Simulate – it is a software developed by Siemens that enables the design, analysis, simulation, and optimization of manufacturing processes, from the factory level down to lines and work cells (https://plm.sw.siemens.com/en-US/tecnomatix/products/process-simulate-software/). Some of its key features include visualization for displaying and analyzing simulation results, human modeling and simulation for analyzing human-centered operations and robotic simulation to simulate robot movements and optimize robot paths for maximum efficiency.

Unity 3D – it is a cross-platform game engine developed by Unity Technologies. This software is widely used for developing video games, Augmented Reality (AR) and Virtual Reality (VR) applications, and other interactive 3D experiences (https://unity.com/). Some of its key features include a powerful editor that enables developers to create and manipulate 3D objects, a physics engine for simulating realistic movement and collisions, a scripting engine for creating custom behaviors and game logic, and support for a wide range of platforms and devices.

Visual Components – it is a 3D simulation software developed by Visual Components Oy (https://www.visualcomponents.com/products/premium/). The software is used to model and simulate production lines, robots, machines, and other industrial equipment for optimizing material flow, reducing cycle times, and improving the overall efficiency of manufacturing and logistics systems. Some of its key features include

drag-and-drop 3D modeling to create 3D models of manufacturing systems, a flexible simulation engine to enable the users to simulate complex manufacturing processes and data visualization to monitor the performance of the simulated system.

Gazebo – it is an open-source software currently maintained by the Open-Source Robotics Foundation (OSRF) (https://classic.gazebosim.org/tutorials?cat = guided_b&tut = guided_b1). Gazebo is a 3D dynamic simulator that is capable of accurately and efficiently simulating populations of robots in complex indoor and outdoor environments. Some of its key features of Gazebo include multiple physics engines for the simulation of rigid-body dynamics, contacts, and collisions, a rich library of robot models and environments, and a wide variety of sensors.

CoppeliaSim (V-rep) – it is a robot simulator by Coppelia Robotics AG (https://www.coppeliarobotics.com/helpFiles/index.html). This software can be used both as a stand-alone application or easily embedded into a main client application. Some of its key features include simulation of factory automation systems, remote monitoring, hardware control, fast prototyping and verification, safety monitoring, fast algorithm development, robotics-related education, and product presentation.

Delmia (3DExperience) - it is a software developed by Dassault Systems, which provides a wide range of software applications for simulating manufacturing processes, production systems, and supply chain management (https://www.3ds.com/products-services/delmia/). Some of its key features include manufacturing process planning and optimization, human modeling and ergonomics, robotics and automation.

Morse – it is an open-source robotics simulation software developed by LAAS-CNRS (https://www.openrobots.org/morse/doc/stable/what_is_morse.html#performances). The software provides realistic 3D simulations of environments ranging from small to large, whether indoor or outdoor, using autonomous robots. Some of its key features include modularity and therefore easy to be extended with new functionalities, multi-robot simulation to simulate robots and their interactions, and a realistic simulation environment supported by 3D graphics and virtual reality.

3.4. DT design for HRC - software comparison

In this section, the authors present the comparative analysis of the commercial software discussed in Section 3.3, based on the key requirements outlined in Section 3.2. It is important to note that the analysis does not aim to rank or promote any particular software tool over another; rather, the goal is to offer an objective report on the software tools currently available in the market to develop DTs for HRC enhancement in manufacturing systems. To facilitate this comparison, Table 6 presents the lists of the commercial software and indicates whether each identified key requirement is fully satisfied (✓), partially satisfied (-) or not satisfied (x) by the respective software. This approach provides a comprehensive overview of the strengths and limitations of each software tool, allowing researchers and practitioners, who are seeking to implement DTs for HRC enhancement in manufacturing systems, to make informed decisions on the software selection based on their specific requirements.

Following, the authors present for each software the information that was used to populate Table 4.

