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Human factors in cobot era: a review of modern production systems features

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Abstract

Collaborative robots are increasingly common in modern production systems, since they allow to merge the productivity of automated systems with the flexibility and dexterity of manual ones. The direct interaction between the human and the robot can be the greatest advantage and the greatest limit of collaborative systems at the same time, depending on how it affects human factors like ergonomics and mental stress. This work presents an overview of collaborative robotics considering three main dimensions: robot features, modern production systems characteristics and human factors. A literature review on how such dimensions interact is addressed and a discussion on the current state of the art is presented, showing the topics that have been already widely explored and the research gaps that should be fulfilled in the future.

Keywords Cobot · Modern production systems characteristics · Human factors

Introduction

In recent years, the demand for a new type of robots, collaborative robots, has increased (The International Federation of Robots, 2020). Indeed, despite the concept of lightweight collaborative robots was first presented by Colgate et al. (1996) as an Intelligent Assist Device (IAD), the requests of the current market have led to their spread during the last decade. This is due to their design, which allows them to share the workspace with human operators (Matheson et al., 2019), thus removing the physical barriers that divided the two resources. This reflects on their external shape, which typically has a smooth round appearance and the absence of sharp edges or rough surfaces, essential for safety and for preventing dangerous or clamping situations. Making the robot to share the workspace with the human operator allows to take advantage of the features of the two resources, combining the flexibility of the operator with the repeatability of the robot.

However, including a new automation within the operator workspace may influence the performance of the operator and introduce new variables to be included, which rely mostly on human factors. In fact, the cobot may not only be a physical obstruction, which reduces the achievable throughput (Faccio et al., 2020), but it may also be a source of psychological stress for the operator. Indeed, the operator is a complex resource to be included in a collaborative system, and as a result, his needs and perception are of great importance (Fletcher et al., 2020). This is especially true in the context of Industry 4.0 (I4.0), where new interconnected technologies are pushing to the integration of new devices in human-centered operations thus pushing the effort on specific human factors.

In this context, human factors are defined as the scientific discipline concerned with the understanding of interactions among human and other elements of a system, with the aim to develop principles, data, and methods used to design systems

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while optimizing human well-being and the overall system performance ISO 126800:2011 (2011). Previous works have proved the impact of human factors on the overall manufacturing process quality in terms of productivity and production cost (Peruzzini & Pellicciari, 2017). In fact, the literature reports that nearly 50–75% of implementations of automation have failed in terms of quality, flexibility and reliability (Chung, 1996), and this is mainly due to the inattention to human-related issues (Castrillón & Cantorna, 2005; Ghani & Jayabalan, 2000). This lack of consideration towards human factors might result in unsuccessful implementations as people will tend to feel frustrated, neglected, and overpowered by robots (Kinzel, 2017). On the other hand, focusing on human factors makes operators feel comfortable with the new technologies, improving their efficiency (Kulic & Croft, 2005). Hence, a major focus of the fourth industrial revolution should be the development of human-centered working environments employing technologies able to support the development of human-automation symbiosis work systems (Romero et al., 2016). Despite previous works have studied the human factors in modern production systems (Zarte et al., 2020; Rauch et al., 2020), this work focuses on human-robot collaboration (HRC) rather than the operator in I4.0.

Indeed, due to the growing interest in collaborative applications, in the last years some literature reviews have been proposed, such as (Matheson et al., 2019; Wang et al., 2019; Gualtieri et al., 2020c; Hentout et al., 2019; Hashemi-Petroodi et al., 2020). However, these works fails at studying the complex interaction of human operators and cobots in terms of modern production systems, i.e., how this interaction affects the features and the requirements of I4.0 technologies. In general, previous works have focused on the technologies and the capabilities related to cobots, their safety features and how their behavior can be influenced by appropriate algorithms. Moreover, despite the literature provides reviews regarding safety and ergonomics for industrial cobots (Gualtieri et al., 2020c), the concept of human factors is not properly examined when considering modern production systems (Industry 4.0) and cobots. We want to consider these interactions because the aim of researchers and practitioners is to design and manage collaborative "human centered" systems for human factors and to meet the characteristics of modern production systems imposed by increasingly demanding markets.

As a result, the aim of this work is to investigate how collaborative robots (cobots), human factors, and modern production systems do interact with each other and, moreover, how each aspect of the three dimensions affects the others. To reach this goal, a literature review is chosen as a suitable approach to identify the interaction between one (or more) of the aforementioned dimensions.

In particular this analysis wants to answer to some research questions:

- Are there any relationships between the three fields and if so what are the results in the literature?
- How should these interactions guide the design and the management models of collaborative systems?
- What are the research challenges in this area?

