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Collaborative robots in manufacturing and assembly systems: literature review and future research agenda

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Abstract

Nowadays, considering the constant changes in customers' demands, manufacturing systems tend to move more and more towards customization while ensuring the expected reactivity. In addition, more attention is given to the human factors to, on the one hand, create opportunities for improving the work conditions such as safety and, on the other hand, reduce the risks brought by new technologies such as job cannibalization. Meanwhile, Industry 4.0 offers new ways to facilitate this change by enhancing human–machine interactions using Collaborative Robots (Cobots). Recent research studies have shown that cobots may bring numerous advantages to manufacturing systems, especially by improving their flexibility. This research investigates the impacts of the integration of cobots in the context of assembly and disassembly lines. For this purpose, a Systematic Literature Review (SLR) is performed. The existing contributions are classified on the basis of the subject of study, methodology, methodology, performance criteria, and type of Human-Cobot collaboration. Managerial insights are provided, and research perspectives are discussed.

Keywords Cobots · Collaborative robots · Literature review · Manufacturing system · Human–machine interaction · Industry 4.0

Introduction

Increasing production volume was one of the main challenges in many industries for a long time. The population's rapid growth was the principal reason for that situation (Malik & Bilberg, 2019b). To face this increasing demand, industrial systems have been developed during the first and second industrial revolutions, and mass production has become a common strategy (Jepsen et al., 2021). This was followed by the introduction of robots into manufacturing systems in the third industrial revolution (Azzi et al., 2012). Their advantages convinced managers to use them widely in different operations, mainly where repetitive tasks were concerned, such as the case of automotive and electronic industries (Xu et al., 2021). In 2019, the market sales value of industrial robotics-worldwide was more than 14 billion US dollars out of which, 3.7 billion US dollars, equal to 26 percent, belonged to automotive industries, and 3.6 billion US dollars, equal to 25 percent, belonged to electronic industries (Statista, 2022a).

For decades, the worldwide usage of robots shows that traditional industrial robots are perfectly fit for mass production. However, nowadays, the challenge that industries face is not just about the production capacity in terms of throughput but is even stronger related to flexibility, customization, and ergonomics (Battini et al., 2015). At the same time, the use of robots has some disadvantages, such as the high investment and operational costs, the difficulty of integrating them in the work environment (e.g., size problems or lack of flexibility), or human-related risks (Serebrenny et al., 2019b). Eventually, the fourth industrial revolution, known as the Industry 4.0, happened not only to increase the flexibility in the production systems but also to enhance human–machine interactions (Lamon et al., 2018). Robotics is still considered as a key technology, as Boston Consulting cited this field among "the nine pillars of Industry 4.0" (Neumann et al., 2021).

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In the Industry 4.0 paradigm, robots are expected to become more flexible and safer while generally being more affordable and more size efficient. Consequently, it should be easier to integrate robots into a work environment, and more opportunities are to be created for human–robot collaborations (Weckenborg & Spengler, 2019). These expectations led to the introduction of Collaborative Robots (Cobots) which help workers in their assigned tasks and improve the results and work conditions by combining workers' skills and robots' physical strength and endurance.

The main differences between cobots and traditional robots are: (a) cobots do not need to perform a task as quickly as robots, so it is safer for workers to be around cobots, and (b) they should not replace workers but cooperate with them, (c) they are supposed to be more flexible than robots, so they should be simple to program, locate, and relocate, (d) they should prepare a safe shared work-space for workers (de Gea Fernández et al., 2017). Besides these advantages, cobots have ergonomic benefits in the case of repetitive or dangerous tasks. In addition, there are the possibilities to use robots to help workers with physical disabilities or aging workforces (EU-OSHA, 2019).

Cobots' advantages have led the industry to use them more and more in recent years. Based on the Statista database, the share of collaborative robots from total unit sales worldwide being 5% in 2018 is expected to reach 13% in 2022 (Statista, 2022b). Also, the market size of the collaborative robot being 700 million US dollars in 2021 is expected to reach nearly 2 billion US dollars in 2030 (NMSC, 2022). However, same as any new technology, cobotization brought some new challenges such as worker's safety, while safety was initially a main argument for adopting cobots. For instance, due to the close interaction of humans and robots, the safety of the workers should be ensured in a collaborative station which could be a complex problem.

In the past decade, safety has been the most referenced topic in collaborative robots' literature and designing a safe cobot was the main target of most researchers in this field (Cardoso et al., 2021, Pinheiro et al., 2022). Researchers started to further study the interaction of "safe cobots" with humans and analyse their individual and collaborative performance. In addition to safety, when cobots and humans interact to achieve a pre-defined goal, many other aspects need to be considered.

Several literature review papers on cobots have been published to assist researchers in exploring the topic. To better understand the differences between other literature review papers with regards to the main ideas, categorization, and key findings, a comprehensive analysis was conducted on literature reviews related to cobots (see Appendix Table 4). By using keywords "cobot" OR "collaborative robot" OR "human-cobot collaboration" OR "HRC" AND "review" in Scopus and Web of Science, 32 papers were found in English. These papers were studied to extract the keydata such as subjects, research field, sources, review method, classification criteria, and key findings were extracted. The number of studies in each research field indicates that these papers mainly focused on the design phase of cobots, robotics, or computer science fields (see Fig. 1), among which significant studies such as Robla-Gomez et al., 2017, El Zaatari et al., 2019, Zhang et al., 2021a, and Costa et al., 2022 can be mentioned. However, recently, some reviews that address human–robot collaboration appeared in the literature such as Simões et al., 2022, Faccio et al., 2023.

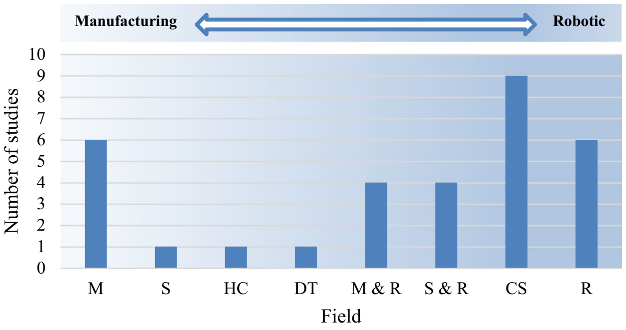


Fig. 1 Number of published literature reviews about collaborative robots in relation to the field of study (M: Manufacturing, R: Robotics, CS: Computer Science, S: Safety, DT: Digital Twin, HC: Health Care)

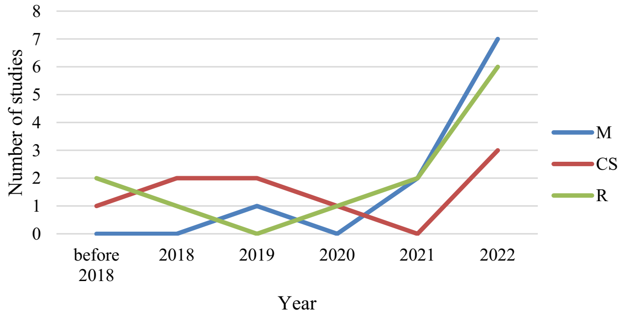


Fig. 2 Number of literature review papers per year (R: Robotics, M: Manufacturing, CS: Computer Science)

Figure 2 shows that besides the robotics and computer science fields, studying manufacturing systems has become more popular in recent years. Moreover, several studies focus on the human–machine dimension (see Appendix Table 4), for example, human–robot communication (Hjorth & Chrysostomou, 2022) or the use of computer science for analyzing human–robot collaboration (Navas-Reascos et al., 2022b) in manufacturing systems.

Among the 32 selected studies, 11 were systematic literature reviews out of which three were in the manufacturing research field, two focused on human factors in collaborative systems, and one focused on workstation design factors. In our systematic literature review (SLR), we expand the analysis of the contributions on cobots and human–robot collaboration according to the following criteria: the subject of study, methodology, methodology, performance criteria, and collaboration scenarios.

The rest of this article is structured as follows. Section "Basic concepts" introduces some basic concepts about cobot's research fields, performance criteria, and collaboration scenarios. Section "SLR Methodology" presents the systematic literature review approach and steps to select papers. In Sect. "Results of the systematic literature review", a demographic analysis is reported, the categorization of the selected papers is explained, and the articles are analyzed in the defined categories. Finally, in Sect. "Research Agenda and conclusions", open questions, and perspectives for human-cobot collaboration are summarized and discussed.

Basic concepts

This section introduces the concepts that will be used further in our literature analysis, namely: (a) subject of study, (b) performance criteria, and (c) collaboration scenarios.

Subject of study

In general, research about cobots concerns either pre-manufacturing or post-manufacturing. In the pre-manufacturing research, researchers aim to improve the design of cobots. Therefore, a cobot is typically considered an isolated entity in these studies, not an entity in a manufacturing system. On the other hand, in the post-manufacturing research, researchers focus on either (I) how to improve the human–robot interaction by changing the cobot's program or controllers or (II) how to use or implement cobots in a production system.

Based on the previous explanations, cobot studies can be divided into three main classes: design, programming, and operation.

- *Design:* The main targets of such papers are to produce a better cobot. Changing the sensors, arms angles, the material used, and arms speed are the most common ways to design new cobots with better performance.
- *Programming:* The program and controller installed on the cobots act as the decision-maker. Therefore, researchers try to find a new way to develop programs/algorithms that can improve cobots' performance.
- *Operation:* Such papers discuss the integration of cobots in manufacturing systems.

Performance criteria

The selection of performance criteria is essential for designing a cobot or a collaborative system (Simões et al., 2022). Every study can consider one or more performance criteria to evaluate their design solutions. In Sect. "Results of the systematic literature review", all performance criteria that have been employed in the cobot's literature are discussed.

Collaboration scenarios

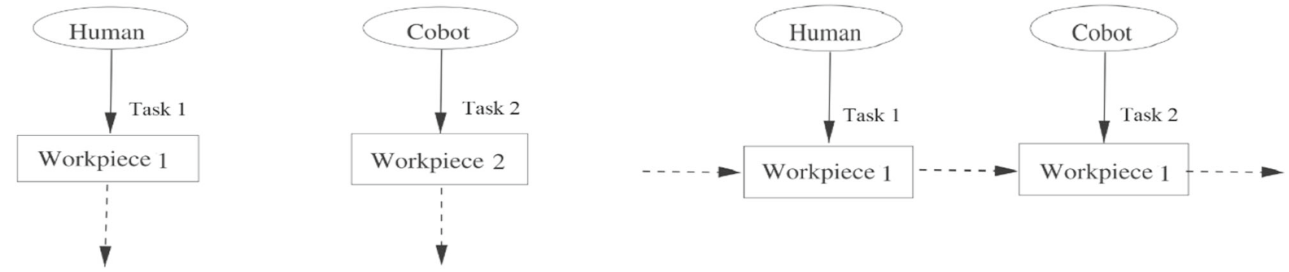
Based on how cobots and humans collaborate to accomplish tasks (processes) in a workstation, the collaboration between humans and cobots can be classified into four different categories: independent, sequential, simultaneous, and supportive (El Zaatari, 2019) (see Fig. 3).

- *Independent:* In this scenario, a human worker and a cobot process two tasks (tasks 1 and 2) separately on two different workpieces (workpieces 1 and 2). In some studies, "independent" scenarios are named "parallel" scenarios.
- *Sequential:* This scenario happens when a human worker and a cobot process two different tasks (tasks 1 and 2) on the same workpiece in serial processes. This scenario is usually used to improve working conditions for workers. Delivery tasks or pick-and-place are two samples.
- *Simultaneous:* Here, a human worker and a cobot process two different tasks (tasks 1 and 2) on the same workpiece at the same time. This scenario is usually used to improve ergonomics. For instance, rivets can be processed by a cobot and screws by a human worker simultaneously. Ensuring the safety of workers in this scenario is of paramount importance.
- *Supportive:* When a human worker and a cobot interactively process a single task on a single workpiece, the scenario is called "supportive". In this scenario, support each other (usually physical support) to accomplish a task. For example, a cobot holds the workpiece and a human worker fastens the screw (Zhang et al., 2021b).

SLR Methodology

In this section, all the research questions were described, then the search strategy and selection criteria were explained in detail. To find, classify, and analyse all relevant articles to the topic of interest and research questions, a Systematic Literature Review (SLR) was performed. The proposed guidelines for SLR studies from Kitchenham (2004) were followed. The SLR steps are applied in the following order:

- Defining research questions
- Specifying search keyworks (inclusion criteria) and search method
- Screening titles, abstract, and conclusions to find irrelevant studies
- Reading carefully all the selected studies



Independent collaboration scenario in assembly systems.

Sequential collaboration scenario in assembly systems.

Simultaneous collaborative scenarios in assembly systems.

Supportive collaborative scenarios in assembly systems.

Fig. 3 Collaboration scenarios (Zhang et al, 2021b)

- Using both forward and backward snowball approaches
- Categorizing, summarizing, and reporting the results to answer the research questions.

Research questions

The first step of the SLR study is defining the research questions. The following questions were selected as the research questions of this study because answering these questions can help researchers to better understand the current situation around cobots implementation and the open questions in this field.

RQ1: What are the performance criteria used in studies related to the implementation of cobots?
RQ2: How many studies considered each collaboration scenario?
RQ3: What are the achievements of each study?
RQ4: What are the open questions about implementation of cobots?

Search and selection strategy

In order to find the papers related to the human-cobot collaboration, two online databases, Scopus and ISI Web of Science, were used.

Inclusion criteria

A combination search expression was used in Scopus and Web of Science database to conduct a systematic literature review on the implementation of cobots in manufacturing systems. The relation between search expressions is drawn in Fig. 4.

By using the defined search expressions and the relation between them, 237 papers were found in both databases.

Exclusion criteria

In the first step, non-English language articles were excluded from the papers. In the next step, the duplicated articles were removed. A two-step systematic approach was applied to extract the irrelevant articles: (1) examining the title, reading the abstract, and conclusions; (2) a full paper reading was considered if the title, abstract, and conclusions could not provide sufficient information about the paper's relevance. All papers not respecting at least one of the following conditions were excluded from the analysis:

- The article does not fit the considered research questions.
- Humans were not considered.
- Cobot is not considered specifically.
- Not related to the manufacturing system.

After the full reading of papers, 183 papers were selected for analysis. Additionally, a forward and backward snowball approach was realised providing 19 papers. All the search and selection processes are described in Fig. 5.

Classification

To classify the final 201 papers, the following dimensions were considered for the analysis of each paper's research questions, results, and conclusions (see Appendix Table 5):

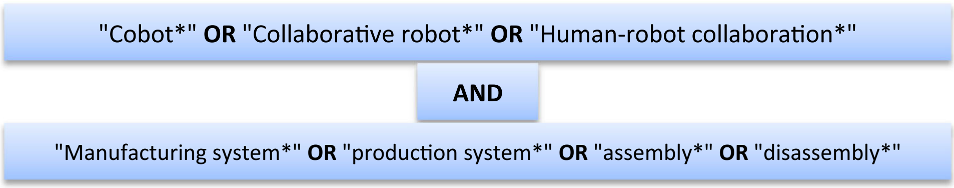


Fig. 4 Keywords and relations for search in databases

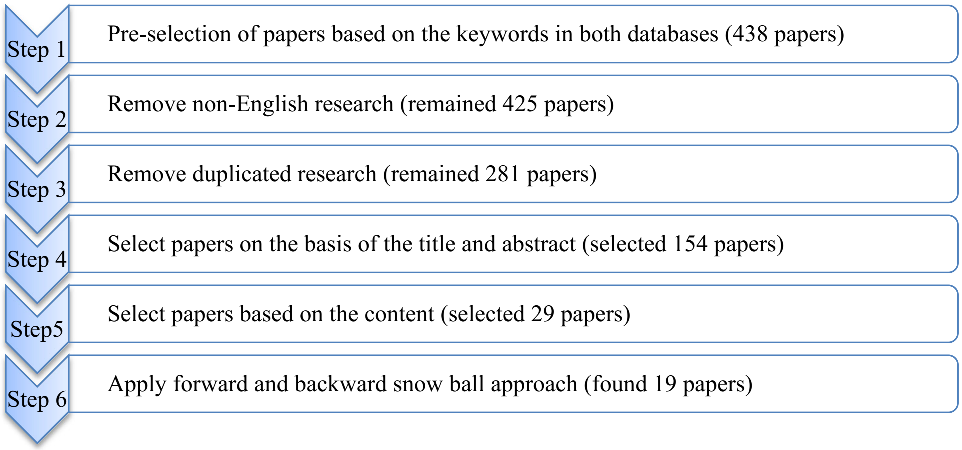


Fig. 5 Search and selection steps

1. Subject of study: design, programming, and/or operation (as explained in Section “Subject of study”).
2. Methodology (key proposition): mathematical approach, mathematical modelling, simulation, framework, comparative case study, or other.
3. Performance criteria: safety, cost, flexibility, productivity, ergonomic, or quality.
4. Human-cobot collaboration type: independent, sequential, simultaneously, and supportive (as explained in Section “Collaboration scenarios”)

Descriptive analysis

In this section, some descriptive analyses related to selected articles were presented. In the next section, the main results of the systematic literature review were addressed. Based on the Scopus database, more than 95% of papers in the field of collaborative robots have been published after 2010. As a preliminary analysis of the published papers filed on cobots in the Scopus database, two networks were elaborated on the most frequent keywords used in all the articles using VOSviewer software (see Fig. 6 and Fig. 7).

Keywords classifications

In Fig. 6, the most frequent keywords are classified based on their relationship in articles. The auto classifier distinguished three different classes. As can be understood from the network and color classification, red color keywords are mostly related to the computer science and programming aspect of cobots, such as deep learning, augmented reality, and simulation. The green color keywords are mostly related to the robotics and design phase of cobots, such as physical human–robot interaction, force control, and motion planning. Additionally, the blue color keywords are mostly related to safety and risk management, such as ergonomic, safety, collision avoidance, and risk assessments.

The most frequently used keywords in cobot studies were “Collaborative robots” and “assembly” which were classified in the green class, mainly related to the robotics and design phase of cobots. This is consistent with the findings from Fig. 1 and Appendix Table 5, which show that most studies until now have been focused on the robotics and computer science aspects of cobots. As inferred from the classification shown in Fig. 6, the majority of the most-used keywords are related to the design and programming phase. However, there are some categorizations and relationships that deserve further attention. For example, "trust" was categorized in the red class, which is closely related to programming. This is because most researchers have attempted to increase trust between humans and cobots by providing better and more reliable programming. "Safety" is one of the most frequently used keywords, alongside “Collaborative robots”, "human–robot collaboration", and "industry 4.0″. It is also connected to both the design and programming phase. "Sensors” is categorized in the programming class, but it is well connected to both other classes due to its importance in designing safe human–robot collaboration.

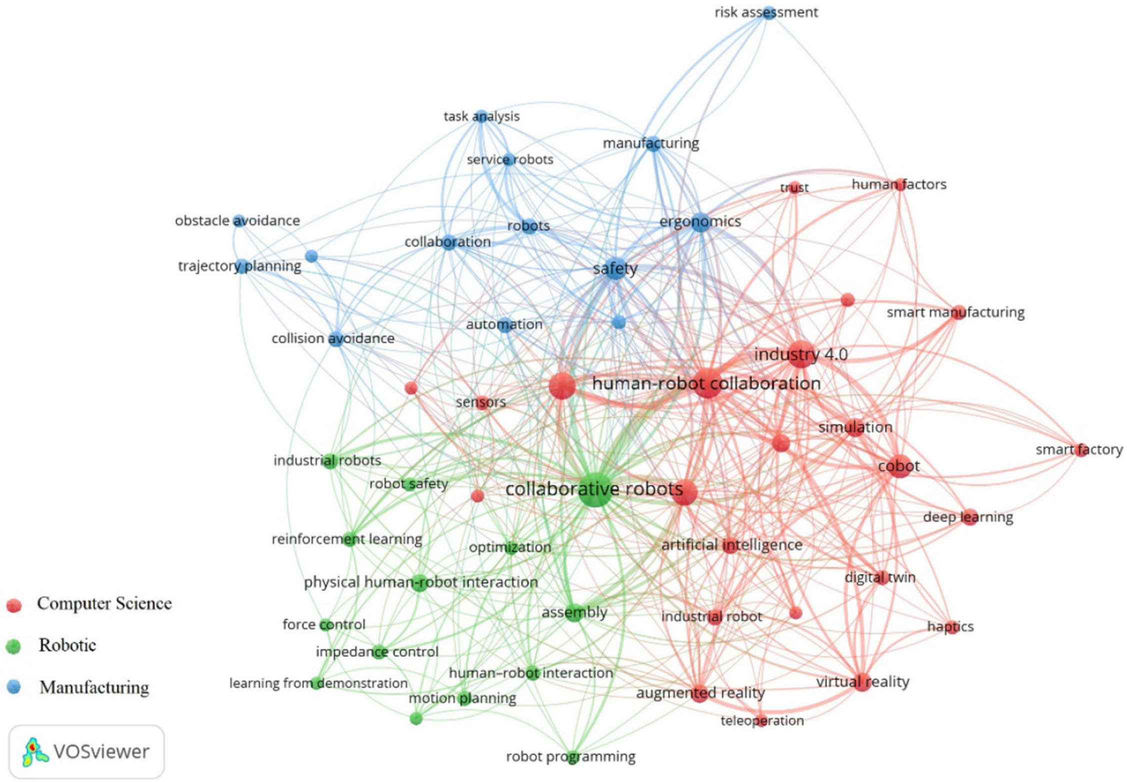


Fig. 6 Clustering of co-occurrence keywords network of the 2251 papers (Scopus Database) using VOSviewer