Wolfram Mathematica

- Human operator simulation: although this software does not offer a dedicated module for human modeling and simulation, it is still possible to create an approximation of a human model by using joints and body segments. Furthermore, kinematic functions such as AngleVector or AngleMatrix enable users to specify joint angles over time and define the motion of the human model.
- Robotic agent simulation: this software integrates a module, called Mathematica's Robotics module, which provides a set of tools and functions for modeling, analyzing, and controlling robots. With this module, end-users can access built-in functions that simplify the process of working with common robotic structures such as manipulators, end-effectors, and sensors. Moreover, the software allows users to generate dynamic simulations and visualizations of robot motion, and to perform both kinematic and dynamic analyses of robot behavior. These capabilities enable users to predict a robot's performance under different conditions, and to optimize its functionality accordingly.
- Ergonomic analysis: the software does not provide a module for ergonomic measurement analysis but functions can be implemented through coding in the supported languages such as Wolfram Language, C, C++, Java,.NET and Python.
- Time measurement analysis: the software does not provide a module for time measurement analysis but functions can be implemented through coding in the supported languages such as Wolfram Language, C, C++, Java,.NET and Python.
- Data Exchange and Interoperability: the software provides users with a range of built-in interfaces for interoperable communication with external software such as LabVIEW, Python, Java,.NET, C, and FORTRAN. Additionally, standard protocols such as HTTP, FTP, and SMTP can be used to achieve interoperability with other software. In addition, Wolfram Mathematica also supports various import and export file formats, such as CSV, HDF5, and FITS, which allows for easy transfer of data to and from other programs.

Process Simulate

- Human operator simulation: the software offers a dedicated module for human modeling and simulation. This module includes highly accurate and reliable human models, such as "Jack" and "Jill," that can be customized to match specific user requirements. Users can adjust the anthropometry of the models allowing for realistic simulation of human motion during a task as well as the evaluation of human factors such as ergonomics and task feasibility before implementation in the real manufacturing system.
- Robotic agent simulation: the software provides the users with a module for robot modeling and simulation. This module allows users to create primitive geometries and joints with attached kinematic chains to create simple mechanisms that can be implemented in simplified simulation models. It also enables the import of CAD models through a CAD translator that is installed during software installation. The CAD translator converts generic CAD models into.jt format, the only format supported by Process Simulate (please note

Table 6
Software comparison.

Software	Human operator simulation	Robotic agent simulation	Ergonomic analysis	Time measurement analysis	Data Exchange and Interoperability
Wolfram Mathematica	–	✓	–	–	✓
Process Simulate	✓	✓	✓	✓	–
Unity 3D	–	–	–	–	✓
Visual components	–	✓	X	–	✓
Gazebo	–	✓	X	X	✓
CoppeliaSim	–	✓	–	–	✓
Delmia	✓	✓	✓	✓	–
Morse	–	✓	X	X	✓

that a license for the import format is required to convert the model to.jt format).
- Ergonomic analysis: the software allows users to perform ergonomic analysis such as OWAS, 3D SSPP/SSP, MFA, LBA, CBL, RULA, NIOSH81, NIOSH91 and Garg analysis. These analyses are integrated into the software and provide insights into the physical efforts required of the workers in performing a task.
- Time measurement analysis: the software integrates the MTM analysis tool, thus enabling opportunities for process improvement and optimization by measuring the time required to complete specific tasks and evaluating the motions involved in those tasks. This allows for the identification of unnecessary or inefficient motions that can be eliminated or improved to reduce cycle time and increase productivity.
- Data and Information Exchange: the software allows the connection of virtual models with real Programmable Logic Controller (PLC) code and hardware (HW) over OPC (OLE for Process Control) interface. This enables users to simulate the behavior of a production line and test the PLC code before implementing it in the real manufacturing system. However, the software's complete interoperability is not assured as it can only interface with Siemens Product Lifecycle Management Software. This is a suite of software applications, developed by Siemens for managing the product's entire lifecycle, including its design, engineering, manufacturing, and maintenance.