By studying the available literature it is possible to see where there are gaps to be filled by future works.

The paper is organized as follows: Sect.“ Key aspects” presents the considered dimensions of Human Factors, cobots and modern production systems, with their relative subdimensions; Sect.“ Methodology” presents the research method; the literature analysis is presented in Sect.“ Literature review”; a discussion on the collected data is shown in Sect.“ Discussion”; Sect.“ Conclusions” draws conclusions.

Key aspects

This section will describe the research focus of the literature considered in the presented review. For each of them, a set of sub-dimensions, i.e. research topics belonging to the three main dimensions.

Human factors

Human factors have been considered along technological aspects for the design of modern collaborative manufacturing workplaces in the context of Industry 4.0 (I4.0) to optimize the workplaces from a human-centered perspective, since they influence the performance of the whole collaborative task.

Similarly to Gervasi et al. (2020), this work adopts a conceptual framework to identify the dimensions of human factors by means of an extensive literature review on HRC problems. A similar approach have been used by Rücker et al. (2018). As a result, the following subdimensions were adopted to evaluate the human factors macro-topic, as summarised in Table 1. The considered human factors contains the specific human factors observed in the literature regarding human-robot collaboration while keeping a general form.

With greater detail, the *physical ergonomics* focuses on the anatomical, anthropometric, physiological, and biomechanical characteristics of humans in relation to collaborative activity. Indeed, it is well studied that musculoskeletal disorders, which are related to the layout, safety and health of the workplace, may impact on the performance of the system (Pini et al., 2016; Gualtieri et al., 2020b). The importance of physical ergonomics is in accordance with Hägele et al. (2002), who stated that one typical activity for industrial robots, thus for cobots, is to replace/aid human operators when a great physical effort is required, e.g., the handling of heavy loads. Moreover, ergonomics should be also consid-

Table 1 Human Factors research topics

Human factors	Description
Physical ergonomics	The physical and musculoskeletal, and sensorial aspects of working and collaborative activities
Mental Workload	The cognitive and emotional aspects related to the work demand (i.e., task complexity), and the human cognitive architecture (i.e., limited cognitive resources) and emotions and moods
Trust	The attitude that the robot helps to achieve a goal in a specific situation, related to the worker's understanding of the robot's abilities and the limitations (i.e., perceived safety, reliability, situation awareness and transparency, and robot motion and pick-up speed)
Acceptance	The aspects related to the subjective believes that the robot may increase the performance at work and that it may be usable without effort, also concerning the potential consequence of the cobot introducing at the workforce community level (e.g., workers role changes, job losses)
Usability	The aspects related to effectiveness, efficiency and satisfaction in achieving specific goals

ered to minimize risks that might derive from repetitive and forceful tasks (Bragança et al., 2019) that can be assigned even to cobots with small payloads. This is fundamental because it contributes to reducing the occupational risk factors related to *Musculoskeletal Disorders* (MSD), which are the most reported causes for absenteeism (Grosse et al., 2015).

Previous works have grouped the physical and mental efforts as workload (Gervasi et al., 2020). However, in this work we preferred to divide the mental efforts experienced by the operator and group the physical efforts with ergonomics. Hence, the *mental workload* subdimension is focused on the mental efforts due to cognitive and/or external stressors, which may be related to the work demand(i.e., task complexity, switching, and instruction format) and the human cognitive architecture (i.e., limited cognitive resources and working memory capacity) (Van Acker et al., 2018). Moreover, the considered mental workload is not only associated with the short-term response to external stressors, modulated by individual preconditions and resources, but also to the emotions and moods experienced by humans which may affect the operator in terms of job performance and satisfaction, and well-being, defined as "affective state" (Rosen et al., 2018).

Trust refers to the factors related to the worker's understanding of the robot's abilities and limitations, i.e. is about how much workers feel comfortable working with collaborative robots and the extent to which the workers believe to be able to accomplish a task through the interaction with it. Hence, it depends on the information available to the workers and the operator experience, especially in case of robot failure (Charalambous et al., 2016). For this reason, trust depends on the operator training and experience and it is critical to bring into being the collaboration and to its success. Moreover, as reported by Hancock et al. (Hancock et al., 2011) human trust is influenced by three sub-categories, namely human-related (e.g., operator's expertise), robot-related (e.g., transparency, the number of information presented to the operator) and environmental-related (e.g., task complexity). It is clear how both cobot and modern systems can directly influence the trust level based on how they are designed.

