Cobots implementation in manufacturing systems: literature review and open questions

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Abstract: In companies, Industry 4.0 technologies offer several advantages in terms of flexibility, data availability and fast reaction to changes. Some of these systems can couple the benefits of human flexibility with assistive technology as collaborative robots (Cobots). Although the recent literature has already discussed how Cobots could bring many benefits to the manufacturing system, their use still requires significant knowledge about system features, design methods for semi-automatic manufacturing lines/cells, micro and macro layout configuration, the impact of Cobots on humans, and more. Without adequate knowledge of the impact of Cobots on the different parts of the manufacturing system, the use of Cobots could find several barriers and practical limits in the short future. In this paper, we try to investigate the Cobots' impact on manufacturing systems and their interaction with humans. To achieve this goal, we conduct a structured literature review. In particular, we classify selected papers by considering the methodology used and some performance factors. Finally, we propose some open questions and a future research agenda.

Keywords: Cobots; Collaborative Robots; Literature Review; Manufacturing System; Industry 4.0

1.Introduction

With a rapid introduction of new products, mass customization and competitive markets, manufacturers are facing new business challenges (Simmert et al. 2019). Therefore, companies are driving towards the so-called fourth industrial revolution, known as industry 4.0, to fulfil the need for faster delivery times, more efficient and automated process, higher quality and customized products (Zheng et al., 2020). In the Industry 4.0 era, production systems can monitor physical processes, create a digital twin of the physical world, and make smart decisions.

Collaborative robots (Cobots) are one of the technological pillars of Industry 4.0. Unlike robots, Cobots are more flexible, cheaper, and smaller. These features and market demands make manufacturers tend to use Cobots in their production systems. At the beginning of the new millennium, the usage and development rate of Cobots were slow, but in the last decade, regarding the development of sensors and Artificial Intelligence (AI), Cobots have been applied significantly. This pattern also is happening in the research area. Over the past decade, researchers have paid more attention to Cobots in their research. In this study, our main aim is to analyse the literature in order to investigate the interactions between humans and Cobots and how they affect the performances of the production systems.

Several review articles have been published focusing on the nature of Cobots themselves, with a special focus on the designing phase (Robla et al, 2017, Liu and Wang 2018, El Zaatari et al, 2019) without discussing how Cobots and humans collaborate in shared workspace environments. Although designing a better Cobot is important, however, the management aspect of human-Cobot collaboration should not be neglected. Using an up-to-date Cobot does not ensure the development of a production system. The questions are how we can implement a Cobot in production system to gain more benefits and what the benefits are. For this reason, the work provides a state-of-the-art analysis in order to identify what has been done to provide new strategies and methods for the implementing a safe and ergonomic workplace by considering all the factors that influence the collaboration between humans and Cobots.

The remainder of this paper is structured as follows. In Section 2, we explain the literature selection methodology. In Section 3, we analyze and categorize the selected papers. Finally, in Section 4, open questions on this topic are provided and discussed.

2. Research Methodology

The literature search was conducted using the Scopus database. We started by considering all papers published in journals from their inception until the end of February 2020, then also conference papers from 2020 up to the end of February 2021 was screened. The literature search consisted of the 4 steps shown in Table 1. In the primary step, a first selection of 1859 papers have been obtained by using the keywords: "collaborative robot" or "Cobot" in the title, abstract or keywords. Based on the Scopus database, 85% of papers in the field of collaborative robots have been published after 2010. According to the 1859 papers, most of the studies have focused on developing new Cobots and improving the existing ones. Besides, we used the VOSviewer software for the found 1859 papers in our initial search to visualize (1) how the attention towards this issue has evolved over the years, and (2) how selected keywords were connected in previous studies, as seen in Figure 1. Basis on the figure 1, although this issue has been considered from the past years (the year 1980), the top-most repeated keywords in previous studies regarding Cobots have been considered recently, particularly human-robot collaboration and interaction in the context of production systems such as assembly systems.