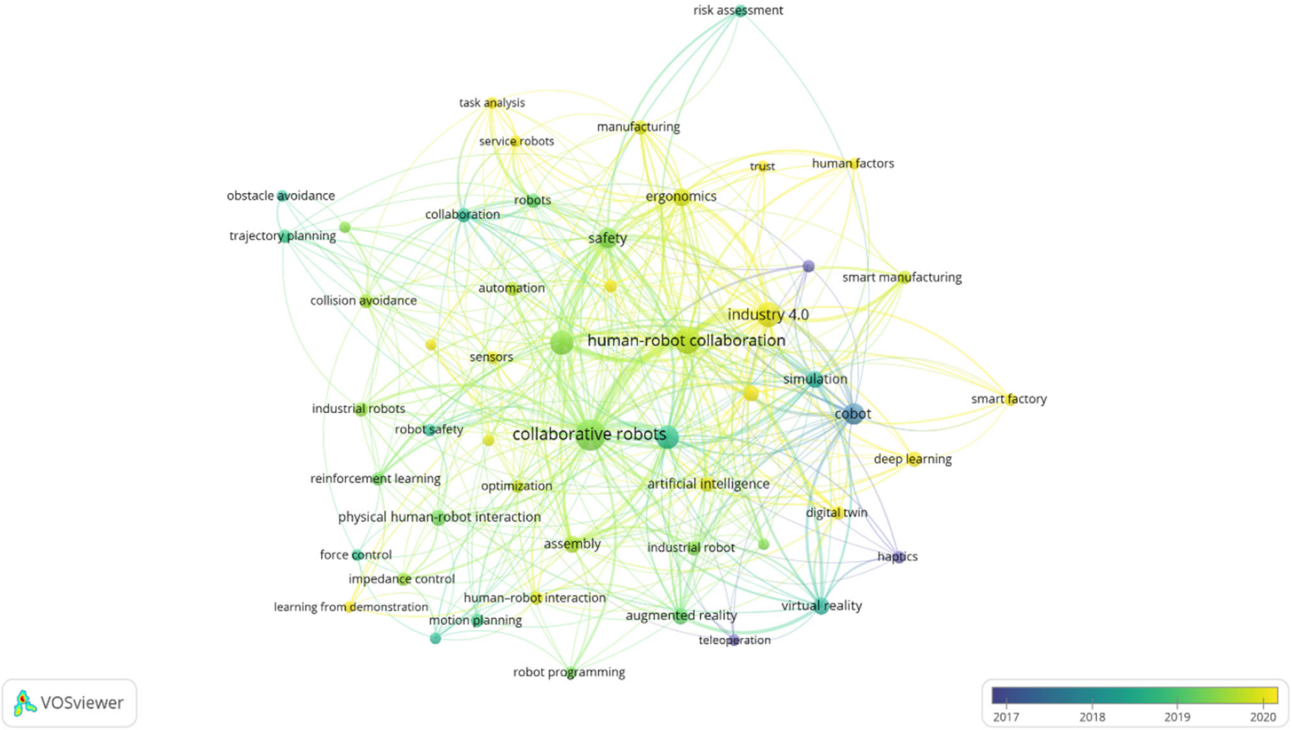
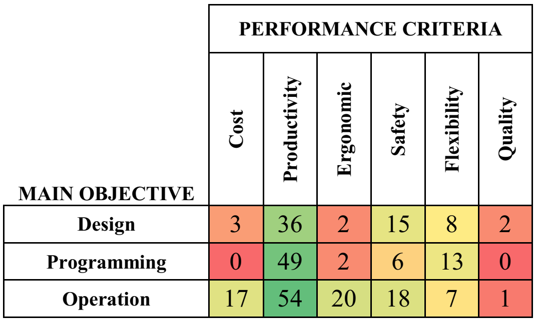


Fig. 7 Publication year demonstration of co-occurrence keywords network of the 2251 papers (Scopus Database) using VOSviewer

Table 1 Frequency of using each performance criterion for each objective



	PERFORMANCE CRITERIA					
MAIN OBJECTIVE	Cost	Productivity	Ergonomic	Safety	Flexibility	Quality
Design	3	36	2	15	8	2
Programming	0	49	2	6	13	0
Operation	17	54	20	18	7	1

Colors represent the relative values in the data, with dark green indicating higher values, yellow indicating intermediate values, and dark red indicating lower values.

Keywords timeline

In addition to the keyword classifications, the keyword timeline in Fig. 7 can also provide insights into the general trends in recent years in the field of cobots. The timeline shows the evolution of the keywords used over time, and it can be seen that there is a shift in the research focus from older keywords related to programming and safety, to more recent keywords related to robotics and design phase, safety, ergonomics, and the incorporation of new technologies such as digital twins, deep learning and smart factory. This indicates a growing trend towards improving the functionality, safety and efficiency of cobots, and incorporating new technologies in the design and operation of cobots. Nearly 30 percent of the top-most repeated keywords belong to papers published in the past 2 years, and more than 90 percent of the top-most repeated keywords belong to papers published in the past five years (see yellow and green nodes in Fig. 7). As seen in Fig. 7, the three oldest keywords among the top repeated keywords are "Cobot", "Haptics", and "Teleoperation". These keywords are categorized in the programming class. The next generation of keywords, represented in green in Fig. 7 and related to years between 2018 and 2020, are mostly related to the robotics or design phase of cobots and safety such as "motion planning", "force control", "impedance control", "collision avoidance", and "obstacle avoidance". "Trust", "service robots", and "ergonomics" from the safety and ergonomic class, and "digital twins", "deep learning", and "smart factory" from the programming class are the most recent keywords used frequently in studies related to cobots. This indicates that the research focus has shifted towards improving the functionality, safety and efficiency of cobots and incorporating new technologies such as digital twins and deep learning in the design and operation of cobots.

Figure 7 also highlights an important outcome. It shows a general shift in research topics related to cobots. The oldest frequent keywords were mostly related to creating a safe and usable collaboration system. A more detailed analysis shows that most of them were frameworks for designing human–robot collaboration or aimed to demonstrate the benefits of cobots for industries. As industries become more familiar with the benefits and safety of cobots, researchers began to focus on designing more efficient systems and improving the functionality of cobots. This shift in research focus reflects the growing acceptance and integration of cobots in industries and also the recent interest in human factors and ergonomics aspects.

Frequency analysis

A Pivot table based on the performance criteria and the main study's objective for all 201 selected articles clearly shows the frequency of research in each field (see Table 1). As shown in the table, productivity was the most frequently considered performance criterion in the articles to examine the production system. This factor alone is considered in more than 60 percent of articles. Safety and flexibility are the other two frequent performance criteria in literature. Quality as the performance criterion was considered just once in the previous studies.

Table 1 showed that performance criteria were not used evenly across different fields. For example, papers that focus on design or programming mainly consider productivity, flexibility, and safety of the collaborative system. One reason for this could be that in these types of studies, the main goal is to enhance the performance of cobots rather than the system as a whole. On the other hand, to evaluate the cost of a collaborative system, it is necessary to consider the entire system. However, in the operation phase, except for productivity and flexibility, other performance criteria are used almost evenly. The number of studies that consider flexibility as a performance criterion is low, mainly due to the difficulty of evaluating flexibility using quantitative measures.

Results of the systematic literature review

Studies in the design and programming category usually try to improve cobots from the mechanical or programming aspect of view. However, the main target of our study is considering cobots from a management aspect of view. Therefore, this section analyses only papers belonging to the operation class (the subject of study is operation).

Since the focus of this study is on the operation phase, a more detailed analysis of the corresponding contributions is provided in Appendix Table 6 regarding this phase. In addition to the methodology and performance criteria, Appendix III summarizes the main problem addressed by each study. This provides a better understanding of the specific challenges that researchers are addressing and what they propose facing that. This facilitates a more comprehensive understanding of the field and the progress that has been made in addressing the key issues related to human–robot collaboration in manufacturing systems.

Context of performance assessment

The first aspect to consider when examining the problem definitions in different studies is the context of performance analysis. Based on the selected articles, it is possible to categorize the context of performance analysis into several classes.

Designing collaborative assembly line

As shown in Table 2, the majority of studies belong to this class. The first studies tried to provide frameworks for designing a collaborative assembly line. Matthias et al. (2011) were the first to propose a framework for designing a collaborative assembly line, and as expected, safety was the considered performance criterion. Afterwards, other studies were published with different performance criteria (Djuric et al., 2016; Schonberger et al., 2018; Cencen et al., 2018; Serebrenny et al., 2019a; Jepsen et al., 2021; Gervasi et al., 2022). After several framework studies, Gil-Vilda et al. (2017) evaluated the performance of a real collaborative assembly line in a comparative case study. Other examples include Wang et al. (2019), D'Souza et al. (2020), Inoue et al. (2021), Sordan et al. (2021), and Navas-Reascos et al., (2022a) with different performance criteria. Simulation was the next methodology used in this class (Malik et al., 2020, 2021; Thomas et al., 2018; Zhu et al., 2022). Although mathematical modeling was the last methodology used for this class, it was the most frequently used methodology for collaborative assembly line balancing. The first study in this category was conducted by Weckenborg & Spengler (2019), who considered cost and ergonomics as performance criteria. However, due to the long history and strong literature in proposing mathematical models for manual assembly line balancing problems, numerous studies have developed new mathematical models to design and optimize a collaborative assembly line (i.e.,Boschetti et al., 2021a, 2021b; Dalle Mura & Dini, 2019; Sadik et al., 2017; Weckenborg et al., 2020; Cohen et al., 2022; Zhu et al., 2022; Abdous et al., 2022).

Designing collaborative disassembly line

Early developments in collaborative assembly lines on one hand, and the advantages of using cobots in hazardous or dangerous tasks on the other hand, have led many researchers to focus on designing collaborative disassembly lines. In this field, researchers have mostly utilized existing frameworks or simulation models to design collaborative systems. For instance, Xu et al. (2021) provided a mathematical model to balance a collaborative disassembly line by considering both productivity and safety. Due to the hazardous nature of some tasks in the disassembly line, the majority of studies have considered safety as a crucial performance criterion for evaluating the collaborative system's design. For example, Lee et al. (2022), Deniz & Ozcelik (2023), and Liao et al. (2023) all attempted to assign the most hazardous tasks to cobots to increase the safety of the disassembly line for human workers. While most studies in this area used mathematical models to balance the collaborative disassembly line, Liu et al. (2022a) compared different reinforcement learning methods to explore the feasibility of designing a collaborative disassembly line.

Task allocation

On first glance, task allocation is a component of designing a collaborative assembly line problem, so it is best categorized as part of the first class. However, new approaches to human–robot communication, such as optical sensors, augmented reality (AR), and motion prediction systems, are aimed at addressing the lack of cognitive ability of cobots (Li et al., 2022). Consequently, in addition to traditional task allocation, real-time task allocation or scheduling has become more popular. Online scheduling allows for immediate task allocation to workers and cobots based on real-time data, such as production rate, task completion time, and machine status. This ensures that the right worker or cobot is assigned to the right task at the right time, thereby optimizing workflow and reducing idle time. Despite the underdeveloped infrastructure for seamless communication between humans and cobots, various researchers have investigated this topic. Petzoldt et al. (2022) and Pabolu et al. (2022) have proposed a framework for dynamic task assignment in a collaborative assembly line and have considered productivity as the performance criteria. Zhang et al., (2022a, 2022e) and Lanzoni et al. (2022) have employed AI approaches in their studies. Li et al. (2022) provides a model for calculating online fatigue in an assembly line and reducing fatigue levels by assigning tasks to cobots.

Table 2 Performance assessment methods and used criteria for cobots operation phase

		Considered criteria				
		Cost	Productivity	Ergonomic	Safety	Flexibility
Method	Mathematical modelling	Weckenborg and Spengler (2019), Dalle Mura and Dini (2019), Dalle Mura & Dini (2022), Li et al., (2021c), Vieira et al. (2022), Zhu et al. (2022), Dalle Mura and Dini (2022), Deniz & Ozcelik (2023), Xiang et al. (2022), Liao et al. (2023), Abdous et al. (2022)	Sadik et al. (2017), Casalino et al., (2019a, Fager et al. (2019), Zhang and Jia (2020), Weckenborg et al. (2020), Xu et al. (2021), Boschetti et al., (2021a), Cohen et al. (2022), Li et al., (2021c), Vieira et al. (2022), Boschetti et al., (2021b), Almasarwah et al. (2022), Nourmohammadi et al. (2022), Keshvarparast et al. (2022), Zhu et al. (2022), Lee et al. (2022), Antonelli and Aliev (2022), Li et al. (2022), Stecke and Mokhtarzadeh (2022	Weckenborg and Spengler (2019), Dalle Mura and Dini (2019), Dalle Mura & Dini (2022), Keshvarparast et al. (2022), Mura & Dini (2023), Dalle Mura and Dini (2022), Li et al. (2022c), Stecke and Mokhtarzadeh (2022), Abdous et al. (2022)	Xu et al. (2021), Lee et al. (2022), Deniz & Ozcelik (2023), Liao et al. (2023)	Weckenborg et al. (2020)
	Mathematical approach	Accorsi et al. (2019), Gualtieri et al. (2019), Belhadj et al. (2022)	Zhang et al., (2021b), Belhadj et al. (2022)	Gualtieri et al. (2019), Zhang et al., (2021b)	Gualtieri et al. (2019)	
	Framework		Djuric et al. (2016), Lamon et al. (2018), Serebrenny et al., (2019a), Malik et al. (2020), Petzoldt et al. (2022), Gervasi et al. (2021), Pabolu et al. (2022)	Lamon et al. (2018); Gervasi et al. (2021)	Matthias et al. (2011), Malik et al. (2020), Berger et al. (2020)	Thomas et al. (2018), Serebrenny et al., (2019a, 2019b), Malik et al. (2020)

Table 2 (continued)

	Considered criteria				
	Cost	Productivity	Ergonomic	Safety	Flexibility
Simulation	Zhu et al. (2022)	Cohen and Shoval (2020), Wojtynek and Wrede (2020), Banziger et al. (2020), Malik et al. (2021), Ibanez et al. (2021), Petzoldt et al. (2022), Zhu et al. (2022), Wang et al. (2022a), Boschetti et al. (2022), Lorenzo et al. (2022)	Banziger et al. (2020), Navas-Reascos et al., (2022a)	Boschetti et al. (2022), Gualtieri et al. (2022)	Thomas et al. (2018)
Comparative case	Karaulova et al. (2019)	Gil-Vilda et al. (2017), Quenehen et al. (2019), Realyvásquez-Vargas et al. (2019), Wang et al. (2019), Karaulova et al. (2019), Gualtieri et al., (2020b), Malik and Brem (2021), Sordan et al. (2022), Ibanez et al. (2021)	Realyvásquez-Vargas et al. (2019), Karaulova et al. (2019), Gualtieri et al., (2020b), Navas-Reascos et al., (2022a)		Inoue et al. (2021)
Other	Peron et al. (2022)	Sadik and Urban (2017b), Gualtieri et al., (2020a), Rega et al. (2021), Gjeldum et al. (2022), Peron et al. (2022), Zhang et al. (2022b), Liu et al. (2022a)	Gualtieri et al., (2020a), Lanzoni et al. (2022)	Bruno and Antonelli (2018), Malik and Bilberg (2019a), Gualtieri et al., (2020a), Rega et al. (2021)	Jepsen et al. (2021)

Workspace design

Workstation design is a critical component in a collaborative assembly line that affects both the safety and productivity of workers. The design must ensure that the work environment is ergonomic and safe for both workers and cobots to minimize the risk of accidents, injuries, and musculoskeletal disorders (Gualtieri et al., 2022). An effective workstation design can enhance workflow efficiency and reduce the time required to complete tasks, thereby minimizing bottlenecks, and streamlining the workflow. Moreover, an adaptable and flexible workstation design is crucial for the long-term success of a collaborative assembly line (Gervasi et al., 2021). The design should accommodate changes in product design, production volumes, and other variables that impact the assembly line's operation. This requires a modular design that enables the quick and efficient reconfiguration of workstations to meet changing needs. In summary, an optimal workstation design is essential for achieving a safe, efficient, and flexible collaborative assembly line. To design a workspace, researchers have proposed frameworks and simulation models. Malik & Bilberg (2019a) proposed a framework for designing a workspace and the positions of cobots, tools, and objects for a safe collaborative system. Malik et al. (2020) provided a new framework for designing productive, safe, and flexible collaborative workspaces and proposed a simulation model to validate it. Wojtynek & Wrede (2020) also developed a new simulation model for collaborative workspaces to design a productive workspace.

Task classification

Task classification is an important aspect of collaborative assembly lines as it helps to identify which tasks are best suited for humans and which tasks are more appropriate for collaborative robots. This ensures that each worker and cobot is performing tasks that are safe and appropriate for their respective capabilities, ultimately improving efficiency and productivity. Task classification can also optimize the allocation of tasks by assigning them based on workers' and cobots' respective strengths and abilities, enabling the assembly line to operate more smoothly. Additionally, it can aid in designing tasks that are compatible with collaborative systems. In 2018, Bruno & Antonelli used an AI classification tool (Decision Tree) to develop a task classification model, considering features such as precision and tools required (Bruno and Antonelli, 2018). In 2019, Antonelli & Bruno extended their work by adding more features to their classification models, resulting in a more complete classification (Antonelli and Bruno, 2019).

Performance criteria

These sections analyse the contributions according to the evaluation criteria used. Five performance criteria have been used in the literature of Cobots operation class: safety, cost, flexibility, productivity, and ergonomics.

Cost

Costs can be considered both in the design phase and the operational phases. Some researchers are interested in the reduction of the cost of designing or manufacturing of cobots. In the operational phase, researchers aim to reduce the cost of implementation of new cobots in a manufacturing system, cost of maintenance, cost of collaboration, or cost of production. Weckenborg & Spengler (2019) and Dalle Mura & Dini (2019) developed a new cost-oriented mathematical modeling for the collaborative assembly line. Accorsi et al. (2019) studied the economic feasibility of using cobots in the food packaging industry. Gualtieri et al. (2019) developed a new evaluation methodology for redesigning a pure manual assembly line into a collaborative assembly line. Karaulova et al. (2019) analyzed an assembly line after establishing cobots. Dalle Mura & Dini (2022), Zhu et al. (2022), Dalle Mura & Dini (2022), Abdous et al. (2022), and Belhadj et al. (2022) developed a mathematical model and considered cost as one of the objective functions. Li et al., (2021c) proposed a bi-objective mathematical model with the second objective function being the minimization of the cost of the assembly line. Fager et al. (2021) calculated the cost-effectiveness of using Cobots in a picking system. Vieira et al. (2022) developed a two-level mathematical model with a detailed discrete-event simulation model. Peron et al. (2022) proposed a Decision Support System (DSS) for implementing assistive technologies in assembly line which cost is one of the performance criteria evaluated. Lee et al. (2022), Liao et al. (2023), and Deniz & Ozcelik (2023) developed a mathematical model for collaborative disassembly line which one of the objective functions is cost. Xiang et al. (2022) developed a mathematical model for a multi-product u-shaped collaborative assembly line and tried to optimize cost of production.

Productivity

Productivity is the most used performance criterion in the 53 selected papers and it was considered in both the design and operational phases. Lamon et al. (2019) related the increased productivity with minimizing cobots' fatigue. Wang et al. (2019) showed the improvement in productivity by using cobots in a real case study. Serebrenny et al., (2019a), Gualtieri et al., (2020b), and Gervasi et al. (2021) suggested a framework to improve productivity. Zhang and Jia (2020), Weckenborg et al. (2020), Boschetti et al., (2021a), Cohen et al. (2022), Boschetti et al., (2021b), Nourmohammadi et al. (2022), Antonelli & Aliev (2022), and Almasarwah et al. (2022) used mathematical models to maximize productivity.

Wojtynek & Wrede (2020), Malik et al. (2021), and Wang et al. (2022a) used simulation to evaluate productivity improvement by implementing cobots in assembly lines. Malik et al. (2020) elaborated a framework to simulate the designed assembly line with virtual reality to evaluate the productivity of the assembly line. Gualtieri et al., (2020a) provided a guideline for designing a product that improves the productivity of the collaborative assembly lines. Xu et al. (2021), Li et al., (2021c), Vieira et al. (2022), Li et al. (2022), and Keshvarparast et al. (2022) developed a multi-objective mathematical model in which one of the objective functions was to improve productivity. Zhang et al., (2021b) applied a new metric, a combination of productivity and ergonomics, to design a collaborative assembly line. Malik & Brem (2021) proposed a framework to use digital twins to simulate collaborative assembly lines. Rega et al. (2021) developed a knowledge-based approach to optimize the productivity of assembly lines. Sordan et al. (2022) used a case study to evaluate the workers' idle time in an assembly line balancing problem. Gjeldum et al. (2022) proposed a 3-level decision support system for task-sharing to improve productivity. Ibanez et al. (2021) and Banziger et al. (2020) developed new simulation software to design a collaborative assembly line to evaluate the productivity of the designed assembly line. Petzoldt et al. (2022) proposed a framework for dynamic task allocation and validate the effectivity of the framework by using simulation model. Peron et al. (2022) proposed a Decision Support System (DSS) for implementing assistive technologies in assembly line which productivity is one of the performance criteria evaluated. Zhang et al. (2022b) used Reinforcement Learning for online task sequencing in a collaborative assembly line which considered productivity as a performance criterion. Pabolu et al. (2022) proposed a digital twin-based framework for evaluating a collaborative assembly line before implementation. Liu et al. (2022a) compare two different Reinforcement Learning methods and the solutions provided by each of them based on productivity evaluation.

Ergonomics

Collaborative systems such as cobots have mainly two kinds of ergonomic issues, cognitive and physical. Cognitive ergonomic issues refer to mental stress and psychological discomfort, which could be felt by operators while collaborating with robots. Papers that have considered cognitive ergonomic issues are rare. Most of the papers considered ergonomics similarly to practices for the assembly lines by considering fatigue, energy expenditure, etc. Realyvásquez-Vargas et al. (2019) tried to reduce the Occupational risk factors (e.g., awkward postures, excessive effort, and repetitive movements) in a real case study by implementing cobots. Weckenborg & Spengler (2019) used the mean work rate as an ergonomic constraint in a new cost-oriented mathematical modeling for collaborative assembly lines. Dalle Mura & Dini (2019) considered tasks' energy expenditure in cost-oriented mathematical modeling. They ensure that assigned tasks' energy expenditure for each worker should not pass the physical limitation of the worker. Gualtieri et al., (2020a) and Gualtieri et al., (2020b) provided a guideline for designing a product that improves the ergonomics of the collaborative assembly lines. Zhang et al., (2021b) used a new metric, the combination of productivity and ergonomics, to design a collaborative assembly line. Dalle Mura & Dini (2022) developed a mathematical model and considered a combination formula of cost and ergonomics as the objective function. Banziger et al. (2020) proposed a simulation method to allocating task to human or robot. Keshvarparast et al. (2022), and Dalle Mura and Dini (2022), developed a multi-objective mathematical model that one of the objective functions was minimizing the total physical workload for each worker. Li et al. (2022) considered fatigue in a collaborative assembly line balancing. Navas-Reascos et al., (2022a) evaluate physical strain and muscular activities in a collaborative assembly line and compare it with the previous manual assembly line.