This is different from the *acceptance* dimension, i.e. the factors influencing the users' opinion and consequently usage/non-usage of a technology. These factors may be related to individual and cultural characteristics (e.g., age, robot experience, and national technological development, job automation) (Turja & Oksanen, 2019), as well to the self-efficacy perception, especially in the case of robots with anthropomorphic characteristics (Latikka et al., 2019). Moreover, it does not only consider the social acceptance, but also the consequence of the cobot introduced in the workforce community (workers role changes, job losses) (Gervasi et al., 2020). The acceptance criterion is therefore assumed to be a self-standing category since robot acceptance is a crucial factor for the success of collaboration (Müller-Abdelrazeq et al., 2019).

Lastly, the *usability* dimension represents the aspects regarding the easiness and satisfaction when using the cobot. Indeed, it is not only important that the operator is capable of operating the cobot with a minimum amount of errors quickly (efficaciously), but also that operating the cobot is satisfactory. A system with poor usability is especially detrimental for human-robot collaboration, since it may obstacle the achievement of shared goals characterizing this kind of interaction. This may lead to a reduction in the use of the cobot and therefore losing the advantages provided by these new systems.

Collaborative robots capabilities

Cobots are designed with particular features that distinguish them from traditional robots, defined by Michalos et al. in (2015) as technological and ergonomic requirements. As far as concerned cobots capabilities, the literature does not provide a clear classification.

A first list was made in (Dhillon, 2012) and it is still relevant; Cohen et al. (2019b) presented their own classification, reporting an exhaustive explanation. These last capabilities are also adopted in this work, as seen in Table 2.

Table 2 Cobot capabilities research topics

Cobot capabilities	Description
Mobility	The ability to easily move the cobot in the production plant
Adaptability	The awareness of the resources, the job characteristics and their implications
Connectivity	The ability to communicate with operators and other robot in the work environment, collecting and providing informatiory
Actuation	The ability to develop safe and smooth trajectories
Consistency	The ability to work in continuous without problems, unless malfunctions
Safety	The ability to work in synergy with the operators, without any risk for his physical and mental health

Thanks to the absence of rigid safety fences, cobots can be transferred from a workstation to another, ensuring a certain *mobility*. Some models present a mobile platform that simplifies this action, but recent studies focus on the possibility of adding cobots on AGV (Automated Guided Vehicles) (Hamner et al., 2010), thus creating a certain scale along this subdimension. Moreover, the mobility is guarantee by the reconfiguration of cobots (Rossi et al., 2020), thanks to their ability to be easy reprogrammed.

When compared to traditional industrial robots, cobots are usually equipped with additional sensors that improve their awareness of the surrounding space, leading to a certain degree of *adaptability*. Modern models have force/torque sensors on each joint that increase the perception of the robots, whereas other models have a camera near the end-effector. To make better use of these sensors, recent studies have been focused on the development of AI (Artificial Intelligence) algorithms (Cipriani et al., 2021). Thanks to these algorithms cobots can learn from their error (Isbell & Shelton, 2001). This means robots can be taught tasks only once, thus improving the usability of the cobot by simplifying the programming task. Furthermore, a given command can be erased if it is no longer useful and their non-volatile memory can be partitioned to have better use of it. The cobots usability is also related to the *connection* between humans and robots, which is achieved by the so-called Human Machine Interface (HMI). Referring to (Goodrich & Schultz, 2008), HMIs can be classified into four main categories, namely *visual displays* (e.g. graphical user interfaces, augmented reality interfaces), *gestures* (e.g. hand and facial movements), *speech and natural language* [e.g. auditory speech and text-based responses, also with Natural Language Interfaces (Ferraguti et al., 2017)], and *physical and haptics interactions*. Among them, visual displays play a major role since cobot capabilities can be improved using social cues (Terzioğlu et al., 2020), and the fastest response to users is provided by wearable sensors (Liu & Wang, 2018).

Regarding *actuation*, in this work we will mainly focus on the cartesian trajectory of the robot, regardless of whether it is point-to-point or linear. In fact, regarding the HF dimension, it is more important to the operator the output motion of the robot, rather than the individual actuators' trajectories. A scale along this subdimension is conceived between traditional linear trajectories and optimally designed ones. Indeed, various authors suggest implementing minimum-jerk trajectories rather than traditional ones (i.e. trapezoidal velocity profile trajectories) (Piazzi & Visioli, 2000; Bianco, 2013). First of all, these trajectories are more psychologically accepted, not giving the human a disturbing or uncomfortable feeling (Rojas et al., 2020). Secondly, they are mechanically gentle trajectories able to mitigate vibrations and wear in the robot's mechanism.