Unity 3D

- Human operator simulation: although the software lacks a specific module for human simulation, it offers a simulation environment where CAD models can be integrated into the scene to recreate scenarios with human operators. Human models can be used as dummies to which specific programming codes can be attached for evaluations and analyses.
- Robotic agent simulation: although the software lacks a specific module for robotic agent simulation, it allows to import CAD models including robot models and provides tools for creating kinematic chains, joints, and scripts to control robotic components.
- Ergonomic analysis: although the software does not provide a module for ergonomic analysis, it allows users to integrate mathematical functions through scripts that can be attached to specific components or joints. By leveraging this functionality, users can perform analyses of human operator ergonomics within the simulation environment.
- Time Measurement analysis: no specific module for time measurement analysis is integrated within the software. However, Unity 3D allows users to integrate mathematical functions through scripts that can be attached to specific components or joints, thus enabling time measurements within the simulation environment.
- Data Exchange and Interoperability: the software supports interoperable communication with other software through several built-in interfaces and APIs. Additionally, Unity supports communication with external software through plugins and extensions, which can be written in languages such as C++, C#, and Java. Furthermore, Unity 3D has built-in support for several industry standards and protocols such as OpenVR, OpenXR, and WebGL, which enable interoperability with a wide range of hardware and software platforms. In terms of data exchange, Unity supports various file formats for importing and exporting assets, including 3D models, animations, textures, and audio. Among the others, these formats include FBX, OBJ, Collada, WAV, and MP3.

Visual Components

- Human operator simulation: the software offers a module for including a human model in the simulation environment, which can be programmed to perform specific operations. However, the human module in the current version of the software only offers approximate simulations and is not suitable for detailed analysis of specific manual operations.
- Robotic agent simulation: the software provides a module specifically for robot modeling and simulation. This module offers a library of pre-built robot models, featuring popular brands such as ABB, Fanuc, and KUKA, along with generic robot models that can be customized to meet specific requirements. In addition, various programming languages, including ABB's RAPID, KUKA's KRL, and FANUC's TP can be used to program the robot models. For users who prefer a graphical approach, the software offers a drag-and-drop visual programming interface, enabling them to create robot programs without the need for coding. Once programmed, the robots can be simulated in the virtual production environment, facilitating the testing and optimization of their behavior and performance. The software offers a suite of tools for testing collision detection, motion planning, and path optimization, as well as analysis tools for evaluating the robot's cycle times and other performance metrics.
- Ergonomic analysis: the software does not provide a specific module for ergonomic analysis.
- Time Measurement analysis: the software does support time measurement analysis, thus enabling users to perform time studies, measure cycle times, and analyze production line efficiency.
- Data Exchange and Interoperability: the software provides several built-in interfaces for interoperable communication with external software, including Python, C#, and.NET. It also supports a variety of import and export file formats, including STEP, IGES, and COLLADA.

Gazebo

- Human operator simulation: although this software lacks a dedicated module for human simulation, it is possible to recreate a human model using the "actor" function of the software (He et al., 2020), which also allows to addition of animations to a joint model. However, in order to accurately control the movement of the human model, it is necessary to create the structure of the joints (with attached hierarchy) by using an additional tool called EMA - Editor for Manual Work Activities. Additionally, the same EMA tool must be used to program the workflow and actions to be performed by the model.
- Robotic agent simulation: this software can generate basic geometric models and import pre-existing 3D models, including robot models, into simulation scenarios. Users can create and configure joints within the software, and adjust parameters such as gravity, density, kinematics, and mass to meet specific requirements.
- Ergonomic analysis: this software does not offer the capability to carry out ergonomic analysis.
- Time Measurement analysis: this software does not support time measurement analysis.
- Data Exchange and Interoperability: Gazebo provides the ability to exchange data via Gazebo Transport [69]. Additionally, the software also supports several plugin APIs, including the C++ plugin API, the ROS plugin API, and the Ignition Gazebo plugin API. These APIs allow to extend the functionality of Gazebo by creating custom plugins that can interact with other software or perform specialized simulation tasks. Gazebo also supports a variety of import and export file formats, including COLLADA, URDF, and SDF and gives the opportunity to incorporate simulative scenarios with several sensors, including monocular or depth cameras to get input data.