Safety

A collision-free collaboration system is a safe collaboration system (Rojas et al., 2021). Opposite to industrial robots, which are usually isolated while workers being restricted from approaching or interacting with the robots, workers and cobots can be assigned to a workstation freely. As a result, worker safety was the first issue that the researchers focused on. That is why, throughout the design process of a cobot, safety is a critical consideration, and the International Organization for Standardization (ISO) sets specific guidelines for safe, collaborative work (ISO 10218-1 and ISO 10218-2). Safety-rated monitored stop, hand guiding, speed and separation monitoring (SSM), and power and force limiting are among the four collaboration scenarios addressed by the safety standards (Costanza et al., 2021). Matthias et al. (2011) and Malik & Bilberg (2019a) provided a framework to ensure the safety of workers in a collaborative system. Gualtieri et al., (2020a) provided a guideline to design a product that is compatible with the safety procedures of the collaborative assembly lines. Malik et al. (2020) provided a framework to simulate the designed assembly line with virtual reality to evaluate the safety of the assembly line. Berger et al. (2020) introduced the "safety Bubble" concept to ensure the safety of workers. Xu et al. (2021), by referring to ISO/TS 15066, ensure the safety of workers by reducing the speed of cobots regarding the distance between worker and cobot.

Rega et al. (2021) developed a knowledge-based approach to optimize the productivity and safety of assembly lines. Lee et al. (2022), Liao et al. (2023), and Deniz & Ozcelik (2023) proposed a mathematical model to safety of human worker in a hazardous disassembly environment.

Flexibility

Flexibility, like safety, is an indicator that researchers usually study in a qualitative way in the cobots design phase. In the literature, two types of flexibility are stated. First, flexible cobot which refers to how fast the cobots can reprogram or mobilize for new procedures; second type, flexible collaboration is about the number of tasks that cobots can possibly do in a given time (design of work cell). The term "flexible cobot" is usually considered in the design phase of a cobot. Cobot designers aim to design and develop a new cobot that can perform various activities by considering flexibility during the design process. "Flexible collaboration" refers to the manufacturing system design. Malik et al. (2020) provided a framework to simulate the designed assembly line with virtual reality to evaluate the flexibility of the assembly line. Jepsen et al. (2021) proposed a new framework to design a flexible assembly line. Inoue et al. (2021) used mobile cobots to transfer products in an assembly line to improve flexibility.

Papers' methodology and adopted performance criteria

Table 2 presents an analysis of the frequency of different performance criteria and methodologies in the literature on cobot operation. The operational phase of cobots is a critical aspect that must be considered to ensure their successful implementation. The results show that most of the studies that developed mathematical models used cost and productivity as their primary performance criteria. However, the number of papers that considered cost as the performance criterion in other methodologies is very low. For example, to best of our knowledge there is not any framework which considered cost as the performance criteria. This finding indicates that cost is not a primary concern in other methodologies. In contrast, productivity is the most frequent performance criterion used in the literature. More than half of the papers considered productivity as the performance criterion, which highlights the importance of improving cobot productivity in the operational phase. The analysis also shows that ergonomics is a relatively neglected performance criterion in cobot operation studies. This result suggests that researchers need to pay more attention to ergonomics in the operational phase to ensure worker well-being. Moreover, the results indicate that safety and flexibility are rare performance criteria in mathematical modeling and mathematical approach methodologies. Instead, most papers that focused on safety and flexibility used framework approaches. Safety is also an interesting topic for review papers, suggesting that there is a need for more research on this topic. The analysis further shows that studies in design or programming classes mainly used simulations to improve the safety of cobots. Simulations were infrequent in papers that considered productivity as the performance criterion. This finding implies that researchers need to incorporate simulations into their studies to improve cobot safety.

In conclusion, the analysis of Table 2 provides valuable insights into the frequency of different performance criteria in cobot operation studies. The results highlight the need for more research on ergonomics, safety, and flexibility in cobot operation. Researchers should also consider using simulations to improve cobot safety and productivity during the operational phase.

Human-cobot collaboration scenarios

Studying cobots requires a deep understanding of the collaboration scenario, which refers to the division of tasks among team members. This is a crucial aspect of the operation phase (e.g. assembly line design) process, as the collaboration scenario chosen can have a significant impact on the planning, efficiency, and overall outcome of the production system (Antonelli & Bruno, 2019). Keshvarparast et al. (2022) have introduced a mathematical model that provides insights into how three different collaboration scenarios (sequential, simultaneous, and supportive) can impact the design and cycle time of collaborative assembly lines.

However, research that considered collaboration scenarios is limited. Table 3 shows that, more than 43% of the 58 selected papers do not consider collaboration scenarios. This is a concerning issue, as the failure to consider the collaboration scenario can lead to inefficiencies, longer cycle times, and decreased productivity. The majority of the studies that failed to consider collaboration scenarios only provided frameworks or comparative case studies. Moreover, studies that provided mathematical models considered at least one scenario, the number of studies that considered multiple scenarios is low, likely due to the complexity of considering all the different scenarios and their varying requirements and assumptions. Although all the studies that provided mathematical models considered at least one scenario, the number of studies that considered multiple scenarios is low, likely due to the complexity of considering all the different scenarios and their varying requirements and assumptions. It is worth mentioning that the specific needs of the industry, the type of tasks being performed, and the available resources, among other factors, can affect the choice of the collaboration scenario. Studying the application sector of the cobots could help practitioners in this matter.

Table 3 Frequency analysis of collaborative scenarios based on methodology

		Not considered	In	Se	Si	Su	In + Se	In + Si	In+ Su	Se + Si	Se + Su	Si + Su	In + Se + Si	In+ Se + Su	Se + Si + Su	all
Key Proportion	**Mathematical modelling**	0	0	4	5	2	1	7	2	1	3	0	0	0	1	0
	Mathematical approach	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0
	Framework	10	2	0	1	1	0	0	0	0	0	0	0	0	0	0
	Simulation	3	2	0	2	0	0	1	1	0	0	0	0	0	0	0
	Comparative case	6	1	2	1	0	0	0	0	1	1	0	0	0	0	0
	Others	10	0	1	0	0	0	1	1	0	0	0	1	0	0	0
Total		30	6	7	9	3	2	10	4	2	4	0	1	0	1	0

Colors represent the relative values in the data, with dark green indicating higher values, yellow indicating intermediate values, and dark red indicating lower values.

**In* Independent, *Se* Sequential, *Si* Simultaneous, *Su* Supportive

Cobots' application industrial sectors

The application sector of cobots is also an important aspect of research, as it helps us understand how these robots can be used in different fields, such as warehouse, automotive, and precision tasks. Cobots are designed to work alongside humans, and they have the potential to increase productivity, improve safety, and reduce costs. However, the specific requirements of different industries and tasks may vary, which is why it is important to understand the task types and industries where cobots are being used. For example, in a warehouse, cobots may be used for picking and packing, while in automotive manufacturing, they may be used for assembly or welding. In precision tasks, cobots may be used for tasks that require a high degree of accuracy, such as inspection or quality control. Understanding the specific task types and industries where cobots are being used can help identify the potential benefits and challenges of using cobots in those applications. The studies included in Appendix Table 6 explore the use of cobots in various positions and for different types of tasks, but they do not provide information on the specific task types or industries where cobots are being used. This lack of specificity highlights the need for more research to fully understand the capabilities and limitations of cobots in different applications. By identifying the specific requirements and challenges of different industries and tasks, researchers can develop cobots that are better suited to those applications, as well as identify areas where further research is needed.

In summary, the application sector of cobots is an important area of research, as it helps us understand how these robots can be used in different fields and for different types of tasks. The lack of specificity in the studies included in Appendix Table 6 highlights the need for more research to fully understand the capabilities and limitations of cobots in different applications. This research can help identify the potential benefits and challenges of using cobots in specific industries and tasks and help develop cobots that are better suited to those applications. Ultimately, understanding the application sector of cobots is crucial to realizing their potential to improve productivity, safety, and cost-effectiveness in a wide range of industries.

Digital twins for assessing the performance of cobots

The performance evaluation approach or method could be also an important topic in the study of cobots. As a complementary technology, which is largely addressed in the Industry 4.0 context, the Digital Twins could be mentioned. Digital twins are virtual replicas of physical systems, products, or processes, created using sensors, IoT devices, and other data-gathering tools to capture real-time data that is used to create a digital representation (Grieves & Vickers, 2017). They have become increasingly important in manufacturing as they enable companies to test new products, optimize production processes, and reduce downtime. By simulating the behaviour of a physical system in a virtual environment, companies can better understand the system's performance and predict how it will respond to changes in the real world (Digital Twin Consortium, 2022). Digital twins are particularly useful in manufacturing where they are used to create a virtual representation of a product or system that can be tested and optimized before the physical product is built. This helps to reduce the time and cost associated with physical testing and prototyping (Nikolakis et al., 2019). They can also be used to monitor and optimize the performance of machines and production lines by gathering data from sensors and other sources to predict when maintenance will be required, reduce downtime, and improve overall efficiency (Zhou et al., 2020).

In collaborative systems where humans and robots work together to complete tasks, digital twins should be used to create a virtual representation of the system including both the human and robot components. This enables researchers to test different configurations and control strategies in a virtual environment before deploying the system in the real world (Fuller et al., 2020; Leng et al., 2021; Perno et al., 2022). To better understand the studies, a general categorization around digital twins is provided (see Fig. 8). As it can be seen in this figure, two different categories existed for studies; first, to develop a digital twin model for using in a collaborative system (Schmidt et al., 2022; Wang et al., 2022b; Yi et al., 2022); second, to use digital twins in a collaborative system.

Real-time monitoring

In some studies, a digital twin based real-time monitoring proposed for collaborative systems. Ye et al. (2022) designed an interface based on digital twins to improve the real-time task allocation controller in a collaborative system. Lorenzo et al. (2022) suggested a framework to use digital twins as real-time production planning. Both the studies used productivity as the performance evaluation criteria. Franceschi et al. (2022) proposed a framework to use digital twins detecting production failure in a real-time monitoring controlling system. In this study, quality was considered as the performance evaluation criteria.

Evaluating

In manufacturing, digital twins are especially beneficial as they enable the creation of a virtual model of a product or system that can be refined and tested before its physical counterpart is constructed. This approach assists in minimizing the expenses and time associated with physical testing and prototyping (Pizoń et al., 2022). Research that uses digital twins for evaluation in collaborative systems can be divided into three classes: (1) evaluating the performance of cobot in the design phase, (2) evaluating the interaction between human and cobot, (3) evaluating the performance of collaborative systems.

Evaluating the performance of cobot in design phase

Lu et al., (2022b) discussed the development of a digital twin-based framework for human–robot collaboration in manufacturing. The framework is designed to be generic and modular, allowing for easy customization and scalability. The authors suggest that this framework can facilitate effective collaboration between humans and robots, leading to improved manufacturing processes and productivity. Sun et al. (2021) proposed a digital twin driven framework to evaluate the cognitive and improve the performance of cobots.

Evaluating the interaction between human and cobot

Pizoń et al. (2022) explored the use of digital twins to evaluate the integration of cobots into manufacturing systems and analyse potential human–robot interactions. Furthermore, they identified some of the benefits that digital twins can bring to collaborative manufacturing systems. However, human digital twins are still very rare in literature and real examples of human/cobot digital representations are urgently needed in the short future (Berti et al., 2022).

Evaluating the performance of collaboration system

Malik et al. (2020) used Augmented Reality (AR) to provide a complete simulation to evaluate productivity, flexibility, and safety for a collaborative assembly line. Pabolu et al. (2022), and Wang et al. (2022b) suggested a framework to evaluate the performance of a designed assembly line. Zhu et al. (2022) proposed a mathematical model for reconfiguration of assembly line to reduce cost of production and improve productivity then, they used digital twins for evaluating the new design before implementing. Choi et al. (2022) presented a mixed reality system that enables safe collaboration between humans and robots using deep learning and digital twin generation. The system integrates real-world and virtual environments to provide a comprehensive and immersive experience. The authors suggest that this system can improve collaboration and safety in various industrial applications.

Overall, digital twins are an important tool for improving human–robot collaboration in manufacturing and other applications. As the technology continues to evolve, digital twins are likely to become even more important in collaborative systems, enabling humans and robots to work together more effectively and efficiently (Grieves & Vickers, 2017; Zhu et al., 2022; Sun et al., 2021), inside a socio-technical ecosystem.

Research agenda and conclusions

According to the performed literature review, Cobots have attracted much attention in the previous 8 Years (from 2014 to 2022). Although the first publication in this field was published in 1994, most subsequent articles have concentrated on the mechanical aspects of enhancing Cobots, while the interaction between humans and Cobots appeared only recently

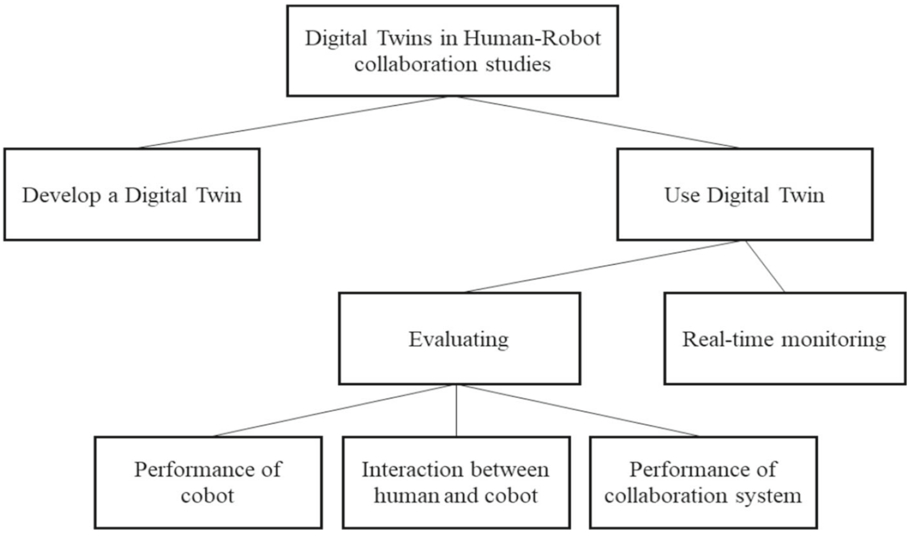


Fig. 8 Digital twins in human–robot collaboration studies

(Cencen et al., 2018). One of the most important reasons for this shifting in the research focus is the safety issues that arise when Cobots are implemented in a human–machine sharing environment (Costanzo et al., 2021). Since the robots were originally isolated in the manufacturing system, the safety procedures were limited only to some specific situations. After introducing the Cobots to the industries, the safety procedure needs to change significantly (Malik & Bilberg, 2019a). With time, new Cobots have been designed in a better way and the safety, flexibility, and productivity of new Cobots are considerably higher than the old ones (Romiti et al., 2021; Lee et al., 2022; Yi et al., 2022). However, as our study has shown previously, the number of studies in this field is still insufficient to cover all the questions and to consider the human factors in a comprehensive way. To identify open questions in the field of cobots and human–robot collaboration in manufacturing systems, the authors analysed all the selected studies and summarized the opinions of the authors in the conclusion of each study.

Hereafter, our findings are discussed more in detail around the major research areas that were emphasized by the authors because of their priority or potential for further investigations.

Performance assessment criteria

Based on the discussion provided in Tables 1 and 2, a set of performance indicators have been used to evaluate cobots. Productivity is the most used performance criterion to evaluate the performance of a collaborative system in all phases of the process, including the robotic, programming, and operation phases. Other studies have measured safety and flexibility indices in the robotic or programming phase, however, there appears a lack of studies concerning the assessment of safety and flexibility performance indices in the cobot operation phase. Additionally, most studies that have considered ergonomic, safety, and flexibility have provided only qualitative frameworks, and a lack of quantitative measures can be detected. In literature, there is a strong need for new quantitative approaches able to jointly measure the ergonomic, safety, and flexibility performances of a collaborative manufacturing system in all the phases of the manufacturing/assembly process.

Collaboration scenario

The most crucial difference between robots and Cobots lies in their ability to collaborate with humans. Real collaboration occurs when the supportive collaboration scenario is in play, where the worker and the Cobot work together to complete a task, resulting in the highest level of collaboration (Zhang et al., 2021b). However, as mentioned in Section "Flexibility" and summarized in Table 3, the number of papers that consider this scenario is still very limited. To fully understand the potential of the collaboration between humans and Cobots, it is essential to study different collaboration scenarios and compare them in real-world situations. There is also a lack of studies considering more than two collaboration scenarios together. This complexity makes it difficult to understand the interplay between different collaboration scenarios (Keshvarparast et al., 2022). Moreover, most of the existing methodological frameworks for designing collaborative assembly lines do not consider collaboration scenarios. Mathematical models, on the other hand, have shown that collaboration scenarios can lead to different optimal designs for assembly lines (Keshvarparast et al., 2022). Future research is needed not only to create new models and approaches but also for comparing different human-cobot collaboration scenarios in real-world situations, in order to fully validate the findings from mathematical models and theoretical studies in real settings. Different collaboration scenarios should also be compared and assessed according to various performance metrics, such as productivity, efficiency, and worker satisfaction.

Task designing and classification

With the introduction of collaborative robots, it is necessary to design tasks that are more suitable for human–robot collaboration (Rega et al., 2021). This means considering the unique capabilities and limitations of both humans and robots, and designing tasks that can be performed safely and efficiently by both (Gualtieri et al., 2020b). By doing so, one can take advantage of the strengths of both humans and robots and create a more effective and efficient collaborative process. However, the lack of sufficient research in this area which is shown in Appendix Table 6 means that many tasks are still being designed in the same way as before, without considering the potential benefits of human–robot collaboration. Therefore, it is essential that researchers focus on studying the differences between traditional task design and task design for human–robot collaboration. By understanding these differences, more effective methods for designing tasks, that are optimized for human–robot collaboration, can be developed. Furthermore, task categorization is also important for assigning tasks to humans or cobots and selecting the best collaboration scenario. This involves considering different aspects linked to each task and to the resource who will execute the task (Bruno & Antonelli, 2018) as task time, value-add time percentage, ergonomic workload, safety level, etc. By categorizing tasks according to specific parameters, it can determine if a task is best suited for human-cobot collaboration or should be performed exclusively by humans or robots (Antonelli & Bruno, 2019). This can help to support the operation manager decision making, optimize the collaborative process, improve performance, and ensure safety.

Workforce diversity

The importance of considering human factors in cobot-human collaboration cannot be overstated (Bogataj et al., 2019, Katiraee et al., 2021; Neumann et al., 2021). The fact that workers can have differing ages, genders, skills, and physical characteristics means that the impact of these factors on the overall production process and the human-cobot relationship must be thoroughly studied. The field of human–robot interaction has only just begun to address these issues. However, as it is mentioned in several new studies, there is much room for exploration and advancement (Schonberger et al., 2018; Gualtieri et al., 2020a; Dalle Mura & Dini, 2022; Petzoldt et al., 2022; Keshvarparast et al., 2022). The effect of differences in age, gender, physical measures, and skills on Cobot acceptability by humans must be explored. This will help us better understand how to design collaborative systems that consider the unique needs and preferences of each worker (Li et al., 2021c, Mura & Dini, 2023). When workforce diversity is considered, also different learning effects need to be investigated. Research on learning curves in collaborative systems is limited, leading to an incomplete understanding of the human–robot interaction and its impact on system performance. This highlights the need for further research in this area to gain insights into the differences in learning and forgetting curves based on worker diversity (Cohen et al., 2022). Understanding the impact of worker diversity on the learning and forgetting curve in collaborative systems can lead to increased efficiency, productivity, and worker satisfaction.

Ergonomic assessment and impact on injury reduction rate

The delegation of uncomfortable and heavy tasks to a collaborative robot has been suggested to improve the ergonomic quality of work by avoiding awkward postures or tiredness caused by repetitive load (Mateus et al., 2019). This approach can solve a multi-objective job allocation problem for humans and Cobots (Zhang et al., 2021b). However, there is limited research on the true ergonomic quality level of work, when it is completed in partnership with a cobot, and further investigation is required to support the assumption that a cobot will always increase the ergonomic level of a task and reduce injuries risk. This limitation is clearly shown in Appendix Table 6. Only Realyvásquez-Vargas et al., 2019, and Karaulova et al., 2019 investigated the ergonomic indexes in a comparative case study and analysed the difference between manual assembly line and collaborative assembly line by an ergonomic point of view. Recent studies assume the ergonomic index for tasks assigned to Cobots equal to zero (Stecke & Mokhtarzadeh, 2022; Li et al., 2022; Dalle Mura & Dini, 2022). However, this assumption neglects the fact that Cobots can create a new ergonomic load on workers (Lacevic et al., 2022; Lanzoni et al., 2022; Mura and Dini, 2023). In addition, some tasks can be done in different ways in the presence of cobot in supportive mode, so ergonomic indexes are not equal to zero. This highlights the need for additional research to accurately assess the true ergonomic quality level of work in collaboration with Cobots by coupling postural, fatigue and cognitive ergonomic assessment.

ML\RL in human pose prediction and task scheduling

The use of Machine Learning (ML) algorithms as the decision-making system for cobots is an important aspect of their functionality. Cobots use motion capturing systems and motion sensors to predict the movements of their human co-workers, which helps to improve their collaboration and increase productivity. Reinforcement Learning (RL) has also been widely used in cobot controllers to optimize training and improve performance. As it can be seen in Appendix Table 6, recently some online scheduling studies used reinforcement learning such as Alessio et al., (2022). Additionally, Liu et al., (2022b), and Zhang et al., (2022b) used reinforcement learning to optimize an assembly line balancing problem. However, more detailed investigation should be conducted to verify the results. Therefore, there is a lack of research in the literature on the use of Machine Learning and Reinforcement Learning to optimize the implementation of cobots in manufacturing systems.