Similarly to traditional robots, cobots, unless faults, are reliable (Sadik & Urban, 2017) and can be used uninterruptedly. However, some fundamental feature distinguish cobot and non-collaborative robot (Bi et al., 2021), hence justifying the need for a *consistency* subdimension. Indeed, collaborative robots require more autonomy in order to synchronize with the operator; moreover, the collaboration requires the cobot to have built-in sensors, thus increasing the risk of failure.

Lastly, the lack of barriers leads to *safety* concerns. Safety is fundamental in this case and to obtain a system where both parts can operate without interference, so there are some elements to add, like *force monitor*, *passive compliance* and *overwork detection*.

There are four main regulations for the safety of robotic systems that are:

- UNI EN ISO 12100: 2010 (2010), regarding the main features to evaluate and reduce the risk in robotic systems;
- UNI EN ISO 10218-2: 2011 (2011) and its integration UNI EN ISO 10218-1: 2012 (2012), , regarding safety requirements of robotic islands;
- ISO TS 15066: 2016 (2016), regarding the safety requirements of collaborative robotic systems.

The latter defines what collaborative systems, collaborative operations and collaborative workspace mean in order to identify collaboration specifications. These specifications, Fig. 1, described in (Bi et al., 2021) and (Vicentini, 2020) are:

- *Safety rated monitored stops (SRMS)*: if humans come too closer to the the robot, it will stop. In this way the safety is guaranteed but the collaboration is not, since robot and operator cannot move simultaneously. It is used in high risk applications in order to reduce the risk itself.

(a) Type 1 – safety rated monitoring stop (SRMS) **(b)** Type 2 – hand guidance (HG)

(c) Type 3 – speed and separation monitoring (SSM) **(d)** Type 4 – power and force limiting (PFL)

Fig. 1 Safety features (Bi et al., 2021; Byner et al., 2019a; Lucci et al., 2020)

- *Hand guiding*: the robot does not work in automatic mode but it is guided by humans. Like *SRMS*, it is used both for high and low risk applications.
- *Speed Separation Monitoring (SSM)*: is used to determine the motion and the velocity of the robot relying on distance and speed between cobot and operator. This kind of safety is necessary to maintain a separation between the two resources that operate in the same space.
- *Power and Force Limiting (PFL)*: is used in reduced space for application to have an easy way to program the robot and personal control by operator. It is a fundamental security to avoid potential injury to human, limiting the power or the force of the cobot.

Artificial intelligence (AI) and machine learning (ML)

Among the most widely used technologies for the realization of software for cobots, artificial intelligence and machine learning can be retrieved. There is a huge literature in this field. Nevertheless, considering AI and ML in relation with cobots, only few contributions are available in the literature.

An example is proposed by Bogue (2022), where the author discusses cobots importance and some application linked to artificial intelligence enabled robots. By considering the same topics, also a computer architecture is proposed by Huh and Hossain (2021).

A big effort in the reinforcement learning, that is a typical application of artificial intelligence for cobots, is proposed in (Isbell & Shelton, 2001; Thomaz et al., 2006). The authors, through the use of a neural network, based on a system of rewards and punishments, were able to teach the cobot all the preferences of its users, in order to modify its behavior accordingly.

Another example of machine learning application is presented by Rossi and Nicholas (2019), where by using a neural network a relationship between the robot's pose and its surroundings is provided. It allows motion planning and obstacle avoidance, directly integrated within the design environment. The method combines haptic teaching with machine learning to create a task specific dataset, giving the cobot the ability to adapt to obstacles without being explicitly programmed at every instruction. Human actions and contact detected are properly analyzed by (Mohammadi Amin et al., 2020) with two different deep learning networks to guarantee safety and to make the cobot having a greater perception of the operator.

An interactive pick and place through the use of machine learning is proposed by Mangat et al. (2021) where, with a cobot equipped with a camera, they improve the collaboration by exploiting objects detection based on training data.

With the same technique, Aliev et al. (Aliev & Antonelli, 2021) realize an automatic machine learning tool to predict breaks of cobots during their interaction with operators, improving, in this way, a safe collaboration.

Furthermore, AI and ML can be used as a picking tool, without the need for long training sessions: in (De Coninck et al., 2020), the authors, with their approach, are able to make cobots taking different objects with only 5 min of training, whether their location in the space.

These techniques are in consolidation and for this, they can be considered as cobot capabilities such as adaptability, connectivity and safety.