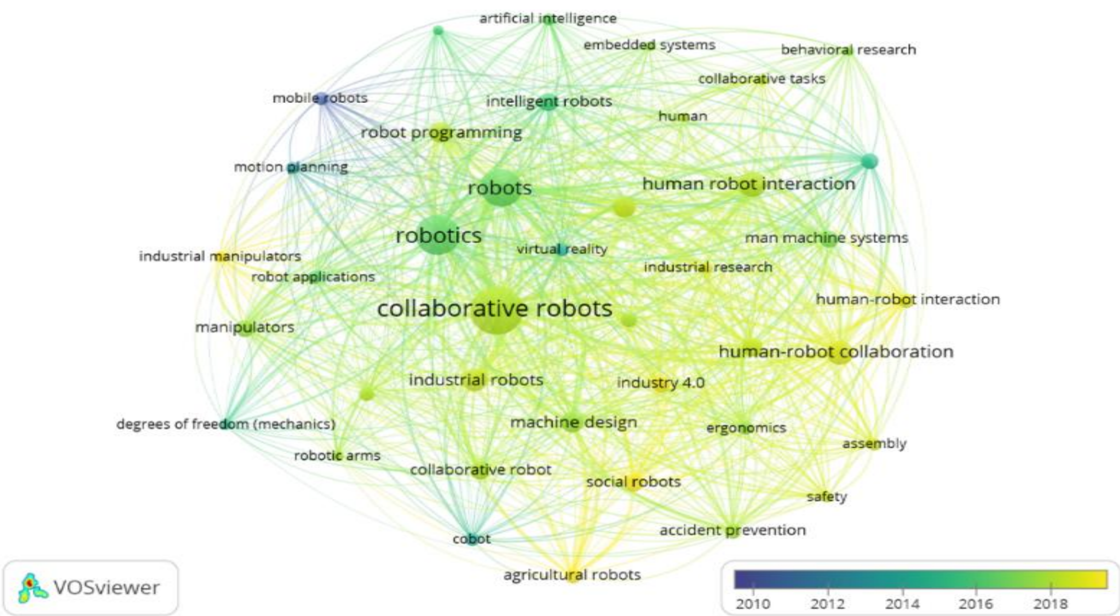

Figure 1: co-occurrence keywords network of the 1859 papers according to the year of publication

In the second step of the search methodology, the keywords used in the first step have been coupled with the keywords: "production systems", "manufacturing system", "assembly" and "disassembly".
The query has been limited to only papers written in English with the subject area "Engineering" or "Computer Science". At the end of the third step, 181 papers have been found according to the selection criteria. The 181 papers have been analysed initially by reading the abstract, methodology and conclusions; further, the full paper has been taken into consideration for the content analysis. We used a content analysis to select the final papers set by using the two questions as follow:

1) How Cobots have been analysed in the selected papers?
   1.1) with a focus only on the Cobots performances and characteristics,
   1.2) with a focus on Cobots and humans together
   1.3) with a focus on Cobots inside the whole production system
2) What is the main focus of papers which have considered Cobots and humans together qt point 1.2?
   2.1) Interaction between humans and Cobots
   2.2) General descriptions/considerations

The final paper selection consisted in all papers which have addressed categories 1.3 and 2.1 and we found in total 36 papers. To classify the final 36 papers, we have considered three main dimensions: 1) the paper target: (i) if they have considered the production performance improvement by applying Cobots or (ii) they have put attention on the interaction of humans and Cobots with aim of improving or measuring performance. 2) the methodology applied: mathematical approach, simulation, framework, comparative case study or artificial intelligent and finally 3) performance factors addressed: safety, cost, flexibility, productivity or ergonomic (in Table 2).

3. Literature Analysis Comparison and Categorisation

Table 1: Review methodology and steps adopted.