Real data collection

The shortage of practical case studies able to provide to the research community a real data collection and open-source databases for supporting future research, method validation and tuning is evident in the literature. To better understand the implementation of cobots in collaborative manufacturing environments, more thorough and comprehensive studies must be conducted in real manufacturing scenarios. This includes not only laboratory testing with human and cobot participants, but also real-world case studies and practical applications that provide a more realistic view of how cobots are impacting the manufacturing industry. Currently, only three studies (i.e., Gil-Vilda et al., 2017; Navas-Reascos et al., 2022a) provide data that can be used to guide future research, highlighting the need for more robust and inclusive data sets to support the growth and development of cobots in the manufacturing industry.

Sustainable human-cobot collaboration

Finally, it is important to consider the sustainability of the human-cobot collaboration in the shared working environment. If humans and robots must cooperate in the same workplace, they will mutually affect and complement each other. Here, the wellbeing of the worker and his behaviour and status parameters will be strategic to react with changes in the scheduling and balancing of the working tasks. The development of digital representation of the workers by collecting real time data regarding workers' status, well-being, health and safety parameters (including postures and fatigue as previously discussed) will be strategic to support the operation manager decision making in the near future. Digital ergonomics tools, biosensors and wearable sensors coupled with ML techniques will be also strategic in this context to design a digital twin for human workers and create effective and sustainable collaborative working environments (Calvo & Gil, 2022; Lin & Lukodono, 2021; Berti et al, 2022). As it can be seen in Appendix Table 6, currently, a few studies investigated a sustainable collaborative system and all of them assert that more studies required to fully developed this issue, also some suggestion provided by these studies (Calvo & Gil, 2022; Gualtieri et al., 2022). As a consequence, the integration of key concepts from the human factors engineering discipline will be strategic to assess cobots use and benefits in the context of Industry 4.0 (Neumann et al., 2021). The so-called "side effects' of the technology" needs to be investigated since there might be side effects associated with the worker comfort and trust of working with a cobot for an entire working shift of 8 h (Neumann et al, 2021).

Conclusions

This study conducted a systematic literature review to explore the integration of collaborative robots (cobots) in manufacturing systems. Accordingly, we searched for papers using the research questions' definitions and the corresponding keywords in two databases (Scopus and Web of Science), resulting in a sample of 438 articles. We then selected 202 papers based on extraction criteria, and an additional 19 papers were found through the snowball approach. The selected studies were classified based on their subject of study, methodology, performance criteria, and collaboration scenarios. Our findings revealed that productivity was the most used performance criterion, while flexibility was the least used due to the challenges in evaluating it. Moreover, collaboration scenarios were often overlooked in the selected studies, leaving gaps in our understanding of the impact of different scenarios on cobot performance. Our analysis of the literature identified several key contributions to the state of the art, including new approaches to cobot design and deployment.

Our study has practical implications for practitioners and researchers working in the field of manufacturing systems. By categorizing studies based on different industries or usage, our findings could guide the selection of the most suitable performance criteria for each cobot application. We carefully analyzed the context of analysis and categorized the problems for selected papers to better understand the frequent issues that studies previously faced. Additionally, we investigated in detail the collaborative scenarios and the importance of digital twins in collaborative systems.

Considering the elaborated research agenda, the following topics could be promising areas for future research, such as evaluating the impact of collaboration scenarios on cobot performance. Finally, it is worth mentioning that this study is not without limitations. For example, while we provided a general overview of performance criteria, future research could explore these criteria in greater depth. Additionally, further research could investigate the use of cobots in specific manufacturing contexts, such as warehouses.

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Appendix

(See Tables 4, 5, and 6).

Table 4 Summary of literature review studies related to cobot

Row	Authors	Subjects	Field	Sources	SL*	Classification criteria	Key finding and insights
1	Green et al. (2008)	Investigation of using AR as a communication way between humans and cobots	CS	Not specified	No	Not any classifications were provided	Suggesting a human–robot interaction model architecture based on AR
2	Nelles et al. (2016)	Investigating head movement-based controller in cobots and its effect on stress and strain of the neck	R	Web of Science; Pubmed; snowball	Yes	Topic/Aim; Task; Study design; Measurements; Population;	Provided strengths and limitations of current methods, and future research guideline
3	Robla-Gomez et al. (2017)	Investigating safety in Human–Robot collaboration	S; R	Not specified	No	Quantifying level of injury by collision; Minimizing injury in the human–robot collision; Collision avoidance	Reviewing the main safety protocols that have been proposed or applied, and presenting some multi-disciplinary approach to estimate and evaluate the injuries or prevent collision
4	Halme et al. (2018)	Investigating the readiness level of vision-based safety system	CS	Not specified	No	Methods; Sensor type; safety function; Separation distance	Actual collaborative scenarios are very rare in literature. Also, the vision-based safety system could move forward to a real industrial test
5	Liu and Wang (2018)	Investigating gesture recognition system as a communication way between humans and cobots	CS	Not specified	No	Essential technical components (sensor technologies, gesture identification, gesture tracking, and gesture classifications)	Provide an analysis related to technological developments during the years. Then provide future technologies developments suggestions
6	Manoharan and Kumaraguru (2018)	Investigation of using cobot to increase the speed of Additive Manufacturing (AM) processes	R	Not specified	No	Single or multiple cobots in trajectory planning	Path planning for a single cobot is significantly easier and less complex to optimize
7	Grischke et al. (2019)	Investigation of using robots as a dental assistant	HC	Not specified	No	Not any classifications were provided	Providing a first concept and pilot study for cobot's application as dental assistance. A more complex framework can significantly increase the chance of acceptance by dentists

Table 4 (continued)

Row	Authors	Subjects	Field	Sources	SL*	Classification criteria	Key finding and insights
8	Bi & Guan(2019)	Investigating Electromyography (EMG)-based motor to predict the intention movement of worker	CS	not specified	No	Parameter to be estimated; model; performance measure; performance	EMG signals can be a reliable approach to predicting human movement intention. Also, EMG signal can be used as a communication way between humans and cobots
9	Matheson et al. (2019)	Investigating real case studies with cobots	M	ScienceDirect; IEEExplore; Web of Science	No	Cobot used; Control system; Application (assembly, human assistance, and machine tending); Objectives (productivity, safety, and HRI)	Summarizing the results of implementing cobots in real case studies. More real case studies investigation should be done
10	El Zaatari et al. (2019)	Investigating different programming methods and effects on HRC	CS	Not specified	No	Communication; Optimization; Learning	All programming approaches and categories have their advantages and disadvantages. Therefore, the programming method should be chosen in light of the real case
11	Chemweno et al. (2020)	Investigating ISO 15066 standard's position in safety protocols for collaborative systems	S, R	Not specified	No	Risk identification; Risk analysis; Risk evaluation	propose a new framework based on ISO 31000 to design safeguards in collaborative environments
12	Dianatfar et al. (2021)	Investigation of using AR and VR as a communication way between humans and cobots	CS	Not specified	No	Methods; Application; Tools; Sensors; Device; Robot Type	a summary of existing AR/VR solutions in Human–robot collaboration. Lack of productivity and focus on safety in existing solutions
13	Arents et al. (2021)	Investigating Human–robot collaboration	M; R	Web of Science; Scopus	Yes	Sensors; Algorithms for HRC; Application; collaboration level; Safety Action; Safety Standard	relation between safety actions and collaboration level, the effect of virtual training on safe collaboration, and the benefits of HRC
14	Zhang et al., (2021a)	Investigating compliant controller for cobots	R	Not specified	No	Compliant controller type (Force-based, model-based, and external force-based)	specifying advantages and disadvantages of different compliant control types

Table 4 (continued)

Row	Authors	Subjects	Field	Sources	SL*	Classification criteria	Key finding and insights
15	Keshvarparast et al. (2021)	Investigating the implementation of cobot in the manufacturing system	M	Scopus	No	Methodologies, performance factors (productivity, safety, flexibility, cost, ergonomic)	the focus of research is mainly on the productivity of the manufacturing system and less on ergonomic aspects
16	Gualtieri et al. (2021)	Investigating safety and ergonomic in HRC	S	Scopus	Yes	Safety (contact avoidance, contact detection and mitigation); Ergonomics (Physical ergonomics, cognetive and organizational ergonomics)	determining the current trend in safety and ergonomics field in recent years
17	Bisen and Payal (2022)	Investigating recent development in cobot	CS	Not specified	No	Cobot programming (communication, optimization, or learning)	Different programming approaches bring different collaboration levels. Complex programming may increase the autonomy of cobot but may lower the flexibility
18	Storm et al. (2022)	Investigating the physical and mental well-being of workers in collaborative systems based on SHELLO approach	S; R	PubMed; PsycINFO; Web of Science; Scopus	Yes	Methodology; Investigated factors; SHELLO component; well-being component	the focus of methodological research is on risk assessments and physical safety, but not the mental health of workers
19	Hassan and Oddo (2022)	Investigation of using cobot in Wire harness assembly process	M; R	Direct; Springer; Scopus; IEEExplore; Web of Science; ProQuest	No	assembly type (manual or collaborative); Topics of interest (collaborative robot, ergonomic, computer vision systems, implementation methodologies)	focus on the productivity of assembly lines and neglect the cost or ergonomic aspect of assembly lines. Additionally, the importance of employing computer vision to increase functionality
20	Baltrusch et al. (2022)	Investigating the effect of tactile sensors in cobots	R	not specified	No	Shape; Materials; Surface texture	The effects of using tactile sensors have been investigated less than what should be. This issue should be further investigated and developed

Table 4 (continued)

Row	Authors	Subjects	Field	Sources	SL*	Classification criteria	Key finding and insights
21	Inkulu et al. (2022)	Investigating the effect of human–robot collaboration on job quality	M	PubMed; Scopus	No	job quality factors (Cognitive Workload, Collaboration Fluency, Trust, and Acceptance and Satisfaction)	Job quality is impacted by workplace design, robot design, and collaboration design. Matching robot capabilities to end-user desires will improve job quality
22	Ramasubramanian et al. (2022)	Investigating mental stress and safety awareness in presence of cobot	S; R	Compendex; Web of Science; PubMed; Ergonomics Abstract;	Yes	Factors that affect workers' mental stress or safety awareness; Methods to measure mental stress; Methods to measure safety awareness	Worker mental stress or safety awareness are correlated with robot-related factors such as robot characteristics, social touching, and trajectory
23	Simões et al. (2022)	Investigating challenges and opportunities in collaborative systems	M; R	not specified	No	Communication between human and robot (one-way, two-way); Application (welding, assembly, inspection, other manufacturing operations)	Difficulties in integrating one-way and two-way human–robot collaboration and different industrial applications were discussed
24	Hopko et al. (2022)	Investigating Machine Learning (ML) in human–robot collaboration	CS	Scopus; IEEExplore; Web of Science	Yes	Metrics of collaborative tasks; ML technique; Cognitive ability; Sensing; Interaction task; Robotic platform; Human role; Cobot role	a detailed analysis of metrics with Interaction task, cognitive abilities with ML technique, and ML technique with interaction task was provided
25	Yan & Jia (2022)	Investigating Digital Twin in HRC	DT	Scopus; Google Scholar	No	Digital Twin approach (SBA, LBA); Benefits and Challenges	While DT in HRC research is lagging, research on the DT for industrial robotic processes is growing quickly. Due to the uncertainty involved in simulating the environment involving the human operator, it is far simpler to develop a digital model of an industrial robot than a collaborative robot

Table 4 (continued)

Row	Authors	Subjects	Field	Sources	SL*	Classification criteria	Key finding and insights
26	Sheikh & Duffy (2022)	Investigating factors for designing workstations in HRC	M	Scopus; Web of Science	Yes	Human operator (cognitive and social process, human comfort, and safety); Technology; Team's performance; Integrated approach to design HRC	The impacts of cobots on physiological, biomechanical, psychological, and general knowledge regarding the design of a human-centred collaboration were attempted to be classified
27	Costa et al. (2022)	Investigating the most frequently addressed Human Factors states, the quantifying methods, and the implications of the states on HRC	R	EBSCO; PubMed; MEDLINE; Engineering Source; Academic Search Ultimate; Compendex	Yes	Human Factors (trust, cognitive workload, Anxiety, safety perception, fatigue); Subjective measures; Objective measures	The most common research methods used were subjective questionnaires, and the most often examined states were anxiety, cognitive workload, and trust. Demographic factors of tested workers missing in most studies
28	Hjorth & Chrysostomou (2022)	Investigating Human Comfort Factors in HRC	R	not specified	No	Human Comfort Factors (ergonomic, motion-based, anthropomorphism, robot sociability); Metrics of measure; Metrics of improvement	The relatively low user acceptability of cobots is the main barrier keeping them from playing a significant role in industries. Developed methods to improve Human Comfort Factor in HRC are relatively low
29	Lu et al., (2022a)	Content analysis on ergonomic in HRC	M	Web of Science; Google Scholar; Scopus	Yes	Leading authors; Leading publishers; Leading country; Word Cloud	The most ergonomic factor used in literature determined
30	Navas-Reascos et al., (2022b)	Investigating Human Factors in HRC	M	ResearchGate; ScienceDirect; IEEE Xplore; Scopus; Web of Science	Yes	Human Factors; Cobot capabilities (mobility, adaptability, connectivity, actuation, consistency, safety); Modern production systems features (flexibility, reconfigurability, cost-oriented, interconnection, agility)	The gap in the literature related to the Human factors in HRC was clarified. Physical ergonomic and mental workload is the main concern of researchers until now
31	Faccio et al. (2023)	Investigation of using AR as a communication way between humans and cobots	R	ACM Digital Library; Web of Science; ScienceDirect; Scopus	Yes	level of interaction; Tracking model; Visualization methods; Visualization equipment	According to the findings, the field of study into employing AR in HRC is still developing. Additionally, techniques based on projectors and HMDs are demonstrating positive effects on operator-related features

Table 4 (continued)

Row	Authors	Subjects	Field	Sources	SL*	Classification criteria	Key finding and insights
32	Semeraro et al. (2023)	Investigating HRC in disassembly systems	M; R	Web of Science; Google Scholar; Scopus	No	Robot; Safety; Robot restrictions; Workplace restrictions; Human–robot communication	The results show that research on HRC in disassembly lines is still in its early stages. Task characteristics in disassembly lines should be more investigated in HRC

*SL Systematic literature

R Robotic, *M* Manufacturing, *CS* Computer Science, *S* Safety, *HC* Health Care, *DT* Digital Twin

Table 5 Selected papers categorization

Row	Authors	Subject of study					Methodology						Considered performance criteria						Collaboration scenarios			
		Design	Programming	Operation			Mathematical modelling	Mathematical approach	Framework	Simulation	Comparative case	Others	Cost	Productivity	Ergonomic	Safety	Flexibility	Quality	Independent	Sequential	Simultaneous	Supportive
				Assembly	Disassembly	Others																
1	Akella Prasad et al. (1999)	*												*								
2	Garber and Lin (2002)	*	*											*								
3	Stanescu et al. (2008)	*												*								
4	Panescu et al. (2009)	*												*								
5	Minca et al. (2010)	*												*								
6	Matthias et al. (2011)	*															*					
7	Minca et al., (2011a)			*					*							*			*			
8	Minca et al., (2011b)	*												*								
9	Müller et al. (2014)	*												*								
10	Unhelkar and Shah (2015)					*						*										
11	Heddy et al. (2015)	*												*								
12	Wang and Lu (2016)	*												*								
13	Coupeté et al. (2016)	*	*											*		*						
14	Djuric et al. (2016)					*			*					*								
15	Sarkar et al. (2017)	*														*						
16	Sadik et al. (2017)	*														*						
17	Kolyubin et al. (2017)					*								*								
18	Mokaram et al. (2017)					*	*							*						*		
19	Djuric et al. (2017)	*												*								
20	Gil-Vilda et al. (2017)		*											*								
21	Sousa et al. (2017)	*	*											*			*					

Table 5 (continued)

Row	Authors	Subject of study					Methodology						Considered performance criteria						Collaboration scenarios			
		Design	Programming	Operation			Mathematical modelling	Mathematical approach	Framework	Simulation	Comparative case	Others	Cost	Productivity	Ergonomic	Safety	Flexibility	Quality	Independent	Sequential	Simultaneous	Supportive
				Assembly	Disassembly	Others																
22	Calitz et al. (2017)	*	*						*					*								
23	Sadik and Urban (2017a)			*							*			*						*	*	
24	Sadik and Urban (2017b)de	*												*		*						
25	Sadik and Urban (2017c)					*						*										
26	Bruno and Antonelli (2018)			*								*				*			*			*
27	Schonberger et al. (2018)			*					*													*
28	Mendes et al. (2018)		*											*								
29	Mitrea and Tamas (2018)		*											*								
30	Weichhart et al. (2018)		*														*					
31	Cencen et al. (2018)					*			*													
32	El Makrini et al. (2018)	*												*								
33	Sadik and Urban (2018)	*															*					
34	Khalid et al. (2018)	*																				
35	Blankemeyer et al. (2018)		*									*					*					
36	Rückert et al. (2018)		*											*								
37	Unger et al. (2018)	*												*								
38	Malik and Bilberg (2018)	*							*					*								
39	Thomas et al. (2018)			*		*			*	*							*				*	

Table 5 (continued)

Row	Authors	Subject of study					Methodology						Considered performance criteria						Collaboration scenarios			
		Design	Programming	Operation			Mathematical modelling	Mathematical approach	Framework	Simulation	Comparative case	Others	Cost	Productivity	Ergonomic	Safety	Flexibility	Quality	Independent	Sequential	Simultaneous	Supportive
				Assembly	Disassembly	Others																
40	Djuric et al. (2018)	*	*													*	*					
41	Pieska et al. (2018)		*																			
42	Islam et al. (2019)		*													*						
43	Malik and Bilberg (2019a)					*						*				*						
44	Casalino et al., (2019a)			*		*	*							*							*	
45	Weckenborg and Spengler (2019)			*			*						*		*				*	*		
46	Quenehen et al. (2019)			*							*			*						*		
47	Fager et al. (2019)					*	*							*						*		
48	Hanna et al. (2019)			*								*										
49	Nogueira et al. (2019)		*					*				*		*								
50	Coupeté et al. (2019)		*									*		*								
51	Mosadeghzad et al. (2019)	*												*								
52	Wojtynek et al. (2019)		*							*				*								
53	Realyvásquez-Vargas et al. (2019)			*							*			*	*					*		
54	Zhao et al. (2019)	*												*								
55	Kanazawa et al. (2019)	*												*								
56	Welfare et al. (2019)					*						*										
57	Lamon et al. (2019)			*					*					*	*							
58	Menegozzo et al. (2019)		*											*								
59	Malik et al. (2019)		*											*			*					

Table 5 (continued)

Row	Authors	Subject of study					Methodology						Considered performance criteria						Collaboration scenarios			
		Design	Programming	Operation			Mathematical modelling	Mathematical approach	Framework	Simulation	Comparative case	Others	Cost	Productivity	Ergonomic	Safety	Flexibility	Quality	Independent	Sequential	Simultaneous	Supportive
				Assembly	Disassembly	Others																
60	Accorsi et al. (2019)					*		*					*						*			
61	Wang et al. (2019)					*					*			*					*			
62	Serebrenny et al., (2019a)					*			*					*			*					
63	Serebrenny et al., (2019b)	*							*								*					
64	Gualtieri et al. (2019)			*				*					*		*	*						
65	Dusadeerungsikul et al. (2019)	*											*	*								
66	Karaulova et al. (2019)			*							*		*	*	*							
67	Olender and Banas (2019)			*								*										
68	Casalino et al., (2019b)		*											*								
69	Antonelli and Bruno (2019)			*		*						*							*	*	*	
70	Ruiz Garcia et al. (2019)		*											*								
71	Dalle Mura and Dini (2019)			*			*						*		*				*			*
72	Naidoo et al. (2019)		*						*													
73	Avalle et al. (2019)	*	*									*		*								
74	Alebooyeh and Urbanic (2019)		*									*		*								
75	Ismail et al. (2020)	*										*					*					
76	Chonsawat and Sopadang (2020)	*										*										
77	Mohammadi Amin et al. (2020)	*														*						
78	Wojtynek et al. (2020)		*						*								*					
79	Hanna et al. (2020)	*									*					*						

Table 5 (continued)

Row	Authors	Subject of study					Methodology						Considered performance criteria						Collaboration scenarios			
		Design	Programming	Operation			Mathematical modelling	Mathematical approach	Framework	Simulation	Comparative case	Others	Cost	Productivity	Ergonomic	Safety	Flexibility	Quality	Independent	Sequential	Simultaneous	Supportive
				Assembly	Disassembly	Others																
80	D'Souza et al. (2020)					*					*											
81	Nieto et al. (2020)	*														*						
82	Maderna et al. (2020)		*											*	*							
83	Gualtieri et al., (2020b)			*							*			*	*							
84	Lee et al. (2020)	*								*				*								
85	von Drigalski et al. (2020)	*																				
86	Zhang and Jia (2020)			*			*							*						*		*
87	Weckenborg et al. (2020)			*			*							*			*			*		*
88	Malik et al. (2020)			*					*			*		*		*	*					
89	Hollerer et al. (2021)	*												*								
90	Wedin et al. (2020)	*												*								
91	Cohen & Shoval (2020)					*				*		*										
92	Psulkowski et al. (2020)	*																				
93	Yu et al. (2020)		*									*		*							*	
94	Wojtynek and Wrede (2020)					*				*				*					*			
95	Fukui et al. (2020)	*														*						
96	Dimitropoulos et al. (2021)	*													*	*						
97	Prioli & Rickli (2020)		*														*					
98	Emeric et al. (2020)		*											*								
99	Le et al. (2020)	*							*				*									

Table 5 (continued)

Row	Authors	Subject of study					Methodology						Considered performance criteria						Collaboration scenarios			
		Design	Programming	Operation			Mathematical modelling	Mathematical approach	Framework	Simulation	Comparative case	Others	Cost	Productivity	Ergonomic	Safety	Flexibility	Quality	Independent	Sequential	Simultaneous	Supportive
				Assembly	Disassembly	Others																
100	Ogas et al. (2020)	*												*								
101	Gualtieri et al., (2020a)					*						*		*	*	*						
102	Rueckert et al. (2020)	*								*						*						
103	Carfì et al. (2020)		*																			
104	Berger et al. (2020)			*		*			*							*						
105	Broum & Simon (2020)					*						*				*						
106	Chemweno et al. (2020)	*										*				*						
107	Liu & Wang (2020)	*														*			*			
108	Oliff et al. (2020)	*							*						*							
109	Banziger et al. (2020)			*						*				*	*							
110	Xu et al. (2021)				*	*	*							*		*						
111	Boschetti et al., (2021b)			*		*	*							*								*
112	Jepsen et al. (2021)					*											*					
113	Inoue et al. (2021)					*					*						*					
114	Soares et al. (2021)		*									*		*								
115	Li et al., (2021b)	*									*			*								
116	Toichoa Eyam et al. (2021)	*												*		*						
117	Arrais et al. (2021)		*											*			*					
118	Leyrer et al. (2021)	*												*			*					
119	Zhang et al., (2021b)			*				*						*	*				*		*	