Modern production systems

When studying human-robot collaboration, it is important to study not only the human factors and cobot capabilities, but also to consider how these resources are part of big-

Table 3 Modern production systems research topics

Modern production systems characteristics	Description
Flexibility	The ability to change the productivity without afflicting negatively the efficiency of the system (volume flexibility) and to wield a large variety of components and produce a wide mix of products (mix flexibility)
Cost oriented	Efficient and effective production systems, that maximize productivity and minimize unit production cost
Reconfigurability	The ability to realize a rapid adjustment of production capacity and functionality
Interconnection	The ability to collect and analyzed data, enabling communication between all members of production systems
Agility	The ability to respond rapidly to changes in demand, both in terms of volume and variety

ger production systems. This is in accordance with Industry 4.0, since it requires the collaboration between the resources. Hence, a third dimensions representing the production systems is required.

The manufacturing industry has evolved through several paradigms and it was influenced by different aspects, such as volume, variety, time, quality, price, brand, and design (Yin et al., 2018). Among these aspects, in this work we considered the aspects represented in Table 3.

First of all, the adoption of cobots is usually justified as a way to merge the *flexibility* of the operator with the capabilities of a robot. Hence, *flexibility* must be considered as it is the most important requirement for modern production systems (Barbazza et al., 2017), and can be divided in:

- *Volume flexibility*: the ability to change the productivity without afflicting negatively the efficiency of the system, and
- *Mix flexibility*: the ability to wield a large variety of components and produce a wide mix of products.

The degrees of flexibility are presented in (Rosati et al., 2013a) proposed a new type of production technology i.e., Fully Flexible Assembly System (F-FAS), and compares the flexibility achievable with the ones obtained with other production technologies. Moreover, besides the flexibility, also unit direct *production cost* is a key aspect that have to be optimized to designed a winning solution (Rosati et al., 2013b); there are recent studies, like (Weckenborg & Spengler, 2019; Grosse et al., 2015; Bi et al., 2021), where the cost criteria has been used as one of the guidelines in the development of techniques and systems for Industry 4.0 (I4.0).

Another important characteristic of the modern production systems is *reconfigurability*, i.e., the ability to realize a rapid adjustment of production capacity and functionality, in response to new market conditions (Mehrabi et al., 2000). Indeed, a *Reconfigurable Manufacturing System* (RMS) can first of all convert production to yield different models, but mainly it can integrate new technologies and production processes; this is a key feature in the actual market, where the products life cycle is decreasing, as well as are increasing requirements of quickly introducing new products.

Furthermore, modern production systems have to be responsive to the orders (Yin et al., 2018) i.e., they should be designed to minimize lead time. Indeed, it is appropriate to reduce the time from when the customer places an order to when he receives the product, hence to be more competitive in the global market. This concept is linked with the idea of speed in production processes, and can be found in literature referred to as *agility* (Kootbally et al., 2015). A proper definition of this subdimension is the ability to produce a broad range of low-cost, high-quality products with short lead times in varying lot sizes built to individual customer specification (Barbazza et al., 2017).

Lastly, what differentiates Industry 4.0 systems from other traditional ones is the *interconnection* between the resources to improve production processes' efficiency and effectiveness (Bortolini et al., 2017). Indeed, the enabling technologies of Industry 4.0 allow to develop new interconnected manufacturing systems (Mourtzis et al., 2019): smart sensors, mobile devices, data acquisition systems. Moreover, it is possible to obtain global feedback that allows to improve the decision-making process and consequently the efficiency of the whole system. Lastly, the connection between software and hardware is fundamental in this aspect, since it allows to improve all the other key aspects considered, such as the flexibility or the costs (Cohen et al., 2019a).

Methodology

This section aims to present how the analysis has been conducted: a *Systematic Literature Review*, e.g. (Adagha et al., 2017), has been carried out. A systematic review is a research method aimed at identifying and analyzing relevant researches within the scope to respond to certain "research questions" (Snyder, 2019).

The methodology proposed by Kitchenham et al. (2009) was followed. We considered different questions:

- What issues have been taken into account?
- How do these issues relate to each other?
- What is lacking in the state of the art?

To answer the questions described in Sect.“ Introduction”, the purpose of the research was considered: the intention is to identify if in the literature is clear how human factors, cobot capabilities and modern production systems are related to each other. Once these relations have been identifying the deficiencies have emerged.