CoppeliaSim

- Human operator simulation: the software has no dedicated module for human operator simulation, but it does offer some representative models of humans in its rich model library. However, these models

do not have specific features for implementing HRC-efficient human simulations. The human models can be handled as if they were robots, but it would be necessary to handle all degrees of freedom of the model. Alternatively, the human models can be handled as if they were animations to make approximate movements to briefly illustrate the action to be represented.
- Robotic agent simulation: the software offers a vast library of robot models that can be easily imported into the virtual environment to create different simulation scenarios. It allows for dynamic analysis, inverse and forward kinematics, collision detection and minimum distance calculation, the implementation of visual and proximity sensors as well as the planning of paths and motions.
- Ergonomic analysis: the software does not offer any feature set for performing ergonomic analysis; however, it allows users to attach scripts to objects in the scene, which could be programmed to perform ergonomic analyses.
- Time Measurement analysis: the software does not offer any feature set for performing time measurement analysis; however, as for the ergonomic analysis, CoppeliaSim allows users to attach scripts to objects in the scene, which could be programmed to calculate process times.
- Data Exchange and Interoperability: CoppeliaSim enables the exchange of data with the outside world through various means, including signals, custom data blocks, plugin and script functions, and WebSocket. Additionally, CoppeliaSim guarantees interoperability through the use of several built-in interfaces for communication with external software, including ROS, MATLAB, Python, Java, C++, and Lua. These interfaces allow to send and receive data between CoppeliaSim and other software, as well as control simulation parameters and perform simulations programmatically.

Delmia (3DExperience)

- Human operator simulation: this software allows the implementation of customizable manikins based on anthropometric standards, which can be tailored to the simulation needs. This feature makes Delmia an ideal tool for modeling human operators.
- Robotic agent simulation: this software offers capabilities for robotic agent simulation, including the ability to model simple 3-D robot models and assign inverse kinematics to them. It also enables defining joints for imported models that lack these characteristics. Delmia's advanced features include validation of welding, riveting, and drilling operations, calculating interference zones and interlocks in multi-robot work cells, and offline programming of multiple robots from different companies while validating specific robot syntaxes. Although Delmia does not have a library of pre-packaged robot models, it allows importing robot CAD models in various formats.
- Ergonomic analysis: this software offers a wide range of ergonomic analysis options, such as vision, reach, space, and posture analysis, biomechanical analysis, push, pull, and carry analysis, lifting and lowering analysis, rapid upper limb assessment, and smart posturing. It is worth noting that the software utilizes Delmia standards for ergonomic analysis, which may differ from international standards.
- Time Measurement analysis: this software includes tools for analyzing cycle times, lead times, and other time-based metrics, as well as tools for optimizing these metrics.
- Data Exchange and Interoperability: DELMIA provides support for data import and export in the ".xml" format during simulation. Additionally, it offers plugin APIs such as the CAA V5/V6 API and the DELMIA Automation API, which can be utilized to expand the functionality of the software by creating custom plugins that can perform specialized simulation tasks or interact with other software. It is important to note that the interoperability of DELMIA is currently limited to software developed by Dassault System, including CATIA, ENOVIA, SIMULIA, and DELMIA Process Engineer.

Morse

- Human operator simulation: while this software does not have a dedicated module for human simulation, it does provide the option to place a human model within the simulated environment. However, these models do not have specific features to enable efficient HRC simulations; in fact, the human models can be manipulated as if they were robots by managing all degrees of freedom of the model.
- Robotic agent simulation: this software offers capabilities for robotic agent simulation by either providing the end-user with a library including some pre-packaged models or directly importing the CAD model within the simulative environment. It provides a range of features for configuring the robot's physical properties, such as mass, joint parameters, etc. and supports the integration of various sensors and actuators.
- Ergonomic analysis: this software does not offer the capability to carry out ergonomic analysis.
- Time Measurement analysis: this requirement is not supported by the software.
- Data Exchange and Interoperability: Morse supports six open-source middlewares, including ROS, YARP, Pocolibs, MOOS, HLA, and Mavlink to facilitate communication and data exchange with external devices, systems and software. Users can choose the middleware that best suits their needs and integrate Morse with various other tools and platforms, allowing for greater flexibility, interoperability and data exchange. Additionally, this software provides a socket-based protocol that enables easy integration with other languages and toolboxes, simplifying the process of exchanging data and information.