Step	Keywords	Selection Criteria	Content Analysis	Paper found	Paper Used
1	Title, Abstract, Keywords = "collaborative robot" or "cobot"			1859	
2	Title, Abstract, Keywords = "collaborative robot" or "cobot" **AND** Title, Abstract, Keywords = "production system" or "manufacturing system" or "assembly" or "disassembly")			358	
3		Limit-to Document Type = "article" and "Conference") **AND** Limit-to Subject Area = "Engineering" or "Computer Science" **AND** Limit-to Language = "English" **AND** Limit-to-Date = "Conference from 2020"		181	
4			Studies which have put attention on the 1) collaboration of human and Cobots with the target of improving or measuring performance and 2) the production performance improvement by applying Cobots.		**36**

Table 2 categorizes the selected 36 papers according to the three different dimensions which have been already described in Section 2 including research target, methodology and performance factors. Performance factors in evaluation are important because based on different performance factors the result of the evaluation will be various. For example, a safer system is not necessarily a more productive system. Thus, choosing the performance factors for evaluations is of paramount importance for every researcher. In this section, a summary of the selected papers is presented according to the defined dimensions. We classified the papers according to the macro performance factors which have been identified by reading all the 36 selected papers. The performance factors can be clustered as follows:

Safety: Unlike traditional industrial robots, , which workers were restricted from approaching the robots by using barriers , Cobots freely interact with the workforce. A safe collaboration between human and Cobots is collaboration without collision and wounded. (Rojas et al, 2020) That is the reason why safety is a fundamental factor in the design phase of a Cobot, and The International Organization for Standardization (ISO) outline some methods for safe collaborative work (ISO 10218-1 and ISO 10218-2). The safety standards address four collaborative scenarios: safety-rated monitored stop, hand guiding, speed and separation monitoring (SSM), and power and force limiting. (Costanza et al., 2021)

Cost: Economic aspect of using Cobots is more complicated. Costs can be considered in the design phase and the functional phase. In the design phase, researchers want to reduce the cost of designing or building Cobots. In the functional phase, researchers are trying to reduce the cost of implementation of new Cobots in a

Table 2. Classification of the 36 selected papers

				Target		Methodology					Performance Factor				
Row	**Year**	**Source**	**Authors**	**Human and Cobot interaction**	**Production system with Cobot**	**Mathematical approach**	**Simulation**	**Framework**	**Comparative Case Study**	**Artificial Intelligence**	**Safety**	**Cost**	**Flexibility**	**Productivity**	**Ergonomics**
1	2016	Article	Djuric & et al.		*			*			*	*		*	
2	2017	Article	Sadik A.R., Urban B.	*						*				*	
3	2017	Article	Gil-Vilda & et al.		*				*					*	
4	2018	Article	Bruno G., Antonelli D.	*				*		*				*	
5	2018	Article	Cencen & et al.		*			*							
6	2018	Article	Wang & et al.	*		*						*		*	*
7	2019	Article	Quenehen & et al.		*				*					*	
8	2019	Article	Weckenborg & et al.		*	*								*	*
9	2019	Article	Mateus & et al.		*			*			*		*	*	*
10	2019	Article	Faccio & et al.	*		*						*		*	
11	2019	Article	Malik A.A., Bilberg A.	*				*			*			*	
12	2019	Article	Stadnicka D., Antonelli D.	*				*			*			*	
13	2019	Article	Antonelli D., Bruno G.	*				*		*				*	
14	2019	Article	Dalle Mura M., Dini G.	*		*						*			*
15	2019	Article	Huang J. & et al.		*			*					*		
16	2020	Conference	Pamminger & et al.		*		*					*		*	*
17	2020	Conference	Quenehen & et al.		*	*						*		*	*
18	2020	Conference	Abdous & et al.		*	*						*			*
19	2020	Conference	Zhang S., Jia Y.	*		*								*	
20	2020	Conference	Maderna & et al.	*		*								*	*
21	2020	Conference	Karami & et al.	*				*					*		
22	2020	Conference	Wojtynek & et al.	*			*						*		
23	2020	Article	Colim & et al.	*				*							*
24	2020	Article	Rega & et al.	*				*			*				*
25	2020	Article	Peron & et al.	*		*						*			
26	2020	Article	Faccio & et al.	*		*								*	
27	2020	Article	Fager & et al.		*	*						*			
28	2020	Article	Fager & et al.		*	*								*	
29	2021	Article	Zhang & et al.	*		*								*	*
30	2021	Conference	Goos & et al.	*						*					*
31	2021	Article	Li & et al.		*	*						*		*	
32	2021	Article	Gualtieri & et al.		*			*						*	
33	2021	Article	Boschetti & et al.	*		*								*	
34	2021	Article	Costanzo & et al.	*						*	*				
35	2021	Conference	Schmidbauer & et al.	*				*					*	*	
36	2021	Article	Cohen & et al.	*	*	*		*				*		*	