Table 5 (continued)

Row	Authors	Subject of study					Methodology						Considered performance criteria						Collaboration scenarios			
		Design	Programming	Operation			Mathematical modelling	Mathematical approach	Framework	Simulation	Comparative case	Others	Cost	Productivity	Ergonomic	Safety	Flexibility	Quality	Independent	Sequential	Simultaneous	Supportive
				Assembly	Disassembly	Others																
120	Malik and Brem (2021)			*							*			*								
121	Dahl et al. (2021)	*							*									*				
122	Rega et al. (2021)			*								*		*		*						
123	Shu and Solvang (2021)	*								*							*					
124	Dalle Mura & Dini (2022)			*		*	*						*		*				*		*	
125	Garcia et al. (2021)		*									*					*					
126	Sordan et al. (2022)			*							*			*							*	
127	Gjeldum et al. (2022)			*								*		*					*			*
128	Wada et al. (2021)	*										*		*								
129	Cohen et al. (2022)			*			*					*		*							*	
130	Li et al., (2021c)			*			*						*	*						*		*
131	Fager et al. (2021)					*	*						*							*		
132	Vieira et al. (2022)			*			*						*	*						*		
133	Malik et al. (2021)			*						*				*					*			
134	Ibanez et al. (2021)			*						*	*			*								
135	Boschetti et al., (2021a			*			*							*								*
136	Lucci et al. (2022)		*									*		*								
137	Almasarwah et al. (2022)			*			*							*							*	
138	Zaatari et al. (2022)		*									*										
139	Belhadj et al. (2022)				*			*				*	*	*					*	*		

Table 5 (continued)

Row	Authors	Subject of study					Methodology						Considered performance criteria						Collaboration scenarios			
		Design	Programming	Operation			Mathematical modelling	Mathematical approach	Framework	Simulation	Comparative case	Others	Cost	Productivity	Ergonomic	Safety	Flexibility	Quality	Independent	Sequential	Simultaneous	Supportive
				Assembly	Disassembly	Others																
140	Nourmohammadi et al. (2022)			*			*							*					*		*	
141	Zhang et al., (2022d)		*									*		*								
142	Yao et al. (2022)					*			*													
143	Cacace et al. (2022)		*						*			*										
144	Keshvarparast et al. (2022)			*			*							*	*					*	*	*
145	Petzoldt et al. (2022)			*										*						*		
146	Navas-Reascos et al., (2022a)			*							*				*					*		*
147	Zaid et al. (2022)	*												*								
148	Roveda et al. (2022)		*											*								
149	Romiti et al. (2021)	*	*											*								
150	Sanna et al. (2022)		*											*	*							
151	Zhu et al. (2022)			*			*			*			*	*					*			*
152	Liu et al., (2022a)		*											*								
153	Andronas et al. (2022)	*																*				
154	Dmytriyev et al. (2022)		*											*								
155	Lee et al. (2022)				*		*							*		*					*	
156	Gervasi et al. (2021)			*					*					*	*	*						
157	Li et al. (2022)		*											*								
158	Zhang et al., (2022b)		*											*								
159	Bright et al. (2022)	*											*									

Table 5 (continued)

Row	Authors	Subject of study					Methodology						Considered performance criteria						Collaboration scenarios			
		Design	Programming	Operation			Mathematical modelling	Mathematical approach	Framework	Simulation	Comparative case	Others	Cost	Productivity	Ergonomic	Safety	Flexibility	Quality	Independent	Sequential	Simultaneous	Supportive
				Assembly	Disassembly	Others																
160	Zhang et al. (2022c)		*											*								
161	Zhang et al. (2022e)		*											*								
162	Lv et al. (2022)		*											*								
163	Yu and Zhang (2022)		*											*		*						
164	Schmidt et al. (2022)		*											*			*					
165	Costanzo et al. (2021)	*	*											*		*						
166	Zhou et al. (2022)		*											*			*					
167	Mueller et al. (2022)		*											*								
168	Giberti et al. (2022)		*						*					*			*					
169	Sun et al. (2021)	*							*					*								
170	Dalle Mura and Dini (2022)			*			*						*		*							
171	Maderna et al. (2022)		*											*								
172	Zhang et al. (2022a)			*								*		*								
173	Deniz & Ozcelik (2023)				*		*						*			*			*		*	
174	Pabolu et al. (2022)			*					*					*					*			
175	Deng et al. (2022)		*											*								
176	Wang et al. (2022a)			*						*				*					*		*	
177	Xiang et al. (2022)				*		*						*						*		*	
178	Liu et al. (2022a)				*		*							*					*		*	
179	Antonelli & Aliev (2022)			*			*							*					*		*	

Table 5 (continued)

Row	Authors	Subject of study					Methodology						Considered performance criteria						Collaboration scenarios			
		Design	Programming	Operation			Mathematical modelling	Mathematical approach	Framework	Simulation	Comparative case	Others	Cost	Productivity	Ergonomic	Safety	Flexibility	Quality	Independent	Sequential	Simultaneous	Supportive
				Assembly	Disassembly	Others																
180	Yu & Chang (2022)		*											*								
181	Li et al. (2022)			*			*							*	*				*		*	
182	Liao et al. (2023)				*		*						*			*				*	*	
183	Stefanakos et al. (2022)	*												*								
184	Ye et nal. (2022)		*											*								
185	Yi S. et al. (2022)		*													*	*					
186	Tuli et al. (2022)		*																			
187	Wang et al. (2022b)		*						*					*								
188	Boschetti et al. (2022)			*						*				*		*					*	
189	Lorenzo et al. (2022)					*			*					*								
190	Valente et al. (2022)	*												*								
191	Chiurco et al. (2022)		*											*								
192	Apostolopoulos et al. (2022)		*											*								
193	Koch et al. (2022)		*											*								
194	Lin et al. (2022)		*											*								
195	Gualtieri et al. (2022)			*					*							*						
196	Franceschi et al. (2022)			*					*									*				
197	Gjeldum et al. (2022)			*								*		*								
198	Stecke and Mokhtarzadeh (2022)			*			*							*	*						*	
199	Peron et al. (2022)			*								*	*	*					*		*	
200	Abdous et al. (2022)			*			*						*		*				*	*		
201	Lanzoni et al. (2022)					*						*			*							
202	Mura & Dini (2023)			*			*								*					*		

Table 6 Summary of contents for operation phase

Row	Authors	Problem	Method	Performance criteria	Evaluation approach	Application sector	Achieved results
1	Matthias et al. (2011)	Designing a collaborative assembly line	Framework	Safety	Traditional approach	Assembly line—not specified	Safety increment based on ISO 10218–2, ISO 12100, ISO 14121
2	Djuric et al. (2016)	Designing a collaborative manufacturing system	Framework	Productivity	Traditional approach	Manufacturing system	Makespan reduction
3	Sadik and Urban (2017b)	Flow shop scheduling with Cobots	Comparative case study	Productivity	Digital Twins—Simulation	Assembly line—not specified	Cycle time reduction
4	Sadik et al. (2017)	Task sharing in collaborative assembly line	Mathematical modeling	Productivity	Digital Twins—Simulation	Assembly line—not specified	Cycle time reduction
5	Gil-Vilda et al. (2017)	Designing a collaborative assembly line	Comparative case study	Productivity	Traditional approach	U-shaped Assembly line—not specified	Makespan reduction
6	Bruno and Antonelli (2018)	Task classification for task sharing and online scheduling	AI _ classification	Not mentioned	Not mentioned	Assembly line—Snowplow mill	A real-time task scheduling controller based on previous task classification
7	Schonberger et al. (2018)	Designing a collaborative workflow	Framework	Not mentioned	Not mentioned	Assembly line—not specified	Designing a collaborative work cell
8	Cencen et al. (2018)	Designing a collaborative assembly line	Framework	Not mentioned	Not mentioned	Assembly line—not specified	Designing a collaborative assembly
9	Thomas et al. (2018)	Designing a flexible collaborative assembly line	Framework, simulation	Flexibility	Digital Twins—Simulation	Assembly line—not specified	Determining the productivity and flexibility of designed assembly lines
10	Malik and Bilberg (2019a)	Work-space design	Framework	Safety	Traditional approach	Work cell—not specified	Supporting the choice of the safety approach in designing a workstation

Table 6 (continued)

Row	Authors	Problem	Method	Performance criteria	Evaluation approach	Application sector	Achieved results
11	Casalino et al., (2019a)	Task scheduling in collaborative assembly line	Mathematical modeling	Productivity	Traditional approach	Assembly line—not specified	Cycle time reduction
12	Weckenborg and Spengler (2019)	Collaborative assembly line balancing	Mathematical modelling	Cost, Ergonomic	Traditional approach	Assembly line—not specified	Cost of production reduced
13	Quenehen et al. (2019)	Task allocation in collaborative assembly line	Comparative case study	Productivity	Traditional approach	Assembly line—Cylinder barrel	Makespan reduction
14	Fager et al. (2019)	Cobot as a kit preparation in assembly line	Mathematical modeling	Productivity	Traditional approach	Kit preparation	Cycle time reduction
15	Realyvásquez-Vargas et al. (2019)	Occupational risk factors reduction in collaborative assembly line	Comparative case study	Productivity, Ergonomic	Traditional approach	Pockets assembly station	Cycle time and risk factors reduction
16	Welfare et al. (2019)	Deploying Cobots in the manufacturing system	Interview	Not mentioned	Not mentioned	Manufacturing system	Deploying challenges clarified
17	Lamon et al. (2018)	Reduce Cabot's fatigue	Framework	Productivity	Traditional approach	Assembly line—not specified	Increase productivity in certain period
18	Accorsi et al. (2019)	Application of Cobots in the food industry	Feasibility Analysis	Cost	Digital Twins—RFID	Packing in catering production system	Estimation of Cobots: Profitable after 2 and half a year
19	Wang et al. (2019)	application of Cobots in die sets	Comparative case study	Productivity	Traditional approach	Work cell—Die sets	Evaluation of Cobots performance: better quality and higher productivity
20	Serebrenny et al., (2019a)	designing a collaborative manufacturing system	Framework	Productivity, Flexibility	Traditional approach	Manufacturing system	Transforming manual assembly line to collaborative assembly line
21	Gualtieri et al. (2019)	new evaluation for collaborative assembly line	Framework	Cost, Ergonomic	Traditional approach	Assembly line—not specified	A new evaluation methodology

Table 6 (continued)

Row	Authors	Problem	Method	Performance criteria	Evaluation approach	Application sector	Achieved results
22	Karaulova et al. (2019)	Lean manufacturing with Cobots	Comparative Case Study	Cost, Productivity, Ergonomic	Traditional approach / Digital Twins—RFID	Work cell	Cobots reduce costs and ergonomic issues, increase productivity, and stay competitive in market
23	Antonelli & Bruno (2019)	task assignment based on tasks characteristics	AI _ Classification	Productivity	Machine Learning—classification	Assembly line—Snowplow mill	A real-time task scheduling controller based on previous task classification
24	Dalle Mura & Dini (2019)	designing collaborative assembly line	Mathematical modelling	Cost, Ergonomic	Traditional approach	Assembly line—Scooter chassis	Reducing the cost by considering workers energy expenditure
25	Chonsawat and Sopadang (2020)	determining the readiness indicators for I 4.0	Bibliometric techniques	Not mentioned	Not mentioned	Assembly line—not specified	Economic efficiency is attractive
26	D'Souza et al. (2020)	Cobot as a piking system in assembly line	Comparative case study	Productivity	Traditional approach	Warehouse—Material transport	Cycle time reduction
27	Gualtieri et al., (2020b)	Collaborative assembly line balancing	Framework	Productivity, Ergonomic	Traditional approach	Assembly line—Cable harnesses	Cycle time and ergonomic improvement
28	Zhang and Jia (2020)	Task allocation in collaborative assembly line	Mathematical modelling	Productivity	Traditional approach	Assembly line—not specified	Cycle time reduction
29	Weckenborg et al. (2020)	collaborative assembly line balancing	Mathematical modelling	Productivity	Traditional approach	Assembly line—not specified	Cycle time reduction
30	Malik et al. (2020)	Virtual reality to design a collaborative workspace	Framework, simulations	Productivity, Safety, Flexibility	Virtual Reality—Simulation	Assembly line—not specified	Determining the productivity, safety, and flexibility of designed assembly lines by simulation

Table 6 (continued)

Row	Authors	Problem	Method	Performance criteria	Evaluation approach	Application sector	Achieved results
31	Cohen and Shoval (2020)	Cobot deployment in assembly line	Simulation, Strategy	Not mentioned	Not mentioned	Assembly line—not specified	A new way to simulate Cobots in assembly line and calculate the performance
32	Wojtynek and Wrede (2020)	work-space design	Simulation	Productivity	Simulation in iWA	Assembly line—not specified	Makespan reduction
33	Gualtieri et al., (2020a)	product designing compatible with collaborative assembly line	Framework	Productivity, Ergonomic, Safety	Traditional approach	Assembly line—not specified	Enhancing productivity, ergonomic and safety by using the new framework to design a product
34	Berger et al. (2020)	make an assembly line safer	Framework	Safety	Digital Twins—Simulation	Assembly line—not specified	A framework to choose safety approach in designing workstation
35	Banziger et al. (2020)	Task allocation in collaborative assembly line	Simulation	Productivity, Ergonomic	Traditional approach / Simulation	Assembly line—Automotive industry	New method for to optimize task allocation in a work cell
36	Xu et al. (2021)	Human–robot collaborative disassembly line balancing	Mathematical modelling	Productivity, Safety	Traditional approach	Disassembly line—bearing coupler	smoothness index of disassembly, and cycle time reduced
37	Boschetti et al., (2021b)	collaborative assembly line balancing	Mathematical approach	Productivity	Traditional approach	Assembly line—not specified	Makespan reduction
38	Jepsen et al. (2021)	Designing a flexible production system	Framework	Flexibility	Digital Twins—Object detection	Assembly line—Drone assembly	Reduction the modifying time for each change
39	Inoue et al. (2021)	designing a reconfigurable manufacturing system by using AGV and Cobots for material transport	Comparative case study	Flexibility	Traditional approach	Warehouse—Material transport	Mobile Cobots cause to eliminate some designing obstacles

Table 6 (continued)

Row	Authors	Problem	Method	Performance criteria	Evaluation approach	Application sector	Achieved results
40	Zhang et al., (2021b)	new metric for collaborative assembly line	Mathematical approach	Productivity, Ergonomic	Traditional approach	Assembly line—cylinder head	Improvement in production time and ergonomic simultaneously
41	Malik and Brem (2021)	improving collaboration between human and cobots by using digital twins	Framework	Productivity	Digital Twins—Simulation	Assembly line—not specified	Cycle time reduction
42	Rega et al. (2021)	safety protocols for designing collaborative assembly line balancing	Knowledge-based approach	Productivity, Safety	Traditional approach	Work cell—not specified	Improving productivity and safety
43	Dalle Mura & Dini (2022)	job rotation in assembly line	Mathematical modeling	Cost, Ergonomic	Traditional approach	Assembly line—Vehicle front-end	Significant improvement in both factors
44	Sordan et al. (2022)	collaborative assembly line balancing	Comparative case study	Productivity	Traditional approach	U-shaped Assembly line—not specified	Idle time reduction
45	Gjeldum et al. (2022)	task allocation in collaborative assembly line	DSS procedure	Productivity	Traditional approach	Assembly line—manual gearbox	Cycle time reduction
46	Cohen et al. (2022)	collaborative assembly line balancing	Mathematical modeling	Productivity	Traditional approach	Assembly line—not specified	Makespan reduction
47	Li et al., (2021c)	collaborative assembly line balancing	Mathematical modeling	Cost, Productivity	Traditional approach	Assembly line—not specified	An optimal Pareto front based on cycle time and cost of an assembly line
48	Fager et al. (2021)	piking system in assembly line	Mathematical approach	Cost	Traditional approach	Assembly line—not specified	Reduction in cost of production, increase in cost of equipment

Table 6 (continued)

Row	Authors	Problem	Method	Performance criteria	Evaluation approach	Application sector	Achieved results
49	Vieira et al. (2022)	production planning and scheduling	Mathematical modeling, Simulation / (ROSA)	Cost, Productivity	Traditional approach	Assembly line—not specified	An optimal Pareto front based on production Makespan and operational costs
50	Malik et al. (2021)	designing collaborative assembly line	Simulation	Productivity	Digital Twins—Simulation	Assembly line—Ventilator production	Cycle time reduction
51	Ibanez et al. (2021)	collaborative assembly line	Simulation, Comparative case study	Productivity	Digital Twins—Simulation	Assembly line—Cable harnesses	Cycle time reduction
52	Boschetti et al., (2021a)	collaborative assembly line balancing	Mathematical modeling	Productivity	Traditional approach / Simulation	Assembly line—not specified	Makespan reduction
53	Almasarwah et al. (2022)	Task allocation in collaborative assembly line	Mathematical modeling	Productivity	Traditional approach	Assembly line—not specified	Reduction in the cycle and idle times and enhance the production rate of an assembly system
54	Keshvarparast et al. (2022)	collaborative assembly line balancing	Mathematical modeling	Productivity, Ergonomic	Traditional approach	Assembly line—Vehicle front-end	Significant improvement in both factors for C-AL
55	Belhadj et al. (2022)	Task allocation and planning in collaborative disassembly line	Mathematical approach, Heuristic strategy approach	Cost, Productivity	Traditional approach	Parallel disassembly line—gear box	Improvement in production time and cost simultaneously
56	Nourmohammadi et al. (2022)	collaborative assembly line balancing and scheduling	Mathematical modeling	Productivity, Number of used recurses	Traditional approach	Assembly line—not specified	Improving in the new proposed metric (combination of cycle time and number of used resources)

Table 6 (continued)

Row	Authors	Problem	Method	Performance criteria	Evaluation approach	Application sector	Achieved results
57	Petzoldt et al. (2022)	Dynamic task allocation for collaborative assembly line	Framework; Simulation	Productivity	Traditional approach	Assembly line—not specified	Dynamic task allocation can improve HRC in assembly tasks, especially when the workload is variable or uncertain
58	Navas-Reascos et al., (2022a)	collaborative assembly line balancing	Simulation; Comparative case study	Ergonomic	Traditional approach	Assembly line—Wire Harness Assembly Process	Ergonomics improvement of assembly process (reduced physical strain and muscular activity for the workers, and improved their overall well-being)
59	Zhu et al. (2022)	Reconfiguring collaborative assembly line by Digital Twin	Simulation; Mathematical Model	Cost; Productivity	Digital Twins—Simulation	Manufacturing system-not specified	use of a digital twin can enable dynamic reconfiguration optimization of intelligent manufacturing systems
60	Lee et al. (2022)	Task allocation and planning collaborative disassembly line	Mathematical Model	Productivity; Safety	Traditional approach	Disassembly—Used Hard Disc Drive	Improvement in disassembly process, with the robot providing support in the most difficult and dangerous parts of the task
61	Gervasi et al. (2021)	A framework to design a human–Robot collaboration	Framework	Productivity; Ergonomic	Traditional approach	Assembly line—Automotive industry	the proposed methodology helped to identify the most appropriate configuration for the task

Table 6 (continued)

Row	Authors	Problem	Method	Performance criteria	Evaluation approach	Application sector	Achieved results
62	Peron et al. (2022)	Decision support system for implementing assistive technologies in assembly lines	Decision Support System	Cost; Productivity	Traditional approach	Assembly line—not specified	Use cobots in low throughput only if operation times are high. In high throughput, best to use both DIs and/or cobots
63	Dalle Mura & Dini (2022)	Job-rotation in collaborative assembly line	Mathematical Model	Cost; Ergonomic	Traditional approach	Assembly line—Vehicle front-end	Cobot implementation improve ergonomics in assembly line
64	Zhang et al. (2022b)	Online task sequence assignment to human and cobot	AI—Reinforcement Learning	Productivity	Traditional approach	Assembly line—not specified	dynamic task assignment can improve the productivity of HRC
65	Deniz & Ozcelik (2023)	collaborative disassembly line task allocation for hazard products	Mathematical Model	Cost; Safety	Traditional approach	Disassembly—Hazard	Cost reduction
66	Pabolu et al. (2022)	Digital twins-based framework for task allocation	Framework	Productivity	Digital Twins—Simulation	Assembly line—not specified	The framework helps to evaluate the performance of assembly line before implementation
67	Wang et al. (2022a)	time-based and event-based simulation for dynamic factors of HRC	Simulation	Productivity	Traditional approach	Assembly line—not specified	Method to analyse the dynamic factors on performance of HRC
68	Xiang et al. (2022)	multi-product u-shaped collaborative disassembly line balancing	Mathematical Model	Cost	Traditional approach	Disassembly—not specified	Cost benefit of using cobots in a multi-product disassembly line

Table 6 (continued)

Row	Authors	Problem	Method	Performance criteria	Evaluation approach	Application sector	Achieved results
69	Liu et al. (2022a)	two-sided collaborative disassembly line balancing	AI—Reinforcement Learning	Productivity	Traditional approach	Disassembly—not specified	Reinforcement learning can be used to find a solution for C-DLB
70	Antonelli and Aliev (2022)	Robust real time optimization of task assignment in C-ALB	Mathematical Model	Productivity	Traditional approach	Assembly line—not specified	Robust solution for C-ALB to decease cycle time
71	Li et al. (2022)	online task reassignment based on fatigue of worker in C-AL	Mathematical Model	Productivity; Ergonomic	Traditional approach	Assembly line—not specified	New multi-modal fatigue model to evaluate fatigue in real time
72	Liao et al. (2023)	Sequence planning for collaborative disassembly line	Mathematical Model	Cost; Safety	Traditional approach	Disassembly—not specified	A model to balance cost, feasibility and safety of C-DL
73	Boschetti et al. (2022)	collision avoidance strategies in C-AL	Simulation	Productivity; Safety	Traditional approach	Assembly line—not specified	Different collision avoidance strategies make different productivity for C-Al
74	Lorenzo et al. (2022)	production planning and near real-time production controlling	Framework	Productivity	Traditional approach	Assembly line—not specified	Digital twin simulation effectively can evaluate performance of C-AL
75	Gualtieri et al. (2022)	Safety guideline for HRC	Framework	Safety	Digital Twins—Simulation	Assembly line—not specified	Guideline for design a safe C-AL by considering system characteristics
76	Gjeldum et al. (2022)	A decision Support System for task allocation in C-AL	Decision Support System	Productivity	Traditional approach	Assembly line—Gearbox	A decision support system to design a productive C-AL
77	Stecke and Mokhtarzadeh (2022)	Collaborative assembly line Balancing	Mathematical Model	Productivity; Ergonomic	Traditional approach	Assembly line—not specified	Cycle time reduction

Table 6 (continued)

Row	Authors	Problem	Method	Performance criteria	Evaluation approach	Application sector	Achieved results
78	Abdous et al. (2022)	Collaborative assembly line Balancing	Mathematical Model	Cost; Ergonomi	Traditional approach	Assembly line—not specified	A balance between cost and ergonomic in C-AL
79	Lanzoni et al. (2022)	Real-time ergonomic analysis of worker with virtual reality	AI—VR	Ergonomic	Digital Twins—Simulation	Work cell	Significant improvements in RULA index for worker
80	Mura & Dini (2023)	Improving ergonomic indexes in collaborative assembly line	Mathematical modeling	Ergonomic	Traditional approach	Assembly line—Electrical scooter	Improvement in noise exposure and energy expenditure in collaborative assembly line

References

Abdous, M. A., Delorme, X., Battini, D., & Berger-Douce, S. (2022). Multi-objective collaborative assembly line design problem with the optimisation of ergonomics and economics. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2022.2153185

Accorsi, R., Tufano, A., Gallo, A., Galizia, F. G., Cocchi, G., Ronzoni, M., Abbate, A., & Manzini, R. (2019). An application of collaborative robots in a food production facility. *Procedia Manufacturing 38*: 341–348. https://doi.org/10.1016/j.promfg.2020.01.044

Akella, P., Peshkin, M., Colgate, E. D., Wannasuphoprasit, W., Nagesh, N., Wells, J., Holland, S., Pearson, T., & Peacock, B. (1999). Cobots for the automobile assembly line. In *Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No. 99CH36288C)* (Vol. 1, pp. 728–733). IEEE. https://doi.org/10.1109/robot.1999.770061

Alebooyeh, M., & Urbanic, R. J. (2019). Neural network model for identifying workspace, forward and inverse kinematics of the 7-DOF YuMi 14000 ABB collaborative robot. *IFAC-PapersOnLine, 52*(10), 176–181.