4. Discussion

This section explores the significance of the results of the work by directly answering the RQs presented in Section 1. Below, each RQ is reiterated, and its corresponding answer is provided.

RQ1: What are the most recent and impactful applications of Digital Twins in enhancing Human-Robot Collaboration across different industries?

The use of DTs for enhancing HRC in manufacturing systems is a relatively new research topic, with the first article published in 2017. However, there has been a significant increase of publications in this area as a result of a growing level of interest and engagement within the scientific community. Despite this trend, only a few countries have dedicated efforts to investigating the use of DTs for HRC enhancement: China, Germany, Greece, and the United Kingdom. The studies primarily focus on assembly/disassembly, material handling, pick & place, and welding operations, with safety, production plans, ergonomics, and collaborative spaces as the top priorities in the simulation scope. In addition, although many of these studies are conducted in controlled environments, it should not be considered an absolute constraint on the application of the DT paradigm. The growing research interest in this area, especially in recent years and in response to the disruptions caused by the Covid-19 pandemic, suggests that this approach could be promising to face real-world challenges in industrial operations.

RQ2: What are the essential factors that must be considered when developing Digital Twins for enhancing Human-Robot Collaboration in manufacturing systems?

The present study has identified five key requirements for software used to develop DTs in manufacturing systems to enhance HRC. Firstly, the software should accurately replicate human operators' actions, as the human body is complex and consists of a vast range of movements and postures. Customization of anthropometric parameters is also important. Secondly, the software should replicate the actions of a real robot, enabling effective collaboration between humans and robots. Specialized software tools are required to implement robot models for HRC simulations. Thirdly, the software should enable ergonomic and time measurement analyses, which play a crucial role in optimizing

human operators' ergonomics and the overall manufacturing system's productivity. Finally, the software should be able to exchange input and output data with the physical world as well as with other software enabling efficient and effective communication and coordination.

Beside, deploying DTs in HRC environments necessitates careful consideration of practical and technical aspects to ensure a seamless implementation. Beginning with data acquisition, appropriate sensors such as Kinect, Kinect Azure, LIDAR, uEye XS Camera, or OptiTrack are indispensable to capture motion and environmental data necessary for robotic and human entities modeling. Moreover, the selection of data acquisition devices, that can efficiently collate real-time data from these sensors while maintaining compatibility and ease of integration, is of utmost importance.

The selected sensors need to be fed into a robust communication infrastructure that supports high-speed, low-latency data transmission, facilitated by high-performance routers and switches. The employment of communication protocols like MQTT, CoAP, or WebSockets that promote efficient data transfer, synchronization between the DT and its physical counterpart, and effective collaboration between human operators and robots is also necessary for minimizing latency in real-time applications, thus optimizing the effectiveness of HRC.

On the computational side, data processing requires high-performance computing hardware equipped with powerful CPUs and GPUs to run complex algorithms and facilitate real-time simulation and interaction within the DT environment. It is also important to consider algorithmic libraries and frameworks that not only support but also optimize the chosen algorithms for data analysis, such as TensorFlow or PyTorch for neural networks or other appropriate machine learning or data analysis libraries.

As the data flows through the system, a suitable simulation environment becomes essential. These platforms offer diverse tools for developing, testing, and validating DTs in HRC, serving as the bedrock for DT development and modeling. Within these environments, there could be the need to employ additional modeling tools and AI/ML frameworks (like TensorFlow, Keras, Scikit-learn) for creating accurate representations and functionalities of robots and human operators and enabling intelligent, adaptive interactions between them.