manufacturing system, cost of maintenance, cost of collaboration and cost of production. Since we focus our attention on the interaction between cobots and humans only papers that include costs in the functional phase have been selected.

Flexibility: it can be divided into two categories. First, how fast the Cobots can reprograming for new procedures, second, what number of tasks can Cobots possibly do (design of work cell). Flexibility is usually considered in the design phase of a Cobot. With considering Flexibility in the design phase, Cobot manufacturers try to design and develop a new Cobot that able to handle various tasks. Flexibility in implementation refers to cell designing. Where the Cobot should locate in a cell.

Productivity: Productivity or cycle time will be considered the number of products that will be produced at a certain time or in other words, how long it will be taken to produce a single product. Productivity is the most repeated factor in the selected papers. The meaning of productivity in different papers are the same, but it was considered in both the design phase and the operational phase.

Ergonomy: In the industrial environment, to evaluate workers' well-being, health conditions and risk assessment, different ergonomic methods and indexes have been applied based on the data which measure physical activities such as RULA, REBA, OCRA, etc.

According to the performance factors classification, we now conduct the literature analysis for the 36 papers we selected. As we can see in Table 2, some papers can analyse more performance factors at the same time.
Djuric et al. (2016) provided a framework for designing and implementing Cobots. Their framework consists of the system level, work-cell level, machine level, and worker level. They considered safety, cost and productivity as the performance factors in all four level. Sadik and Urban (2017) used Holonic control architecture and artificial agents to solve a flow shop scheduling problem with one worker and one Cobot. They tried to reduce the time of producing a product, so they consider productivity as their performance factor. Gil-Vilda et al. (2017) and Quenehen et al, (2018), in a real case study, implemented a Cobot in a U-Shape assembly line and woke cell to figure out using a Cobot can improve the productivity of the U-Shape assembly line. Bruno and Antonelli (2018) and Antonelli and Bruno (2019) these papers have two steps. In the first step, they classified the tasks based on the task description. In the second step, they provided a framework for task assignment to human and Cobots in a collaborative work cell regarding improving productivity. Cencen et al, (2018) provided a methodology for designing collaboration between human and Cobots. they did not want to reduce the cost and time of collaboration, but they tried to reduce the cost and time of designing a collaboration system. Wang et al, (2018) developed a framework for online optimizing task scheduling for Cobot. In this way, they used a cost function and considered cost, productivity and ergonomy. They tried to reduce the human effort in their optimization.
Weckenborg and Spengler (2019) developed the first mathematical modelling to optimize the implementation of Cobot in an assembly line. Productivity was their evaluation factor in their optimization, but their used ergonomy constraint, mean work rate (MWR), in their model. Mateus et al, (2019) developed a methodology for designing the collaborative cell. In this paper, they mentioned that safety, flexibility, productivity and ergonomic should be considered in the design phase. In their eyes, a flexible collaborative cell can manage more different tasks, and an ergonomic collaborative cell will prevent physical overexertion. Faccio et al, (2019) developed a new mathematical modelling for comparison between different robotic assembly line by considering the direct cost of production and time of production as the performance factors. Malik and Bilberg (2019) proposed a new framework for task allocation between human and Cobots in a collaborative work cell. They considered task characteristics and based on that tried to improve the safety and productivity of a collaboration system. Stadnicka and Antonelli (2019) had the same work but instead of task characteristic, they considered human skills for task assignment with the same factors. Dalle Mura and Dini (2019) developed a mathematical model for designing an assembly line that uses collaborative robots to reduce the cost of production. They considered ergonomy, the physical workload on workforces, in the constrains. Huang et al, (2019) suggested a strategy for improving the flexibility of work cells to make a disassembly line capable of doing more different tasks. Pamminger et al, (2019) tried to develop a simulation approach for evaluating the cost, productivity, and workload of workers in a disassembly line before the implementation of a Cobot in a disassembly line. Quenehen et al, (2020) provide a mathematical approach for evaluating the collaboration of human and robots. For evaluation, they considered the cost of production in one equation and productivity and relaxation time (ergonomy) in another. Abdous et al, (2020) developed a mathematical model with two objective functions to design an assembly line that has Cobot. In the first objective function, they considered the fatigue and recovery model and tried to maximize the ergonomic level, and in the second one, they tried to minimize the cost of production. Zhang and Jia (2020) developed mathematical modelling for task distribution in a collaborative manufacturing system to increase the productivity of the manufacturing system. In their task distribution, they considered worker capability as a constraint. Maderna et al, (2020) proposed a new mathematical algorithm for online scheduling of Cobots' task to maximize productivity and reduce worker efforts. Karami et al, (2020) used the FLEXHRC framework for allocating tasks to human and Cobots. this approach designed to make collaboration more flexible. Wojtynek et al, (2020) also provided an assistive approach for designing a flexible collaborative workspace. Colim et al, (2020) proposed a new framework for designing more ergonomic assembly line. They used the Ergonomic Workplace Analysis (EWA) method which has 14 topics. (like general physical activity, lifting task, …) Rega et al,