Alessio, A., Aliev, K., & Antonelli, D. (2022). Robust adversarial reinforcement learning for optimal assembly sequence definition in a cobot workcell. *Advances in manufacturing III: Volume 2-production engineering: Research and technology innovations, industry 4.0* (pp. 25–34). Springer International Publishing. https://doi.org/10.1007/978-3-030-99310-8_3

Almasarwah, N., Abdelall, E., Suer, G. A., Pagan, J., & You, Y. (2022). Collaborative robots' assembly system in the manufacturing area, assembly system 4.0. *The International Journal of Advanced Manufacturing Technology, 122*(2), 1069–1081.

Andronas, D., Arkouli, Z., Zacharaki, N., Michalos, G., Sardelis, A., Papanikolopoulos, G., & Makris, S. (2022). On the perception and handling of deformable objects–A robotic cell for white goods industry. *Robotics and Computer-Integrated Manufacturing, 77*, 102358.

Antonelli, D., & Aliev, K. (2022). Robust assembly task assignment in human robot collaboration as a Markov decision process problem. *Procedia CIRP, 112*, 174–179.

Antonelli, D., & Bruno, G. (2019). Dynamic distribution of assembly tasks in a collaborative workcell of humans and robots. *FME Transactions, 47*(4), 723–730.

Apostolopoulos, G., Andronas, D., Fourtakas, N., & Makris, S. (2022). Operator training framework for hybrid environments: An augmented reality module using machine learning object recognition. *Procedia CIRP, 106*, 102–107.

Arents, J., Abolins, V., Judvaitis, J., Vismanis, O., Oraby, A., & Ozols, K. (2021). Human–robot collaboration trends and safety aspects: A systematic review. *Journal of Sensor and Actuator Networks, 10*(3), 48.

Arrais, R., Costa, C. M., Ribeiro, P., Rocha, L. F., Silva, M., & Veiga, G. (2021). On the development of a collaborative robotic system for industrial coating cells. *The International Journal of Advanced Manufacturing Technology, 115*(3), 853–871.

Avalle, G., De Pace, F., Fornaro, C., Manuri, F., & Sanna, A. (2019). An augmented reality system to support fault visualization in industrial robotic tasks. *IEEE Access, 7*, 132343–132359.

Azzi, A., Battini, D., Faccio, M., & Persona, A. (2012). Sequencing procedure for balancing the workloads variations in case of mixed model assembly system with multiple secondary feeder lines. *International Journal of Production Research, 50*(21), 6081–6098.

Baltrusch, S. J., Krause, F., de Vries, A. W., van Dijk, W., & de Looze, M. P. (2022). What about the human in human robot collaboration? A literature review on HRC's effects on aspects of job quality. *Ergonomics, 65*(5), 719–740. https://doi.org/10.1080/00140139.2021.1984585

Banziger, T., Kunz, A., & Wegener, K. (2020). Optimizing human–robot task allocation using a simulation tool based on standardized work descriptions. *Journal of Intelligent Manufacturing, 31*, 1635–1648.

Battini, D., Delorme, X., Dolgui, A., & Sgarbossa, F. (2015). Assembly line balancing with ergonomics paradigms: Two alternative methods. *IFAC-PapersOnLine, 48*(3), 586–591.

Belhadj, I., Aicha, M., & Aifaoui, N. (2022). Product disassembly planning and task allocation based on human and robot collaboration. *International Journal on Interactive Design and Manufacturing (IJIDeM), 16*(2), 803–819.

Berger, T., Bonte, T., Santin, J. J., & Sallez, Y. (2020). The concept of" safety bubble" to build ethical reconfigurable assembly systems. *IFAC-PapersOnLine, 53*(2), 17023–17028.

Berti, N., Serena, F., Mattia, G., Monica, R., & Daria, B. (2022). Real-time postural training effects on single and multi-person ergonomic risk scores. *IFAC-PapersOnLine, 55*(10), 163–168.

Bi, L., & Guan, C. (2019). A review on EMG-based motor intention prediction of continuous human upper limb motion for human-robot collaboration. *Biomedical Signal Processing and Control, 51*, 113–127.

Bisen, A. S., & Payal, H. (2022). Collaborative robots for industrial tasks: A review. *Materials Today: Proceedings, 52*, 500–504.

Blankemeyer, S., Wiemann, R., Posniak, L., Pregizer, C., & Raatz, A. (2018). Intuitive robot programming using augmented reality. *Procedia CIRP, 76*, 155–160.

Bogataj, D., Battini, D., Calzavara, M., & Persona, A. (2019). The ageing workforce challenge: Investments in collaborative robots or contribution to pension schemes, from the multi-echelon perspective. *International Journal of Production Economics, 210*, 97–106.

Boschetti, G., Bottin, M., Faccio, M., Maretto, L., & Minto, R. (2022). The influence of collision avoidance strategies on human-robot collaborative systems. *Ifac-Papersonline, 55*(2), 301–306.

Boschetti, G., Bottin, M., Faccio, M., & Minto, R. (2021a). Multi-robot multi-operator collaborative assembly systems: a performance evaluation model. *Journal of Intelligent Manufacturing, 32*(5), 1455–1470.

Boschetti, G., Faccio, M., Milanese, M., & Minto, R. (2021b). C-ALB (Collaborative Assembly Line Balancing): a new approach in cobot solutions. *The International Journal of Advanced Manufacturing Technology, 116*(9), 3027–3042.

Bright, T., Adali, S., & Bright, G. (2022). Low-cost sensory glove for human–robot collaboration in advanced manufacturing systems. *Robotics, 11*(3), 56.

Broum, T., & Šimon, M. (2020). Safety requirements related to collaborative robots in the Czech Republic. *MM Science Journal*. https://doi.org/10.17973/MMSJ.2020_03_2019136

Bruno, G., & Antonelli, D. (2018). Dynamic task classification and assignment for the management of human-robot collaborative teams in workcells. *The International Journal of Advanced Manufacturing Technology, 98*(9), 2415–2427.

Cacace, J., Caccavale, R., Finzi, A., & Grieco, R. (2022). Combining human guidance and structured task execution during physical human–robot collaboration. *Journal of Intelligent Manufacturing*. https://doi.org/10.1007/s10845-022-01989-y

Calitz, A. P., Poisat, P., & Cullen, M. (2017). The future African workplace: The use of collaborative robots in manufacturing. *SA Journal of Human Resource Management, 15*(1), 1–11.

Calvo, R., & Gil, P. (2022). Evaluation of collaborative robot sustainable integration in manufacturing assembly by using process time savings. *Materials, 15*(2), 611.

Cardoso, A., Colim, A., Bicho, E., Braga, A. C., Menozzi, M., & Arezes, P. (2021). Ergonomics and human factors as a requirement to implement safer collaborative robotic workstations: A literature review. *Safety, 7*(4), 71.

Carfì, A., Villalobos, J., Coronado, E., Bruno, B., & Mastrogiovanni, F. (2020). Can human-inspired learning behaviour facilitate human–robot interaction? *International Journal of Social Robotics, 12*(1), 173–186.

Casalino, A., Mazzocca, E., Di Giorgio, M. G., Zanchettin, A. M., & Rocco, P. (2019a). Task scheduling for human-robot collaboration with uncertain duration of tasks: a fuzzy approach. In *2019a 7th International Conference on Control, Mechatronics and Automation (ICCMA)* (pp. 90–97). IEEE. https://doi.org/10.1109/ICCMA46720.2019.8988735

Casalino, A., Zanchettin, A. M., Piroddi, L., & Rocco, P. (2019b). Optimal scheduling of human–robot collaborative assembly operations with time petri nets. *IEEE Transactions on Automation Science and Engineering, 18*(1), 70–84.

Cencen, A., Verlinden, J. C., & Geraedts, J. M. P. (2018). Design methodology to improve human-robot coproduction in small-and medium-sized enterprises. *IEEE/ASME Transactions on Mechatronics, 23*(3), 1092–1102.

Chemweno, P., Pintelon, L., & Decre, W. (2020). Orienting safety assurance with outcomes of hazard analysis and risk assessment: A review of the ISO 15066 standard for collaborative robot systems. *Safety Science, 129*, 104832.

Chiurco, A., Frangella, J., Longo, F., Nicoletti, L., Padovano, A., Solina, V., Mirabelli, G., & Citraro, C. (2022). Real-time Detection of Worker's Emotions for Advanced Human-Robot Interaction during Collaborative Tasks in Smart Factories. *Procedia Computer Science*, *200*, 1875–1884. https://doi.org/10.1016/j.procs.2022.01.388

Choi, S. H., Park, K. B., Roh, D. H., Lee, J. Y., Mohammed, M., Ghasemi, Y., & Jeong, H. (2022). An integrated mixed reality system for safety-aware human-robot collaboration using deep learning and digital twin generation. *Robotics and Computer-Integrated Manufacturing, 73*, 102258.

Chonsawat, N., & Sopadang, A. (2020). Defining SMEs' 4.0 readiness indicators. *Applied Sciences, 10*(24), 8998.

Cohen, Y., & Shoval, S. (2020). A new cobot deployment strategy in manual assembly stations: Countering the impact of absenteeism. *IFAC-PapersOnLine, 53*(2), 10275–10278.

Cohen, Y., Shoval, S., Faccio, M., & Minto, R. (2022). Deploying cobots in collaborative systems: Major considerations and productivity analysis. *International Journal of Production Research, 60*(6), 1815–1831.

Costa, G. D. M., Petry, M. R., & Moreira, A. P. (2022). Augmented reality for human-robot collaboration and cooperation in industrial applications: A systematic literature review. *Sensors, 22*(7), 2725.

Costanzo, M., De Maria, G., Lettera, G., & Natale, C. (2021). A multimodal approach to human safety in collaborative robotic workcells. *IEEE Transactions on Automation Science and Engineering, 19*(2), 1202–1216.

Coupeté, E., Moutarde, F., & Manitsaris, S. (2016) A user-adaptive gesture recognition system applied to human-robot collaboration in factories. In *Proceedings of the 3rd International Symposium on Movement and Computing* (pp. 1–7). https://doi.org/10.1145/2948910.2948933

Coupeté, E., Moutarde, F., & Manitsaris, S. (2019). Multi-users online recognition of technical gestures for natural human–robot collaboration in manufacturing. *Autonomous Robots, 43*(6), 1309–1325.

Dahl, M., Bengtsson, K., & Falkman, P. (2021). Application of the sequence planner control framework to an intelligent automation system with a focus on error handling. *Machines, 9*(3), 59.

Dalle Mura, M., & Dini, G. (2019). Designing assembly lines with humans and collaborative robots: A genetic approach. *CIRP Annals, 68*(1), 1–4.

Dalle Mura, M., & Dini, G. (2022). Job rotation and human–robot collaboration for enhancing ergonomics in assembly lines by a genetic algorithm. *The International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-021-08068-1

Dalle Mura, M., & Dini, G. (2023). Improving ergonomics in mixed-model assembly lines balancing noise exposure and energy expenditure. *CIRP Journal of Manufacturing Science and Technology, 40*, 44–52.

de Gea Fernández, J., Mronga, D., Günther, M., Knobloch, T., Wirkus, M., Schröer, M., Trampler, M., Stiene, S., Kirchner, E., Bargsten, V., & Bänziger, T. (2017). Multimodal sensor-based whole-body control for human–robot collaboration in industrial settings. *Robotics and Autonomous Systems*, *94*, 102–119. https://doi.org/10.1016/j.robot.2017.04.007

de Sousa, G. B., Olabi, A., Palos, J., & Gibaru, O. (2017). 3D metrology using a collaborative robot with a laser triangulation sensor. *Procedia Manufacturing, 11*, 132–140. https://doi.org/10.1016/j.promfg.2017.07.211

Deng, X., Liu, J., Gong, H., Gong, H., & Huang, J. (2022). A human-robot collaboration method using a pose estimation network for robot learning of assembly manipulation trajectories from demonstration videos. *IEEE Transactions on Industrial Informatics*. https://doi.org/10.1109/TII.2022.3224966

Deniz, N., & Ozcelik, F. (2023). Bi-objective optimization-based multi-criteria decision-making framework for disassembly line balancing and employee assignment problem. *Kybernetes*, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/K-06-2022-0857

Dianatfar, M., Latokartano, J., & Lanz, M. (2021). Review on existing VR/AR solutions in human–robot collaboration. *Procedia CIRP, 97*, 407–411.

Digital Twin Consortium. (2022). What is a digital twin? Available at https://www.digitaltwinconsortium.org/initiatives/the-definition-of-a-digital-twin/

Dimitropoulos, N., Michalos, G., & Makris, S. (2021). An outlook on future hybrid assembly systems-the Sherlock approach. *Procedia Cirp, 97*, 441–446.

Djuric, A., Rickli, J. L., Jovanovic, V. M., & Foster, D. (2017). Hands-on learning environment and educational curriculum on collaborative robotics. *ASEE Annual Conference Proceedings, 2017*, 1–15.

Djuric, A., Rickli, J., Sefcovic, J., Hutchison, D., & Goldin, M. M. (2018). Integrating collaborative robots in engineering and engineering technology programs. In *ASME International Mechanical Engineering Congress and Exposition* (Vol. 52064, p. V005T07A013). American Society of Mechanical Engineers.

Djuric, A. M., Urbanic, R. J., & Rickli, J. L. (2016). A framework for collaborative robot (CoBot) integration in advanced manufacturing systems. *SAE International Journal of Materials and Manufacturing, 9*(2), 457–464.

Dmytriyev, Y., Insero, F., Carnevale, M., & Giberti, H. (2022). Brain—computer interface and hand-guiding control in a human–robot collaborative assembly task. *Machines, 10*(8), 654.

D'Souza, F., Costa, J., & Pires, J. N. (2020). Development of a solution for adding a collaborative robot to an industrial AGV. *Industrial Robot: The International Journal of Robotics Research and Application, 47*(5), 723–735.

Dusadeerungsikul, P. O., Sreeram, M., He, X., Nair, A., Ramani, K., Quinn, A. J., & Nof, S. Y. (2019). Collaboration requirement planning protocol for HUB-CI in factories of the future. *Procedia Manufacturing, 39*, 218–225.

El Makrini, I., Elprama, S.A., Van den Bergh, J., Vanderborght, B., Knevels, A.J., Jewell, C.I., Stals, F., De Coppel, G., Ravyse, I., Potargent, J., & Berte, J. (2018). Working with walt: How a cobot was developed and inserted on an auto assembly line. *IEEE Robotics & Automation Magazine, 25*(2), 51–58. https://doi.org/10.1109/MRA.2018.2815947

El Zaatari, S., Marei, M., Li, W., & Usman, Z. (2019). Cobot programming for collaborative industrial tasks: An overview. *Robotics and Autonomous Systems, 116*, 162–180.

Emeric, C., Geoffroy, D., & Paul-Eric, D. (2020). Development of a new robotic programming support system for operators. *Procedia Manufacturing, 51*, 73–80.

EU-OSHA. Digitalisation and occupational safety and health. (2019). https://osha.europa.eu/en/publications/digitalisation-and-occupational-safety-and-health-eu-osharesearch-programme

Faccio, M., Granata, I., Menini, A., Milanese, M., Rossato, C., Bottin, M., & Rosati, G. (2023). Human factors in cobot era: a review of modern production systems features. *Journal of Intelligent Manufacturing, 34*(1), 85–106.

Fager, P., Calzavara, M., & Sgarbossa, F. (2019). Kit preparation with cobot-supported sorting in mixed model assembly. *IFAC-PapersOnLine, 52*(13), 1878–1883.

Fager, P., Sgarbossa, F., & Calzavara, M. (2021). Cost modelling of onboard cobot-supported item sorting in a picking system. *International Journal of Production Research, 59*(11), 3269–3284.

Franceschi, P., Mutti, S., Ottogalli, K., Rosquete, D., Borro, D., & Pedrocchi, N. (2022). A framework for cyber-physical production system management and digital twin feedback monitoring for fast failure recovery. *International Journal of Computer Integrated Manufacturing, 35*(6), 619–632.

Fukui, H., Shimizu, T., Maeda, I., Nobuhiro, M., Okada, K., Dohi, M., Fujitani, S. & Fujita, T. (2020, December). Development of devices applied to collaborative robot production system based on Collaborative Safety/Safety2. 0. In *ISR 2020; 52th International Symposium on Robotics* (pp. 1–6). VDE. https://ieeexplore.ieee.org/abstract/document/9307466

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. *IEEE Access, 8*, 108952–108971.

Garber, M., & Lin, M. C. (2002). Constraint-based motion planning for virtual prototyping. In *Proceedings of the seventh ACM symposium on Solid modeling and applications* (pp. 257–264).

Garcia, M. A. R., Rauch, E., Salvalai, D., & Matt, D. (2021). AI-based human-robot cooperation for flexible multi-variant manufacturing. In: *Proceedings of the 11th International Conference on Industrial Engineering and Management 2021* (pp. 1194–1203). IEOM.

Garcia, M. A. R., Rojas, R., Gualtieri, L., Rauch, E., & Matt, D. (2019). A human-in-the-loop cyber-physical system for collaborative assembly in smart manufacturing. *Procedia CIRP, 81*, 600–605.

Gervasi, R., Mastrogiacomo, L., Maisano, D. A., Antonelli, D., & Franceschini, F. (2021). A structured methodology to support human–robot collaboration configuration choice. *Production Engineering, 16*(4), 435–451.

Giberti, H., Abbattista, T., Carnevale, M., Giagu, L., & Cristini, F. (2022). A methodology for flexible implementation of collaborative robots in smart manufacturing systems. *Robotics, 11*(1), 9.

Gil-Vilda, F., Sune, A., Yagüe-Fabra, J. A., Crespo, C., & Serrano, H. (2017). Integration of a collaborative robot in a U-shaped production line: A real case study. *Procedia Manufacturing, 13*, 109–115.

Gjeldum, N., Aljinovic, A., Crnjac Zizic, M., & Mladineo, M. (2022). Collaborative robot task allocation on an assembly line using the decision support system. *International Journal of Computer Integrated Manufacturing, 35*(4–5), 510–526.

Green, S. A., Billinghurst, M., Chen, X., & Chase, J. G. (2008). Human-robot collaboration: A literature review and augmented reality approach in design. *International Journal of Advanced Robotic Systems, 5*(1), 1.

Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. *Transdisciplinary perspectives on complex systems: New findings and approaches*, 85–113. https://doi.org/10.1007/978-3-319-38756-7_4

Grischke, J., Johannsmeier, L., Eich, L., & Haddadin, S. (2019). Dentronics: review, first concepts and pilot study of a new application domain for collaborative robots in dental assistance. In *2019 International Conference on Robotics and Automation (ICRA)* (pp. 6525–6532). IEEE.

Gualtieri, L., Monizza, G. P., Rauch, E., Vidoni, R., & Matt, D. T. (2020a). From design for assembly to design for collaborative assembly-product design principles for enhancing safety, ergonomics and efficiency in human-robot collaboration. *Procedia CIRP, 91*, 546–552.

Gualtieri, L., Palomba, I., Merati, F. A., Rauch, E., & Vidoni, R. (2020b). Design of human-centered collaborative assembly workstations for the improvement of operators' physical ergonomics and production efficiency: A case study. *Sustainability, 12*(9), 3606.

Gualtieri, L., Rauch, E., & Vidoni, R. (2021). Emerging research fields in safety and ergonomics in industrial collaborative robotics: A systematic literature review. *Robotics and Computer-Integrated Manufacturing, 67*, 101998.