In the future it will be also necessary to ensure that DTs adhere to relevant industry standards and compliance protocols, such as IEC 62541, ISO 10218, or other applicable standards.

RQ3: Which solutions and tools are appropriate for developing and deploying Digital Twins specifically designed for Human-Robot Collaboration in the context of manufacturing systems?

The list of software identified in this research study is available in Table 6 and is reported in the following: Wolfram Mathematica, Process Simulate, Unity 3D, Visual Components, Gazebo, CoppeliaSim, Delmia and Morse.

RQ4: Which constraints and obstacles are to be considered when implementing Digital Twins in manufacturing systems to enhance Human-Robot Collaboration (HRC)?

The examination of software benchmarking has shed light on a critical research gap within the realm of DTs for HRC in manufacturing systems. This study has brought to the forefront the glaring absence of comprehensive software solutions tailored to digital twin development for HRC.

The analysis indicates that current commercial software solutions do not fully meet the critical requirements identified as necessary for optimizing Human-Robot Collaboration (HRC) within manufacturing systems from a Digital Twin (DT) perspective. This suggests that there may be a gap between the capabilities of existing software and the specific needs or objectives of HRC in manufacturing systems. As a result, organizations may need to consider custom development or the potential for emerging solutions to address these requirements effectively. Many of these software programs are developed with a modular approach, primarily emphasizing robot simulation. This has been the dominant trajectory in research and development in recent decades, with human simulation often taking a backseat. Furthermore, only a limited number of software packages incorporate ergonomic and time measurement analysis to their full extent. While most offer some degree of data exchange and interoperability capabilities, they often do not fully meet the holistic needs of HRC.

This study is proposed as a resource for both researchers and practitioners committed to advancing HRC in the manufacturing domain through the implementation of digital twins. By delving into software benchmarking within this field, the analysis allows readers to access crucial information about the most widely used software options for developing digital twins, and how this software have been employed in scientific literature in this field of interest. This insight serves as a compass, guiding individuals towards the most suitable software solutions that align with their research objectives and practical applications.

Implementing DTs in HRC environments poses notable challenges and necessitates careful consideration. Integration complexity is a significant hurdle due to the imperative for data consistency between the physical and virtual entities and the need for seamless interoperability among diverse devices and technologies in HRC systems. Ensuring accuracy and precision in both the modeling of the physical object in the DT and the sensors' data, which are crucial for the DT's continuous update, is challenging (Eichler et al., 2017). Addressing real-time performance issues, such as minimizing latency in data transmission and processing and achieving synchronization between the DT and its physical counterpart, is crucial for the effectiveness of real-time applications (Wu et al., 2023). The DT-HRC system should also be scalable and flexible, able to expand without substantial performance degradation and adapt to various robotic hardware, sensors, and application requirements. Security and privacy concerns are paramount, given the continuous data exchange, with the need to secure communication channels and data while also respecting the privacy of human operators in the environment (Tabassum et al., 2023). Usability and user experience are vital, requiring the design of intuitive user interfaces and effective user feedback mechanisms. Reliability and maintenance of the DT-HRC system under various operational conditions need proactive strategies for troubleshooting and minimizing downtime. Continuous validation and verification of the DT's accuracy and the entire system's performance are essential for maintaining integrity and expected functionality.

In essence, this research equips readers with the knowledge to make informed decisions when selecting software for their specific needs. It not only illuminates the shortcomings of existing commercial software but also highlights the distinctive features and limitations of each option available in the HRC realm. As a result, readers can tailor their software choices to precisely match the demands of their research studies or industrial projects.

Furthermore, our findings emphasize the critical necessity for the development of dedicated software solutions tailored explicitly to the requirements of HRC in manufacturing systems. These solutions should seamlessly integrate all the essential components of HRC, bringing them together within a unified and coherent tool. This call to action underscores the urgency of bridging the gap in the current software landscape, ultimately paving the way for more efficient and effective digital twin development in the context of HRC.