(2020) proposed a knowledge base approach for designing a collaboration between human and Cobots regarding increasing safety and productivity. Peron et al, (2020) introduced a decision support model for implementing Cobots and other assistive equipment in the manufacturing system. The evaluation factor of this DSM is the cost of production. Faccio et al, (2020) provided a mathematical model for evaluating the performance of collaboration between human and Cobots. in this paper, product characteristics were considered as an effective factor in the collaboration. Fager et al, (2020) in two different paper developed mathematical modelling for a human and robot collaborative picking system in an assembly line. The first mathematical modelling is cost-oriented, and the second one is time-oriented.

Zhang et al, (2021) suggested an integrated mathematical modelling for evaluating and optimizing the productivity and ergonomic risk in both manual and collaborative assembly line. Goos et al, (2021) used artificial intelligence for evaluating the ergonomic parameters of the assembly line. They used the RULA scoring system for evaluating the ergonomic score of each design and provide the possibility to select the more ergonomic favourable design. Li et al, (2021) proposed a multi-objective migrating birds optimization algorithm for optimizing cost and balancing an assembly line that uses Cobots. Gualtieri et al, (2021) defined a new methodology for evaluating assembly cycle time and a feasibility study for implementing Cobots. Boschetti et al, (2021) developed a new evaluation formula for evaluating the performance of collaboration between human and Cobots based on productivity. Costanzo et al, (2021) used an artificial intelligence approach (computer vision) to evaluate the safety factors of collaboration. Based on their approach, the critical issue of safety for each collaboration design can be determined. Schmidbauer et al, (2021) developed a framework for task-sharing between human and Cobots. the productivity and flexibility of the workspace are the two factors that they considered in their framework. Cohen et al, (2021) provide a summary of the major consideration aspect in the design phase of collaborative work-cell, then provide a mathematical productivity analysis.

4. Discussion and Open Questions

Our research shows that a growing attention has been dedicated to Cobots in last few years. Although the first article in this filed was published in 1980, until now, most of articles focused on robotic aspect of improving Cobots, while the interaction between human and Cobots only appeared a few years ago.