Gualtieri, L., Rauch, E., & Vidoni, R. (2022). Development and validation of guidelines for safety in human-robot collaborative assembly systems. *Computers & Industrial Engineering, 163*, 107801.

Gualtieri, L., Rauch, E., Vidoni, R., & Matt, D. T. (2019). An evaluation methodology for the conversion of manual assembly systems into human-robot collaborative workcells. *Procedia Manufacturing, 38*, 358–366.

Halme, R. J., Lanz, M., Kämäräinen, J., Pieters, R., Latokartano, J., & Hietanen, A. (2018). Review of vision-based safety systems for human-robot collaboration. *Procedia CIRP, 72*, 111–116.

Hanna, A., Bengtsson, K., Dahl, M., Erős, E., Götvall, P. L., & Ekström, M. (2019). Industrial challenges when planning and preparing collaborative and intelligent automation systems for final assembly stations. In *2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)* (pp. 400–406). IEEE.

Hanna, A., Bengtsson, K., Götvall, P. L., & Ekström, M. (2020). Towards safe human robot collaboration-Risk assessment of intelligent automation. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)* (Vol. 1, pp. 424–431). IEEE.

Hassan, S. A., & Oddo, C. M. (2022). Tactile sensors for Material recognition in Social and Collaborative Robots: A brief review. In *2022 IEEE International Symposium on Medical Measurements and Applications (MeMeA)* (pp. 1–5). IEEE.

Heddy, G., Huzaifa, U., Beling, P., Haimes, Y., Marvel, J., Weiss, B., & LaViers, A. (2015). Linear temporal logic (LTL) based monitoring of smart manufacturing systems. In *Proceedings of the Annual Conference of the Prognostics and Health Management Society. Prognostics and Health Management Society. Conference* (Vol. 6). NIH Public Access.

Hjorth, S., & Chrysostomou, D. (2022). Human–robot collaboration in industrial environments: A literature review on non-destructive disassembly. *Robotics and Computer-Integrated Manufacturing, 73*, 102208.

Hollerer, S., Fischer, C., Brenner, B., Papa, M., Schlund, S., Kastner, W., Fabini, J., & Zseby, T. (2021). Cobot attack: a security assessment exemplified by a specific collaborative robot. *Procedia Manufacturing, 54*, 191–196.

Hopko, S., Wang, J., & Mehta, R. (2022). Human factors considerations and metrics in shared space human-robot collaboration: A systematic review. *Frontiers in Robotics and AI, 9*, 6.

Ibáñez, V. R., Pujol, F. A., Ortega, S. G., & Perpiñán, J. S. (2021). Collaborative robotics in wire harnesses spot taping process. *Computers in Industry, 125*, 103370.

Inkulu, A. K., Bahubalendruni, M. V. A. R., Dara, A., & Sankaranarayanasamy, K. (2022). Challenges and opportunities in human robot collaboration context of Industry 4.0—A state of the art review. *Industrial Robot, 49*(2), 226–239. https://doi.org/10.1108/IR-04-2021-0077

Inoue, S., Urata, A., Kodama, T., Huwer, T., Maruyama, Y., Fujita, S., Shinno, H. & Yoshioka, H. (2021). High-precision mobile robotic manipulator for reconfigurable manufacturing systems. *International Journal of Automation Technology*, *15*(5), 651–660. https://doi.org/10.20965/ijat.2021.p0651

Islam, S. O. B., Lughmani, W. A., Qureshi, W. S., Khalid, A., Mariscal, M. A., & Garcia-Herrero, S. (2019). Exploiting visual cues for safe and flexible cyber-physical production systems. *Advances in Mechanical Engineering, 11*(12), 1687814019897228.

Ismail, B. I., Khalid, M. F., Kandan, R., Ahmad, H., Mydin, M. N. M., & Hoe, O. H. (2020). Cobot fleet management system using cloud and edge computing. In *2020 IEEE 7th International Conference on Engineering Technologies and Applied Sciences (ICETAS)* (pp. 1–5). IEEE.

Jepsen, S. C., Worm, T., Johansen, A., Lazarova-Molnar, S., Kjægaard, M. B., Kang, E. Y., ... & Schwee, J. H. (2021). A research setup demonstrating flexible industry 4.0 production. In *2021 International Symposium ELMAR* (pp. 143–150). IEEE.

Kanazawa, A., Kinugawa, J., & Kosuge, K. (2019). Incremental learning of spatial-temporal features in human motion patterns with mixture model for planning motion of a collaborative robot in assembly lines. In *2019 International Conference on Robotics and Automation (ICRA)* (pp. 7858–7864). IEEE.

Karaulova, T., Andronnikov, K., Mahmood, K., & Shevtshenko, E. (2019). Lean automation for low-volume manufacturing environment. *Annals of DAAAM and Proceedings of the International DAAAM Symposium, 0059–0068*, 30.

Katiraee, N., Calzavara, M., Finco, S., Battini, D., & Battaïa, O. (2021). Consideration of workers' differences in production systems modelling and design: State of the art and directions for future research. *International Journal of Production Research, 59*(11), 3237–3268.

Keshvarparast, A., Battaia, O., Pirayesh, A., & Battini, D. (2022). Considering physical workload and workforce diversity in a collaborative assembly line balancing (C-ALB) optimization model. *IFAC-PapersOnLine, 55*(10), 157–162.

Keshvarparast, A., Katiraee, N., Finco, S., & Battini, D. (2021). Cobots implementation in manufacturing systems: literature review and open questions. *Proceedings of the Summer School Francesco Turco.*. https://www.research.unipd.it/handle/11577/3440137

Khalid, A., Kirisci, P., Khan, Z. H., Ghrairi, Z., Thoben, K. D., & Pannek, J. (2018). Security framework for industrial collaborative robotic cyber-physical systems. *Computers in Industry, 97*, 132–145.

Kitchenham, B. (2004). Procedures for performing systematic reviews. *Keele, UK, Keele University*, *33*(2004), 1–26. 10.1.1.122.3308

Koch, J., Büsch, L., Gomse, M., & Schüppstuhl, T. (2022). A methods-time-measurement based approach to enable action recognition for multi-variant assembly in human-robot collaboration. *Procedia CIRP, 106*, 233–238.

Kolyubin, S. A., Shiriaev, A. S., & Jubien, A. (2017). Refining dynamics identification for co-bots: Case study on KUKA LWR4+. *IFAC-PapersOnLine, 50*(1), 14626–14631.

Lacevic, B., Zanchettin, A. M., & Rocco, P. (2022). Safe Human-robot collaboration via collision checking and explicit representation of danger zones. *IEEE Transactions on Automation Science and Engineering*.

Lamon, E., Peternel, L., & Ajoudani, A. (2018). Towards a prolonged productivity in industry 4.0: A framework for fatigue minimisation in robot-robot co-manipulation. In *2018 IEEE-RAS 18th International Conference on Humanoid Robots (Humanoids)* (pp. 1–6). IEEE.

Lanzoni, D., Cattaneo, A., Vitali, A., Regazzoni, D., & Rizzi, C. (2022). Markerless motion capture and virtual reality for real-time ergonomic analysis of operators in workstations with collaborative robots: a preliminary study. In *Advances on Mechanics, Design Engineering and Manufacturing IV: Proceedings of the International Joint Conference on Mechanics, Design Engineering & Advanced Manufacturing, JCM 2022, June 1–3, 2022, Ischia, Italy* (pp. 1183–1194). Cham: Springer International Publishing.

Le, C.H., Le, D.T., Arey, D., Gheorghe, P., Chu, A.M., Duong, X.B., Nguyen, T.T., Truong, T.T., Prakash, C., Zhao, S.T. & Mahmud, J. (2020). Challenges and conceptual framework to develop heavy-load manipulators for smart factories. *International Journal of Mechatronics and Applied Mechanics, 8*(2), 209–216. http://gala.gre.ac.uk/id/eprint/29752

Lee, H., Liau, Y. Y., Kim, S., & Ryu, K. (2020). Model-based human robot collaboration system for small batch assembly with a virtual fence. *International Journal of Precision Engineering and Manufacturing-Green Technology, 7*, 609–623.

Lee, M. L., Behdad, S., Liang, X., & Zheng, M. (2022). Task allocation and planning for product disassembly with human–robot collaboration. *Robotics and Computer-Integrated Manufacturing, 76*, 102306.

Leng, J., Wang, D., Shen, W., Li, X., Liu, Q., & Chen, X. (2021). Digital twins-based smart manufacturing system design in Industry 4.0: A review. *Journal of Manufacturing Systems, 60*, 119–137.

Leyrer, T., Varis, P., Wallace, W., Gangadar, P., Mandhana, M., Jayarajan, P., & Karaiyan, S. (2021). Analysis and implementation of multi-protocol gigabit Ethernet switch for real-time control systems. In *2021 IEEE International Conference on Communications Workshops (ICC Workshops)* (pp. 1–6). IEEE. https://doi.org/10.1109/ICCWorkshops50388.2021.9473718

Li, G., Holseker, E., Khodabandeh, A., Sneltvedt, I. G., BjrnY, E., & Zhang, H. (2021a). Development of A Manufacturing System for Gear Assembly using Collaborative Robots. In *2021a IEEE International Conference on Mechatronics and Automation (ICMA)* (pp. 22–27). IEEE. https://doi.org/10.1109/ICMA52036.2021.9512631

Li, S., Zheng, P., Fan, J., & Wang, L. (2021b). Toward proactive human–robot collaborative assembly: A multimodal transfer-learning-enabled action prediction approach. *IEEE Transactions on Industrial Electronics, 69*(8), 8579–8588.

Li, X., Xu, W., Yao, B., Ji, Z., & Liu, X. (2022). Dynamic task reallocation in human-robot collaborative workshop based on online biotic fatigue detection. In *2022 IEEE 18th International Conference on Automation Science and Engineering (CASE)* (pp. 116–122). IEEE. https://doi.org/10.1109/ICMA52036.2021.9512631

Li, Z., Janardhanan, M. N., & Tang, Q. (2021c). Multi-objective migrating bird optimization algorithm for cost-oriented assembly line balancing problem with collaborative robots. *Neural Computing and Applications, 33*(14), 8575–8596.

Liao, H. Y., Chen, Y., Hu, B., & Behdad, S. (2023). Optimization-based disassembly sequence planning under uncertainty for human-robot collaboration. *Journal of Mechanical Design, 145*(2), 022001.

Lin, C. H., Wang, K. J., Tadesse, A. A., & Woldegiorgis, B. H. (2022). Human-robot collaboration empowered by hidden semi-Markov model for operator behaviour prediction in a smart assembly system. *Journal of Manufacturing Systems, 62*, 317–333.

Lin, C. J., & Lukodono, R. P. (2021). Sustainable human–robot collaboration based on human intention classification. *Sustainability, 13*(11), 5990.

Liu, H., & Wang, L. (2018). Gesture recognition for human-robot collaboration: A review. *International Journal of Industrial Ergonomics, 68*, 355–367.

Liu, H., & Wang, L. (2020). Remote human–robot collaboration: A cyber–physical system application for hazard manufacturing environment. *Journal of Manufacturing Systems, 54*, 24–34.

Liu, Y., Zhou, M., & Guo, X. (2022a). An improved Q-learning algorithm for human-robot collaboration two-sided disassembly line balancing problems. In *2022a IEEE International Conference on Systems, Man, and Cybernetics (SMC)* (pp. 568–573). IEEE. https://doi.org/10.1109/SMC53654.2022.9945263

Liu, Z., Liu, Q., Xu, W., Wang, L., & Zhou, Z. (2022b). Robot learning towards smart robotic manufacturing: A review. *Robotics and Computer-Integrated Manufacturing, 77*, 102360.

Lorenzo, R., Elisa, N., & Marco, M. (2022). Local digital twin-based control of a cobot-assisted assembly cell based on dispatching rules. *IFAC-PapersOnLine, 55*(2), 372–377.

Lu, L., Xie, Z., Wang, H., Li, L., & Xu, X. (2022a). Mental stress and safety awareness during human-robot collaboration-review. *Applied Ergonomics, 105*, 103832.

Lu, X., Li, X., Wang, W., Chao, K. M., Xu, L., De Vrieze, P., & Jing, Y. (2022b). A generic and modularized Digital twin enabled human-robot collaboration. In *2022b IEEE International Conference on e-Business Engineering (ICEBE)* (pp. 66–73). IEEE. https://doi.org/10.1109/ICEBE55470.2022.00021

Lucci, N., Monguzzi, A., Zanchettin, A. M., & Rocco, P. (2022). Workflow modelling for human–robot collaborative assembly operations. *Robotics and Computer-Integrated Manufacturing, 78*, 102384.

Maderna, R., Poggiali, M., Zanchettin, A. M., & Rocco, P. (2020). An online scheduling algorithm for human-robot collaborative kitting. In *2020 IEEE international conference on robotics and automation (ICRA)* (pp. 11430–11435). IEEE. https://doi.org/10.1109/ICRA40945.2020.9197431

Maderna, R., Pozzi, M., Zanchettin, A. M., Rocco, P., & Prattichizzo, D. (2022). Flexible scheduling and tactile communication for human–robot collaboration. *Robotics and Computer-Integrated Manufacturing, 73*, 102233.

Malik, A. A., & Bilberg, A. (2018). Digital twins of human robot collaboration in a production setting. *Procedia Manufacturing, 17*, 278–285. https://doi.org/10.1016/j.promfg.2018.10.047

Malik, A. A., & Bilberg, A. (2019a). Developing a reference model for human–robot interaction. *International Journal on Interactive Design and Manufacturing (IJIDeM), 13*(4), 1541–1547.

Malik, A. A., & Brem, A. (2021). Digital twins for collaborative robots: A case study in human-robot interaction. *Robotics and Computer-Integrated Manufacturing, 68*, 102092.

Malik, A. A., Andersen, M. V., & Bilberg, A. (2019). Advances in machine vision for flexible feeding of assembly parts. *Procedia Manufacturing, 38*, 1228–1235.

Malik, A. A., Masood, T., & Bilberg, A. (2020). Virtual reality in manufacturing: Immersive and collaborative artificial-reality in design of human-robot workspace. *International Journal of Computer Integrated Manufacturing, 33*(1), 22–37.

Malik, A. A., Masood, T., & Kousar, R. (2021). Reconfiguring and ramping-up ventilator production in the face of COVID-19: Can robots help? *Journal of Manufacturing Systems, 60*, 864–875.

Malik, A. A., & Bilberg, A. (2019b). Complexity-based task allocation in human-robot collaborative assembly. *Industrial Robot, 46*(4), 471–480. https://doi.org/10.1108/IR-11-2018-0231

Manoharan, M., & Kumaraguru, S. (2018). Path planning for direct energy deposition with collaborative robots: A review. In *2018 Conference on Information and Communication Technology (CICT)* (pp. 1–6). IEEE. https://doi.org/10.1109/INFOCOMTECH.2018.8722362

Matheson, E., Minto, R., Zampieri, E. G., Faccio, M., & Rosati, G. (2019). Human–robot collaboration in manufacturing applications: A review. *Robotics, 8*(4), 100.

Matthias, B., Kock, S., Jerregard, H., Kallman, M., Lundberg, I., & Mellander, R. (2011). Safety of collaborative industrial robots: Certification possibilities for a collaborative assembly robot concept. In *2011 IEEE International Symposium on Assembly and Manufacturing (ISAM)* (pp. 1–6). Ieee. https://doi.org/10.1109/ISAM.2011.5942307

Mateus, J. C., Claeys, D., Limère, V., Cottyn, J., & Aghezzaf, E. H. (2019). A structured methodology for the design of a human-robot collaborative assembly workplace. *The International Journal of Advanced Manufacturing Technology, 102*, 2663–2681.

Mendes, N., Safeea, M., & Neto, P. (2018). Flexible programming and orchestration of collaborative robotic manufacturing systems. In *2018 IEEE 16th International Conference on Industrial Informatics (INDIN)* (pp. 913–918). IEEE. https://doi.org/10.1109/INDIN.2018.8472058

Menegozzo, G., Dall'Alba, D., Roberti, A., & Fiorini, P. (2019). Automatic process modeling with time delays neural network based on low-level data. *Procedia Manufacturing, 38*, 125–132.

Minca, E., Dragomir, O. E., Dragomir, F., & Enache, M. A. (2011a). Temporal recurrent modelling appllied to manufacturing flexible lines served by collaborative robots. In *2011a 8th Asian Control Conference (ASCC)* (pp. 749–754). IEEE.

Minca, E., Dragomir, O. E., Dragomir, F., & Stefan, V. (2010). Application for manufacturing systems served by collaborative robots monitoring. In 2010 IEEE International Conference on Automation and Logistics (pp. 138–143). IEEE. https://doi.org/10.1109/ICAL.2010.5585397

Minca, E., Dragomir, O. E., Dragomir, F., Enache, M. A., & Radaschin, A. (2011b). Assembly-disassembly flexible lines and collaborative robots considered as hierarchical systems in temporal recurrent modelling. In *2011b 9th World Congress on Intelligent Control and Automation* (pp. 69–74). IEEE. https://doi.org/10.1109/WCICA.2011.5970637

Mitrea, D., & Tamas, L. (2018). Manufacturing execution system specific data analysis-use case with a cobot. *IEEE Access, 6*, 50245–50259.

Mohammadi Amin, F., Rezayati, M., van de Venn, H. W., & Karimpour, H. (2020). A mixed-perception approach for safe human–robot collaboration in industrial automation. *Sensors, 20*(21), 6347.

Mokaram, S., Aitken, J.M., Martinez-Hernandez, U., Eimontaite, I., Cameron, D., Rolph, J., Gwilt, I., McAree, O. & Law, J. (2017). A ROS-integrated API for the KUKA LBR iiwa collaborative robot. *IFAC-PapersOnLine*, *50*(1), 15859–15864. https://doi.org/10.1016/j.ifacol.2017.08.2331

Mosadeghzad, M., Kalym, D., Kaliyanurov, Z., & Alizadeh, T. (2019). Towards enhancing modular production systems by integrating a collaborative robotic manipulator. In *2019 IEEE International Conference on Mechatronics and Automation (ICMA)* (pp. 1750–1755). IEEE. https://doi.org/10.1109/ICMA.2019.8816444

Mueller, R., Marx, S., Kanso, A., & Adler, F. (2022). *Intuitive Robot programming and path planning based on human-machine interaction and sensory data for realization of various aircraft application scenarios* (No. 2022-01-0011). SAE Technical Paper. https://doi.org/10.4271/2022-01-0011

Müller, R., Vette, M., & Scholer, M. (2014). Inspector robot–a new collaborative testing system designed for the automotive final assembly line. *Assembly Automation, 34*(4), 370–378.

Naidoo, N., Bright, G., & Stopforth, R. (2019, January). A distributed framework for programming the artificial intelligence of mobile robots in smart manufacturing systems. In *2019 Southern African Universities Power Engineering Conference/Robotics and Mechatronics/Pattern Recognition Association of South Africa (SAUPEC/RobMech/PRASA)* (pp. 34–41). IEEE. https://doi.org/10.1109/RoboMech.2019.8704788

Navas-Reascos, G. E., Romero, D., Rodriguez, C. A., Guedea, F., & Stahre, J. (2022a). Wire harness assembly process supported by a collaborative robot: A case study focus on ergonomics. *Robotics, 11*(6), 131.

Navas-Reascos, G. E., Romero, D., Stahre, J., & Caballero-Ruiz, A. (2022b). Wire harness assembly process supported by collaborative robots: Literature review and call for R&D. *Robotics, 11*(3), 65.

Nelles, J., Kohns, S., Spies, J., Brandl, C., Mertens, A., & Schlick, C. M. (2016). Analysis of stress and strain in head based control of collaborative robots—A literature review. *Advances in Physical Ergonomics and Human Factor*. https://doi.org/10.1007/978-3-319-41694-6_70

Neumann, W. P., Winkelhaus, S., Grosse, E. H., & Glock, C. H. (2021). Industry 4.0 and the human factor—A systems framework and analysis methodology for successful development. *International Journal of Production Economics, 233*, 107992.

Nieto, W., Arias-Correa, M., & Madrigal-González, C. (2020). Acquisition and evaluation of depth data from humans, in robotized industrial environments. *Journal of Physics: Conference Series IOP Publishing, 1547*(1), 012016.

Nikolakis, N., Alexopoulos, K., Xanthakis, E., & Chryssolouris, G. (2019). The digital twin implementation for linking the virtual representation of human-based production tasks to their physical counterpart in the factory-floor. *International Journal of Computer Integrated Manufacturing, 32*(1), 1–12.

NMSC. (2022). Size of the collaborative (cobot) robot market worldwide in 2020 and 2021, with a forecast for 2022 to 2030 (in million U.S. dollars) [Graph]. In *Statista*. Retrieved March 08, 2022, from https://www.statista.com/statistics/748234/global-market-size-collaborative-robots/

Nogueira, R., Reis, J., Pinto, R., & Gonçalves, G. (2019). Self-adaptive cobots in cyber-physical production systems. In *2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)* (pp. 521–528). IEEE. https://doi.org/10.1109/ETFA.2019.8869165

Nourmohammadi, A., Fathi, M., & Ng, A. H. (2022). Balancing and scheduling assembly lines with human-robot collaboration tasks. *Computers & Operations Research, 140*, 105674.

Ogas, E., Avila, L., Larregay, G., & Moran, D. (2020). Object grasping with a robot arm using a convolutional network. *International Journal of Mechatronics and Automation, 7*(3), 113–121.

Olender, M., & Banas, W. (2019). Cobots–future in production. *International Journal of Modern Manufacturing Technologies, 11*(3), 103–109.

Oliff, H., Liu, Y., Kumar, M., & Williams, M. (2020). Improving human–robot interaction utilizing learning and intelligence: A human factors-based approach. *IEEE Transactions on Automation Science and Engineering, 17*(3), 1597–1610.

Pabolu, V. K. R., Shrivastava, D., & Kulkarni, M. S. (2022). A digital-twin based worker's work allocation framework for a collaborative assembly system. *IFAC-PapersOnLine, 55*(10), 1887–1892.