The integration of DTs into Human-Robot Collaboration HRC scenarios also raises several profound ethical, societal, and legal considerations that warrant careful examination. Ethically, the use of DTs in HRC introduces questions about the boundaries of human-robot interaction and control. As DTs enable a high degree of real-time monitoring and simulation, there is the potential for invasive surveillance of human workers. Ensuring that the data collected and utilized by DTs respects individuals' privacy and autonomy is paramount (Braun, 2021). Furthermore, issues of transparency and accountability arise when decisions made by robots, informed by DTs, impact human safety and well-being (Wullenkord and Eyssel, 2020). Ethical guidelines must be established to govern the responsible use of DTs in HRC, emphasizing

transparency, informed consent, and fairness.

From a societal perspective, the widespread adoption of DTs in HRC may have significant implications for the workforce. Automation and enhanced collaboration between robots and humans facilitated by DTs can lead to shifts in employment dynamics. While it may create new opportunities and improve efficiency, it also raises concerns about job displacement and the need for retraining and upskilling to adapt to changing roles in an HRC setting. There is a pressing need for proactive policies and strategies to address these potential disruptions, ensuring that the benefits of DT-enabled HRC are shared equitably among society.

On the legal front, the use of DTs in HRC introduces complex liability issues. Determining responsibility in the event of accidents or errors becomes more intricate when human actions and decisions are intertwined with those of robots informed by DTs (Weber-Lewerenz, 2021). Legal frameworks must evolve to establish clear lines of accountability and liability. Additionally, intellectual property rights may come into play when DTs are used to model and optimize collaborative processes. Legal frameworks will need to adapt to address issues related to data ownership, data sharing, and intellectual property protection in HRC scenarios involving DTs (Kendzierskyj et al., 2019). Achieving a balance between fostering innovation and safeguarding individual rights within a legal framework will be a key challenge. Overall, the ethical, societal, and legal implications of implementing DTs in HRC underscore the importance of comprehensive and thoughtful governance frameworks that promote responsible and beneficial deployment.

5. Conclusion

This paper explores the potential of using DTs to support HRC in manufacturing systems, with a specific focus on the ability of DTs to provide a realistic simulation environment for testing and optimizing collaboration strategies. The study includes a systematic literature review devoted to understand how the scientific community perceives the application of DTs to support HRC in manufacturing systems and identify the main trends in this research area. While the review indicates that there is a growing interest, further research efforts are needed to expand the existing knowledge base and to address the challenges and limitations in the implementation of DTs for HRC in manufacturing systems. These might include issues related to data accuracy, real-time integration, human-robot interaction dynamics, and more.

Security is another significant concern. Manufacturing systems typically involve sensitive data and critical operations, so safeguarding the DT and the associated data from cyber threats and unauthorized access is paramount. Moreover HRC introduces its own set of complexities. Ensuring that the DT accurately models and simulates these interactions, considering factors such as worker safety and ergonomics, is challenging.

The second part of the work focused on the definition of the main key requirements that software should have to develop proper DTs for HRC in manufacturing systems along with an overview on commercial software and benchmark. The results of this benchmark reveal that no software can currently and efficiently integrate all the identified key requirements for developing DTs for HRC. Future research initiatives should consider addressing several pivotal areas to further enhance the efficacy and integration of DTs in collaborative environments. Firstly, developing innovative algorithms for real-time synchronization between DTs and physical counterparts is crucial to reduce latency and improve system responsiveness, facilitating smoother human-robot interaction. Secondly, constructing robust security frameworks is vital to safeguard data integrity and confidentiality within DT-HRC systems, protecting both robotic and human elements. Attention should also be directed towards creating adaptive DTs that can autonomously optimize performance in response to environmental and task changes, and developing user-friendly interfaces to broaden DT-HRC technology accessibility and adoption across various industries. Conducting empirical studies in diverse real-world scenarios is essential to validate and refine proposed models, contributing to the advancement of DTs in HRC.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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