Process and data analysis

The research carried out was manual through the collection of relevant works in different search engines:

- ResearchGate
- ScienceDirect
- IEEE Xplore
- Scopus
- Web of Science

Since there has been an extensive literature on the aforementioned dimensions, to refine the search the works had to comply with some inclusion criteria:

- works had to contain keywords such as *cobots, human factors, human aspects, human-robot interaction, human-robot collaboration, ergonomics, mental strain, industry 4.0, robot safety, trust*. More focused keywords were then considered for a refined selection (e.g., *assembly* or *task allocation*).
- works had to be presented in the last decade (2009–2021) since industrial cobots are a recent topic in the literature. However, human factors are a topic already studied in the literature, despite having never been contextualized with cobot to the authors' knowledge. Thus some older works, such as (Chan et al., 2006; Chung, 1996; Ogorodnikova, 2008), were considered to better present the effects of I4.0 and HRC on human factors.
- works had to correlate at least two dimensions in order to satisfy the criterion of utility necessary for the identification of the relationships in the various fields.

Each paper has been classified considering:

- the source
- the authors
- the topic area
- the research questions
- summary of the study
- future works

As a result, after accurate read-through of more than 200 papers by the authors, 95 papers were found to fully fit our criteria. As per request, parameters belonging to at least two dimensions were identified according to the subdimensions presented in Sect. “ Key aspects”, as summarized in Tables 3, 4, 6 in the Appendix. The results were grouped and analyzed with a two-term comparison for clarity; from these, we can identify ongoing challenges that still need to be solved in the field, comparing them with the exiting reviews. As an indicator, we adopted the number of publications for each year to identify trends in the research direction on which each dimension is focused. Our analysis of these parameters is presented in the following discussion.

Literature review

This section aims to present and analyze how the considered dimensions, i.e. human factors, cobots and modern production systems are connected in the literature.

Human factors and cobot capabilities

Starting from the mobility, its relation with the HF are not considered in the literature, since only one work presents both these aspects. As mentioned in "Collaborative robots capabilities", (Cohen et al., 2019b) considered different cobot capabilities and introduced psychological and sociological considerations on the adoptions of cobots, mainly focusing on the acceptance of cobots as helpers of operators. Indeed, the authors highlight how collaborative robots are not considered to replace operators as traditional robots, and therefore the fear of humans should subside considerably.

On the other hand, adaptability has been considered by different works, which is in accordance with the concept of modern manufacturing systems. In particular, regarding the use of the adaptability capability to improve human factors, the majority of works have been focusing on physical ergonomics, and especially on measuring the status of the operator. Indeed, works such as (Bragança et al., 2019; Kim et al., 2021; Bettoni et al., 2020) developed systems to measure the physical (and mental) workload on the human operator, and based on this information the cobot dynamically adapts to him/her, by taking physically demanding tasks (Peternel et al., 2018), or by bringing the operator into a suitable ergonomic working pose (Kim et al., 2021). It should be noted that the majority of this methods are also adopted to reduce the mental workload on the operator, as seen in (Prati et al., 2021; Faber et al., 2017). The adaptability of the robot has also been used to improve the acceptance and the trust of the operator. As stated by (Savur et al., 2019), trust is about managing human expectations; therefore, the authors developed a system to monitor human physiological responses to measure trust and suitably adapting the robot speed, acceleration and trajectory. As seen in (Lasota & Shah, 2015), improving the acceptance and trust of the operator leads to reduced idle times and improved productivity, similar to improving physical ergonomics. Lastly, developing systems that consider user experience allows for improving usability.

Similarly, connectivity, as another fundamental aspect of the modern production systems, has been studied. One of the advantages of cobots in comparison to traditional robots is the ability to be easily reprogrammed (Galin & Meshcheryakov, 2020). This capability allows adapting to the uncertainties typical of manual labor, de facto substituting the operator in physical intensive works, hence, improving the physical ergonomics (Salunkhe et al., 2019). To convey information to the cobot, using the teach pendant could be a solution; however, these are physically demanding to use, hence reducing the benefits on ergonomics (Tang & Webb, 2018). Hence, several works have focused on contactless gesture control (Liu & Wang, 2018; El Makrini et al., 2018). (Pohlt et al., 2018) compared the user experience with gesture inputs and touch feedback, showing that the users preferred the latter, despite the performance of the system is similar in both scenarios, with similar task completion time. Other systems have been considered, such as voice-based systems (Nordqvist & Lindblom, 2018; Savur et al., 2019) or graphical supports (Eimontaite et al., 2019; Tan et al., 2009), which have been adopted to provide feedback to the operator. In particular, in (Eimontaite et al., 2019) static graphical signs have been adopted since it displays information with little to no prior experience and does not depend on the language. This reduces mental stress by allowing the user to understand unfamiliar situations, leading to the feeling of being in control. These systems can also be adopted in a multi-modal scenario, comprehending different types of communications (Sauppé & Mutlu, 2015; Maurtua et al., 2017; Kildal et al., 2018) to take advantage of their different advantages. This is seen in (Maurtua et al., 2017), where the authors adopted a feedback mechanism (LED) in conjunction with tactile input. This feature reduced the perceived response time, improving the trust in the system; moreover, the authors stated that communication is fundamental to improve the sense of safety. Connectivity is also used to adapt the other elements of automation composing the system to the operator and improve the physical ergonomics and mental workload, as seen in (Bettoni et al., 2020). Lastly, other forms of nonverbal communication towards the operator are based on the motion of the cobot, as seen in (Terzioğlu et al., 2020), where the authors adopted arm motions and hand gestures (with the gripper) to develop a non-verbal communication used to increase the sense of trust and acceptance.