Panescu, D., Pascal, C., Sutu, M., & Varvara, G. (2009). Collaborative robotic system obtained by combining planning and holonic architecture. *2009 Advanced technologies for enhanced quality of life* (pp. 138–143). London: IEEE. https://doi.org/10.1109/AT-EQUAL.2009.36

Perno, M., Hvam, L., & Haug, A. (2022). Implementation of digital twins in the process industry: A systematic literature review of enablers and barriers. *Computers in Industry, 134*, 103558.

Peron, M., Sgarbossa, F., & Strandhagen, J. O. (2022). Decision support model for implementing assistive technologies in assembly activities: A case study. *International Journal of Production Research, 60*(4), 1341–1367.

Petzoldt, C., Niermann, D., Maack, E., Sontopski, M., Vur, B., & Freitag, M. (2022). Implementation and evaluation of dynamic task allocation for human-robot collaboration in assembly. *Applied Sciences, 12*(24), 12645.

Pieskä, S., Kaarela, J., & Mäkelä, J. (2018). Simulation and programming experiences of collaborative robots for small-scale manufacturing. In *2018 2nd International Symposium on Small-scale Intelligent Manufacturing Systems (SIMS)* (pp. 1–4). IEEE. https://doi.org/10.1109/SIMS.2018.8355303

Pinheiro, S., Correia Simões, A., Pinto, A., Van Acker, B.B., Bombeke, K., Romero, D., Vaz, M. & Santos, J. (2021). Ergonomics and safety in the design of industrial collaborative robotics: A systematic literature review. *Occupational and Environmental Safety and Health III*, 465–478. https://doi.org/10.1007/978-3-030-89617-1_42

Pizoń, J., Gola, A., & Świć, A. (2022). The role and meaning of the digital twin technology in the process of implementing intelligent collaborative robots. *Advances in manufacturing III: Volume 1-mechanical engineering: Research and technology innovations, Industry 4.0* (pp. 39–49). Cham: Springer International Publishing.

Prioli, J. P. J., & Rickli, J. L. (2020). Collaborative robot based architecture to train flexible automated disassembly systems for critical materials. *Procedia Manufacturing, 51*, 46–53.

Psulkowski, S., Frketic, J., Parker, H., Werner, R., & Dickens, T. (2020). Investigating inter-weld bonds under tension in mechatronic AM processing. *Composites and Advanced Materials Expo*, CAMX 2020. https://www.nasampe.org/store/viewproduct.aspx?id=17720103

Quenehen, A., Pocachard, J., & Klement, N. (2019). Process optimisation using collaborative robots-comparative case study. *IFAC-PapersOnLine, 52*(13), 60–65.

Ramasubramanian, A. K., Mathew, R., Kelly, M., Hargaden, V., & Papakostas, N. (2022). Digital twin for human-robot collaboration in manufacturing: Review and outlook. *Applied Sciences, 12*(10), 4811.

Realyvásquez-Vargas, A., Arredondo-Soto, K. C., García-Alcaraz, J. L., Márquez-Lobato, B. Y., & Cruz-García, J. (2019). Introduction and configuration of a collaborative robot in an assembly task as a means to decrease occupational risks and increase efficiency in a manufacturing company. *Robotics and Computer-Integrated Manufacturing, 57*, 315–328.

Rega, A., Vitolo, F., Di Marino, C., & Patalano, S. (2021). A knowledge-based approach to the layout optimization of human–robot collaborative workplace. *International Journal on Interactive Design and Manufacturing (IJIDeM), 15*(1), 133–135.

Robla-Gómez, S., Becerra, V. M., Llata, J. R., Gonzalez-Sarabia, E., Torre-Ferrero, C., & Perez-Oria, J. (2017). Working together: A review on safe human-robot collaboration in industrial environments. *IEEE Access, 5*, 26754–26773.

Romiti, E., Malzahn, J., Kashiri, N., Iacobelli, F., Ruzzon, M., Laurenzi, A., Hoffman, E.M., Muratore, L., Margan, A., Baccelliere, L. & Cordasco, S. (2021). Toward a plug-and-work reconfigurable cobot. *IEEE/ASME transactions on mechatronics, 27*(5), 3219–3231. https://doi.org/10.1109/TMECH.2021.3106043

Roveda, L., Testa, A., Shahid, A. A., Braghin, F., & Piga, D. (2022). Q-Learning-based model predictive variable impedance control for physical human-robot collaboration. *Artificial Intelligence, 312*, 103771.

Rojas, R. A., Garcia, M. A. R., Gualtieri, L., & Rauch, E. (2021). Combining safety and speed in collaborative assembly systems–An approach to time optimal trajectories for collaborative robots. *Procedia CIRP, 97*, 308–312.

Rückert, P., Adam, J., Papenberg, B., Paulus, H., & Tracht, K. (2018). Calibration of a modular assembly system for personalized and adaptive human robot collaboration. *Procedia CIRP, 76*, 199–204.

Rueckert, P., Muenkewarf, S., & Tracht, K. (2020). Human-in-the-loop simulation for virtual commissioning of human-robot-collaboration. *Procedia CIRP, 88*, 229–233.

Sadik, A. R., & Urban, B. (2017a). An ontology-based approach to enable knowledge representation and reasoning in worker–cobot agile manufacturing. *Future Internet, 9*(4), 90.

Sadik, A. R., & Urban, B. (2017b). Flow shop scheduling problem and solution in cooperative robotics—case-study: One cobot in cooperation with one worker. *Future Internet, 9*(3), 48.

Sadik, A. R., & Urban, B. (2017c). Towards a complex interaction scenario in worker-cobot reconfigurable collaborative manufacturing via reactive agent ontology-case-study: Two workers in cooperation with one cobot. In *Proceedings of the 9th International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management,* 27–38. https://doi.org/10.5220/0006487200270038

Sadik, A. R., & Urban, B. (2018). CPROSA-holarchy: An enhanced PROSA model to enable worker—cobot agile manufacturing. *International Journal of Mechanical Engineering and Robotics Research, 7*(3), 296–304. https://doi.org/10.18178/ijmerr.7.3.296-304

Sadik, A. R., Taramov, A., & Urban, B. (2017). Optimization of tasks scheduling in cooperative robotics manufacturing via johnson's algorithm case-study: One collaborative robot in cooperation with two workers. In *2017 IEEE conference on systems, process and control (ICSPC)* (pp. 36–41). IEEE. https://doi.org/10.1109/SPC.2017.8313018

Sanna, A., Manuri, F., Fiorenza, J., & De Pace, F. (2022). BARI: An affordable brain-augmented reality interface to support human-robot collaboration in assembly tasks. *Information, 13*(10), 460.

Sarkar, S., Ghosh, G., Mohanta, A., Ghosh, A., & Mitra, S. (2017). Arduino based foot pressure sensitive smart safety system for industrial robots. In *2017 Second International Conference on Electrical, Computer and Communication Technologies (ICECCT)* (pp. 1–6). IEEE. https://doi.org/10.1109/ICECCT.2017.8118009

Schmidt, B., Sánchez De Ocãna Torroba, A., Grahn, G., Karlsson, I., Ng, A. (2022). Augmented reality approach for a user interface in a robotic production system. In *SPS2022: Proceedings of the 10th Swedish Production Symposium* (Vol. 21, p. 240). IOS Press. https://doi.org/10.3233/ATDE220143

Schönberger, D., Lindorfer, R., & Froschauer, R. (2018). Modeling workflows for industrial robots considering human-robot-collaboration. In *2018 IEEE 16th International Conference on Industrial Informatics (INDIN)* (pp. 400–405). IEEE. https://doi.org/10.1109/INDIN.2018.8471999

Semeraro, F., Griffiths, A., & Cangelosi, A. (2023). Human–robot collaboration and machine learning: A systematic review of recent research. *Robotics and Computer-Integrated Manufacturing, 79*, 102432.

Serebrenny, V., Lapin, D., & Mokaeva, A. (2019a). The perspective flexible manufacturing system for a newly forming robotic enterprises: Transition framework from the concept to science-driven product. In *Lecture Notes in Engineering and Computer Science* (pp. 458–463).

Serebrenny, V., Lapin, D., & Mokaeva, A. (2019b). The perspective flexible manufacturing system for a newly forming robotic enterprises: approach to organization subsystem formation. In *Lecture notes in engineering and computer science: proceedings of the world congress on engineering and computer science* (pp. 438–441).

Sheikh, A., & Duffy, V. G. (2022). Revolutionizing ergonomics in manufacturing processes using collaborative robots: A systematic literature review. In *Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management. Anthropometry, Human Behavior, and Communication: 13th International Conference, DHM 2022, Held as Part of the 24th HCI International Conference, HCII 2022, Virtual Event, June 26–July 1, 2022, Proceedings, Part I* (pp. 289–305). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-05890-5_23

Shu, B., & Solvang, B. (2021). Architecture for task-dependent human-robot collaboration. In *2021 IEEE/SICE International Symposium on System Integration (SII)* (pp. 207–212). IEEE. https://doi.org/10.1109/IEEECONF49454.2021.9382703

Simões, A. C., Pinto, A., Santos, J., Pinheiro, S., & Romero, D. (2022). Designing human-robot collaboration (HRC) workspaces in industrial settings: A systematic literature review. *Journal of Manufacturing Systems, 62*, 28–43.

Soares, I., Petry, M., & Moreira, A. P. (2021). Programming robots by demonstration using augmented reality. *Sensors, 21*(17), 5976.

Sordan, J. E., Oprime, P. C., Pimenta, M. L., Lombardi, F., & Chiabert, P. (2022). Symbiotic relationship between robotics and Lean Manufacturing: A case study involving line balancing. *The TQM Journal, 34*(5), 1076–1095.

Stanescu, A. M., Nita, A., Moisescu, M. A., & Sacala, I. S. (2008). From industrial robotics towards intelligent robotic systems. In *2008 4th International IEEE Conference Intelligent Systems* (Vol. 1, pp. 6–73). IEEE. https://doi.org/10.1109/IS.2008.4670441

Statista. (2022a). Sales value of the industrial robotics market worldwide from 2018 to 2022a, by application area (in million U.S. dollars) [Graph]. In *Statista*. Retrieved March 08, 2022a, from https://www.statista.com/statistics/1018262/industrial-robotics-sales-value-worldwide-by-application-area/.

Statista. (2022b). Share of traditional and collaborative robot unit sales worldwide from 2018 to 2022b [Graph]. In *Statista*. Retrieved March 08, 2022b, from https://www.statista.com/statistics/1018935/traditional-and-collaborative-robotics-share-worldwide/

Stecke, K. E., & Mokhtarzadeh, M. (2022). Balancing collaborative human–robot assembly lines to optimise cycle time and ergonomic risk. *International Journal of Production Research, 60*(1), 25–47.

Stefanakos, I., Calinescu, R., Douthwaite, J., Aitken, J., & Law, J. (2022). Safety controller synthesis for a mobile manufacturing cobot. In *Software Engineering and Formal Methods: 20th International Conference, SEFM 2022, Berlin, Germany, September 26–30, 2022, Proceedings* (pp. 271–287). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-17108-6_17

Storm, F.A., Chiappini, M., Dei, C., Piazza, C., André, E., Reißner, N., Brdar, I., Delle Fave, A., Gebhard, P., Malosio, M. & Peña Fernández, A. (2022). Physical and mental well-being of cobot workers: A scoping review using the Software–Hardware–Environment–Liveware–Liveware–Organization model. *Human Factors and Ergonomics in Manufacturing & Service Industries, 32*(5), 419–435. https://doi.org/10.1002/hfm.20952

Sun, X., Zhang, R., Liu, S., Lv, Q., Bao, J., & Li, J. (2021). A digital twin-driven human–robot collaborative assembly-commissioning method for complex products. *The International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-021-08211-y

Thomas, A., Guerra-Zubiaga, D. A., & Cohran, J. (2018). Digital factory: Simulation enhancing production and engineering process. In *ASME International Mechanical Engineering Congress and Exposition* (Vol. 52019, p. V002T02A077). American Society of Mechanical Engineers. https://doi.org/10.1115/IMECE2018-88334

Toichoa Eyam, A., Mohammed, W. M., & Martinez Lastra, J. L. (2021). Emotion-driven analysis and control of human-robot interactions in collaborative applications. *Sensors, 21*(14), 4626.

Tuli, T. B., Henkel, M., & Manns, M. (2022). Latent space based collaborative motion modeling from motion capture data for human robot collaboration. *Procedia CIRP, 107*, 1180–1185.

Unger, H., Markert, T., & Müller, E. (2018). Evaluation of use cases of autonomous mobile robots in factory environments. *Procedia Manufacturing, 17*, 254–261. https://doi.org/10.1016/j.promfg.2018.10.044

Unhelkar, V. V., & Shah, J. A. (2015). Challenges in developing a collaborative robotic assistant for automotive assembly lines. In *Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction Extended Abstracts* (pp. 239–240). https://doi.org/10.1145/2701973.2702705

Valente, A., Pavesi, G., Zamboni, M., & Carpanzano, E. (2022). Deliberative robotics–a novel interactive control framework enhancing human-robot collaboration. *CIRP Annals, 71*(1), 21–24.

Vieira, M., Moniz, S., Gonçalves, B. S., Pinto-Varela, T., Barbosa-Póvoa, A. P., & Neto, P. (2022). A two-level optimisation-simulation method for production planning and scheduling: The industrial case of a human–robot collaborative assembly line. *International Journal of Production Research, 60*(9), 2942–2962.

Von Drigalski, F., Schlette, C., Rudorfer, M., Correll, N., Triyonoputro, J. C., Wan, W., Tsuji, T., & Watanabe, T. (2020). Robots assembling machines: learning from the world robot summit 2018 assembly challenge. *Advanced Robotics, 34*(7–8), 408–421. https://doi.org/10.1080/01691864.2019.1705910

Wada, H., Kinugawa, J., & Kosuge, K. (2021). Reactive motion planning using time-layered C-spaces for a collaborative robot PaDY. *Advanced Robotics, 35*(8), 490–503.

Wang, C., & Lu, L. (2016). Building lightweight robots using single-motor drives—a survey and concept study. In *2016 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)* (pp. 676–682). IEEE. https://doi.org/10.1109/AIM.2016.7576846

Wang, K. B., Dailami, F., & Matthews, J. (2019). Towards collaborative robotic polishing of mould and die sets. *Procedia Manufacturing, 38*, 1499–1507.

Wang, X., Setchi, R., & Mohammed, A. (2022a). Modelling uncertainties in human-robot industrial collaborations. *Procedia Computer Science, 207*, 3652–3661.

Wang, Y., Feng, J., Liu, J., Liu, X., & Wang, J. (2022b). Digital twin-based design and operation of human-robot collaborative assembly. *IFAC-PapersOnLine, 55*(2), 295–300.

Weckenborg, C., & Spengler, T. S. (2019). Assembly line balancing with collaborative robots under consideration of ergonomics: A cost-oriented approach. *IFAC-PapersOnLine, 52*(13), 1860–1865.

Weckenborg, C., Kieckhäfer, K., Müller, C., Grunewald, M., & Spengler, T. S. (2020). Balancing of assembly lines with collaborative robots. *Business Research, 13*(1), 93–132.

Wedin, K., Johnsson, C., Åkerman, M., Fast-Berglund, Å., Bengtsson, V., & Alveflo, P. A. (2020). Automating nut tightening using Machine Learning. *IFAC-PapersOnLine, 53*(2), 10291–10296.

Weichhart, G., Fast-Berglund, Å., Romero, D., & Pichler, A. (2018). An agent-and role-based planning approach for flexible automation of advanced production systems. In: *2018 International Conference on Intelligent Systems (IS)* (pp. 391–399). IEEE. https://doi.org/10.1109/IS.2018.8710546

Welfare, K. S., Hallowell, M. R., Shah, J. A., & Riek, L. D. (2019). Consider the human work experience when integrating robotics in the workplace. In *2019 14th ACM/IEEE international conference on human-robot interaction (HRI)* (pp. 75–84). IEEE. https://doi.org/10.1109/HRI.2019.8673139

Wojtynek, M., & Wrede, S. (2020). InteractiveWorkspace Layout focusing on the reconfiguration with collaborative robots in modular production systems. In *ISR 2020; 52th International Symposium on Robotics* (pp. 1–8). VDE.

Wojtynek, M., Leichert, J., & Wrede, S. (2020). Assisted planning and setup of collaborative robot applications in modular production systems. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)* (Vol. 1, pp. 387–394). IEEE. https://doi.org/10.1109/ETFA46521.2020.9212083

Wojtynek, M., Steil, J. J., & Wrede, S. (2019). Plug, plan and produce as enabler for easy workcell setup and collaborative robot programming in smart factories. *KI-Künstliche Intelligenz, 33*(2), 151–161.

Xiang, C., Liu, P., Guo, J., Wang, J., Qin, S., Qi, L., & Zhao, J. (2022). Multi-neighborhood parallel greedy search algorithm for human-robot collaborative multi-product hybrid disassembly line balancing problem. In *2022 IEEE International Conference on Systems, Man, and Cybernetics (SMC)* (pp. 866–871). IEEE. https://doi.org/10.1109/SMC53654.2022.9945502

Xu, W., Cui, J., Liu, B., Liu, J., Yao, B., & Zhou, Z. (2021). Human-robot collaborative disassembly line balancing considering the safe strategy in remanufacturing. *Journal of Cleaner Production, 324*, 129158.

Yan, Y., & Jia, Y. (2022). A review on human comfort factors, measurements, and improvements in human-robot collaboration. *Sensors, 22*(19), 7431.

Yao, X., Ma, N., Zhang, J., Wang, K., Yang, E., & Faccio, M. (2022). Enhancing wisdom manufacturing as industrial metaverse for industry and society 5.0. *Journal of Intelligent Manufacturing*. https://doi.org/10.1007/s10845-022-02027-7

Ye, Z., Jingyu, L., & Hongwei, Y. (2022). A digital twin-based human-robot collaborative system for the assembly of complex-shaped architectures. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. https://doi.org/10.1177/09544054221110960

Yi, S., Liu, S., Xu, X., Wang, X. V., Yan, S., & Wang, L. (2022). A vision-based human-robot collaborative system for digital twin. *Procedia CIRP, 107*, 552–557.

Yu, T., & Chang, Q. (2022). Motion planning for human-robot collaboration based on reinforcement learning. In *2022 IEEE 18th International Conference on Automation Science and Engineering (CASE)* (pp. 1866–1871). IEEE. https://doi.org/10.1109/CASE49997.2022.9926471

Yu, T., Huang, J., & Chang, Q. (2020). Mastering the working sequence in human-robot collaborative assembly based on reinforcement learning. *IEEE Access, 8*, 163868–163877.

Yu, Y. H., & Zhang, Y. T. (2022). Collision avoidance and path planning for industrial manipulator using slice-based heuristic fast marching tree. *Robotics and Computer-Integrated Manufacturing, 75*, 102289.

Zaatari, S. E., Wang, Y., Hu, Y., & Li, W. (2022). An improved approach of task-parameterized learning from demonstrations for cobots in dynamic manufacturing. *Journal of Intelligent Manufacturing, 33*(5), 1503–1519.

Zaid, I. M., Halwani, M., Ayyad, A., Imam, A., Almaskari, F., Hassanin, H., & Zweiri, Y. (2022). Elastomer-based visuotactile sensor for normality of robotic manufacturing systems. *Polymers, 14*(23), 5097.

Zhang, R., Li, J., Zheng, P., Lu, Y., Bao, J., & Sun, X. (2022a). A fusion-based spiking neural network approach for predicting collaboration request in human-robot collaboration. *Robotics and Computer-Integrated Manufacturing, 78*, 102383.

Zhang, R., Lv, Q., Li, J., Bao, J., Liu, T., & Liu, S. (2022b). A reinforcement learning method for human-robot collaboration in assembly tasks. *Robotics and Computer-Integrated Manufacturing, 73*, 102227.

Zhang, S., & Jia, Y. (2020). Capability-driven adaptive task distribution for flexible Multi-Human-Multi-Robot (MH-MR) manufacturing systems. *SAE Technical Paper Series*. https://doi.org/10.4271/2020-01-1303

Zhang, S., Huang, H., Huang, D., Yao, L., Wei, J., & Fan, Q. (2022c). Subtask-learning based for robot self-assembly in flexible collaborative assembly in manufacturing. *The International Journal of Advanced Manufacturing Technology, 120*(9–10), 6807–6819.

Zhang, T., Du, Q., Yang, G., Chen, C. Y., Wang, C., & Fang, Z. (2021a). A review of compliant control for collaborative robots. In *2021a IEEE 16th Conference on Industrial Electronics and Applications (ICIEA)* (pp. 1103–1108). IEEE. https://doi.org/10.1109/ICIEA51954.2021.9516193

Zhang, T., Sun, H., Zou, Y., & Chu, H. (2022d). An electromyography signals-based human-robot collaboration method for human skill learning and imitation. *Journal of Manufacturing Systems, 64*, 330–343.

Zhang, Y. J., Liu, L., Huang, N., Radwin, R., & Li, J. (2021b). From manual operation to collaborative robot assembly: An integrated model of productivity and ergonomic performance. *IEEE Robotics and Automation Letters, 6*(2), 895–902.

Zhang, Z., Peng, G., Wang, W., Chen, Y., Jia, Y., & Liu, S. (2022e). Prediction-based human-robot collaboration in assembly tasks using a learning from demonstration model. *Sensors, 22*(11), 4279.

Zhao, J., Yang, F., Liu, W., Liu, F., Li, F., Wang, H., & Zhang, H. (2019). An approximation model based on kernel ridge regression for robot kinematics simulation. In *2019 IEEE 23rd International Conference on Computer Supported Cooperative Work in Design (CSCWD)* (pp. 313–318). IEEE. https://doi.org/10.1109/CSCWD.2019.8791915

Zhou, G., Luo, J., Xu, S., & Zhang, S. (2022). A cooperative shared control scheme based on intention recognition for flexible assembly manufacturing. *Frontiers in Neurorobotics*. https://doi.org/10.3389/fnbot.2022.850211

Zhou, G., Zhang, C., Li, Z., Ding, K., & Wang, C. (2020). Knowledge-driven digital twin manufacturing cell towards intelligent manufacturing. *International Journal of Production Research, 58*(4), 1034–1051.

Zhu, Q., Huang, S., Wang, G., Moghaddam, S. K., Lu, Y., & Yan, Y. (2022). Dynamic reconfiguration optimization of intelligent manufacturing system with human-robot collaboration based on digital twin. *Journal of Manufacturing Systems, 65*, 330–338.