Figure 2 represents a heat map based on the information gather in Table 2. This heat map illustrates which kind of performance factors have been assessed by the different methodologies. Based on Figure 2, most of the 36 selected papers used a mathematical approach or (i.e., Faccio et al, 2019, Boschetti et al, 2021) framework as their methodology (i.e., Colim et al, 2020, Schmidbauer et al, 2021). On other hand, productivity is the most repeated factor for measuring the performance of collaboration between human and Cobots. Also, ergonomic and cost related performance factors have been largely considered, while safety and flexibility performance measures have been rarely applied.

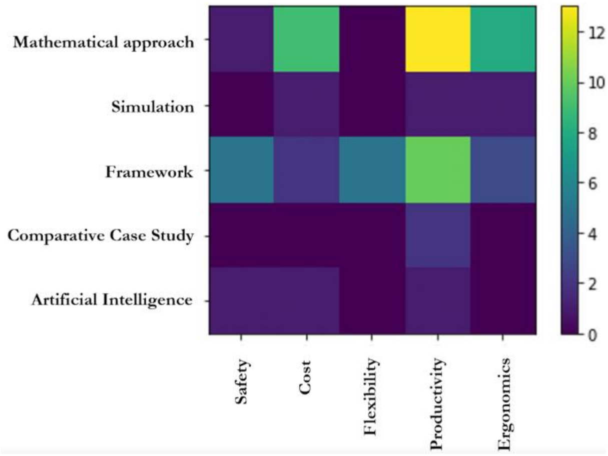

Figure 2: heat map representing the methodology and performance factors investigated in the 36 selected papers.

Also, as it shown in table 2, only two research considered human factors. Both of them considered skills of workers in their research and other human factors, such as age, gender, physical capacity are neglected.

According to the literature analysis discussed in the previous paragraph, it is possible to define some open research questions as follows.

QUESTION 1: Cobots are robots which have a close interaction with humans. Thus, the vital role of human factors and workers' differences, to improve the interaction between human and Cobots cannot be neglected. Workers can be different from each other in terms of various characteristics such as age, gender, skill and physical attributes and these differences can impact on the overall production systems and the human-cobot interaction (Katiraee et al, 2021; Neumann et al, 2021). However, up to now, the number of papers which have taken into account human diversity factors in the field of human-cobot interaction are rare. Therefore, a big open question that could be asked is linked to the impacts of workforce diversity on the interaction between human and Cobots. In particular, the effect of worker age and level of experience on the cobot acceptance level by humans need to be investigated.

QUESTION 2: In the work-cells with repetitive tasks, learning and forgetting curves have a great impact on the performance of system. Until now, there are numerous learning curve regarding to manual assembly line (i.e., Tamás and Kolta, 2020). However, the learning curve in using a cobot to perform a task has been never investigated in the analysed literature.

QUESTION 3: Task sharing between human and Cobots is a very important problem to reach an efficient interaction. Until now, there is only a few frameworks for solving this problem (i.e., Wang et al, 2018). New mathematical models should be developed to optimize the task sharing and task allocation between humans and cobots according to the specific objectives to be achieved. Here, different kinds of collaboration need to be deeply investigated and compared (sequential, simultaneously, parallel task allocation).

QUESTION 4: Delegating appropriate tasks to the cobot may relieve the operator of awkward postures or fatigue from repetition of load (i.e., Mateus et al, 2019). In those condition, designing such a process would result in solving a multi objective task allocation problem among human and cobot. However, there is a lack of investigation regarding the real ergo quality level of a task when it is performed in collaboration with a cobot, and more investigations are needed to support the hypothesis that cobot will always improve the ergo-level of the task.

QUESTION 5: Additional to all above open questions, a lack of real case studies and protocols to explain how to conduct laboratory testing with humans and cobots in order to collect data is missing. The real data collection is also a needed activity in this context, since only 2 works out of 36 provide a large data collection useful to support future research (i.e., Gil-Vilda 2017).

By answering these five questions, researchers can pave the way for the best use of robots. Answering any of these questions requires extensive research. In our research, we have tried to provide researchers with a proper classification of articles. Different performance indexes described, and the selected papers categorized based on performance factors and methodology. For the future research, we are going to provide more detailed descriptions about both performance factors and Cobots category in design and implementation phases.

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