This shows how the actuation can be adopted in other forms other than simply defining a smooth trajectory between the robot working positions. In this regard, actuation is fundamental to improve the user experience, in particular, to reduce mental stress and improve trust and acceptance. Indeed, the improvement on physical ergonomics obtained in these works is mainly achieved by the introduction of the collaborative robot or by the adoption of intelligent systems as seen previously (Bragança et al., 2019), despite also presenting trajectories that reduce the mental stress. In particular, (Rojas et al., 2020) presented minimum jerk trajectories to reduce mental stress, and (Bortot et al., 2013) clearly shows the influence of the robot trajectory on the user stress. The obtained results show that, along with a smooth trajectory, another fundamental requisite for the trajectory is to be predictable, hence, the authors proposed straight-line motions. Moreover, as previously seen in (Lasota & Shah, 2015), an optimal robot motion improves the efficiency of the team, increasing acceptance and satisfying the operator's expectations.

Lastly, regarding the safety capability, our literature review identified little to no works focusing on the effects of industrial-grade safety systems on the human operator. On the other hand, safety is considered as fundamental to guarantee the trust of the operator and improving the performance of the system (Maurtua et al., 2017). For this reason, in (Heydaryan et al., 2018) the authors identified safety as one of the four criteria to evaluate the efficiency of the collaborative work cell among physical ergonomics (in the form of human fatigue), quality and productivity. Moreover, an assembly work cell has been developed and the work presents different systems to prevent collisions, such as safety mats and laser scanners. In addition, works focusing on actuation and adaptability are also present in this dimension, highlighting its importance in HRC systems. On the other hand, it has been studied how a high level of trust of the operator can result in accidents, since operators tend to take greater risks (Vinayak & Sharma, 2019). It is to be noted, though, that most of the accidents are related to human errors or bad workplace design (Jiang & Gainer, 1987) so it is necessary to educate workers and technicians in the right way so that the trust level does not result in a higher degree of accidents (Karwowski et al., 1991; Malm et al., 2010).

Human factors and modern production systems features

For starters, the literature on modern production systems is mainly focused on the improvement of the human operator well-being, intended as physical ergonomics and mental workload, while optimizing the performance of the system. In (Michalos et al., 2018) it is suggested to follow a multi-criteria analysis when defining both in the layout design phase and the task allocation one. Thus, the proposed method compares possible solutions in terms of productivity, ergonomics, and process quality, generating an optimal layout and corresponding assignment plan from the product data. Task allocation and line balancing are also considered in (Johannsmeier & Haddadin, 2016; Pearce et al., 2018; Weckenborg & Spengler, 2019), with the latter also considering ergonomics in the design and allocation phase. In particular, in (Pearce et al., 2018), the authors proposed a planner that aims to maximize productivity or minimize the human workload. Considering atomic actions in the planner, thus controlling it in real-time, allows to adapt the system to unpredictable elements, which are likely to happen in a dynamic environment.

Focusing on the order picking job, (Grosse et al., 2015) identifies 4 critical elements to improve human factors. Indeed, order picking is a typical manual activity due to the required flexibility. However, the characteristics of manual systems (physical workload, but also learning) lead to under-performance of the system; moreover, the repetitive actions in order picking may result in musculoskeletal disorders. For the four critical elements, i.e., perceptual, mental, physical, and psychosocial, the authors consider the effects of these aspects on the performance and quality of the system and the health impact. Lastly, considering human factors may reduce work-related illness and absenteeism, reducing long-term costs; however, the authors state the need to quantify the improvements in human factors to define the optimal trade-off between investments in ergonomic design and lower long-term costs.

Indeed, modern production systems may not lead to the desired improvements in human factors. An example is presented in (Mühlemeyer, 2019), where the authors presented the consequences in the adoption of a collaborative robot to aid the operator in a demanding task, e.g., a packaging task. Considering the purely manual scenario, the body posture, manual handling operations, and distribution of body posture/movement with intolerable overload lead to physical ergonomic problems. Moreover, the cycle time of 7s and the repetitive tasks lead to intolerable mental overload. On the other hand, the adoption of a cobot deteriorates the situation, despite the respect of safety measures. Indeed, the synchronous motion with the cobot increases the frequency of hand motion, worsening the physical stress. Moreover, the reduced cycle time and the reduction of contact with other operators greatly deteriorate the mental condition. Similar results are presented in (Dombrowski & Wagner, 2014). The authors focused on the mental stress due to the reconfigurability of modern production systems. Indeed, by making use of sensors, modern systems are capable of adapting the production sequence and optimally distributing the tasks. Hence, the operator's future tasks are not predictable, impeding the operator to develop plans thus increasing mental stress.

Regarding the interconnection feature, we want to focus on (Kinzel, 2017). As stated by the author, I4.0 aims to connect all elements through smart connection systems, and it is important to consider human factors when designing this connection. It is necessary to make all the humans connected to the system feel like part of its design process, to improve the acceptance as their needs are considered.

Lastly, regarding agility, only one paper has been found on the subject. (Peruzzini & Pellicciari, 2017) identified a flaw in the literature since the agility obtained using the sensors typical of modern production systems aims to optimize the efficiency, costs, and productivity without considering human factors, i.e., it should adapt not only to process parameters but also to the characteristics of the operator. By simulating the system behavior it is possible to identify weaknesses in the system and adapt it by taking corrective actions; hence, when a certain adaptive behavior is executed, the virtual model allows to identify the goodness of the solution.

Modern production systems features and cobot capabilities

According to (Cohen et al., 2019b), mobile robots can be grouped in different levels, from wheeled movable cobots to fully autonomous mobile cobots. Each of these levels provide for different advantages, and this is proved by the considered review. Indeed, (Fast-Berglund et al., 2016) presents a solution composed of 3 flexible assembly units, with each stations placed on flexible wagons. This solution allows to rearrange the system into u-cells or lines or single stations in a cost-effective way. On the other hand, (D'Souza et al., 2020) proposed a solution composed by an AGV and a collaborative robot to perform order picking tasks. As previously stated, order picking tasks require high flexibility, due to the different types, shapes, and dimensions of the products. The interest in this work lays on the description of the practical implementation of the system, in particular of the communication between the human operator and the cobot/AGV.

Regarding adaptability, the considered works were already analyzed in the previous comparisons. However, works such as (Faber et al., 2017), can be studied from a different point of view: the cognitive control unit which aims to reduce the mental and physical strain of the operator also allows for a flexible system. Indeed, the proposed system easily generates assembly graph through an automated assembly-by-disassembly strategy, which is based on the CAD data of the product. Similarly, the majority of works regarding connectivity have been presented. It is interesting to note that this capability can be exploited to monitor the process and provide communication to the operator (Salunkhe et al., 2019; Kim et al., 2021), but also as communication with different hardware systems (D'Souza et al., 2020). Michalos et al. (2015) presents industrial case studies where the communication between human operator and robot is used to improve the cobot positioning. Moreover, since safety is a fundamental aspect for HRC, the authors discuss safety related aspects, e.g., presenting Power and Force Limiting method as the only viable solution when the space separation between operator and cobot is insufficient. Three aims of safety strategies are presented, i.e., controlled impacts (crash safety), stopping the activities before imminent collision (active safety), and avoid collision without stopping the system activities (adaptive safety), with the latter one fundamental for reconfigurable systems. Similarly, (Byner et al., 2019b) focused on safety strategies and their practical realization. In particular, the authors focus on Speed and Separation Monitoring, with two methods to compute the robot speed required to safely avoid collision. A prototype has been implemented with an industrial robot, and by measuring the position and velocity of the operator with a laser scanner, the speed limit of the robot is dynamically changed, improving the productivity of the system.

On the other hand, despite its importance, focusing on improving the operator safety may increase the payback period, reducing the economic advantages of cobots, as seen in (Realyvásquez-Vargas et al., 2019). However, the authors state that an increase in productivity of about 18.3% is also expected in their case study. In any case, the costs of safety systems should be considered, and cost effective solutions, e.g., signals as seen in (Eimontaite et al., 2019), can be adopted to provide safety information.

Lastly, as seen also in the comparison between Cobot capabilities and Human Factors, Consistency has been neglected and proper study should be carried out, as it will be discussed in the following section.

Discussion

From the literature review, it is possible to summarize the research focus by using some charts and tables. In particular, from Fig. 2 it can be found that:

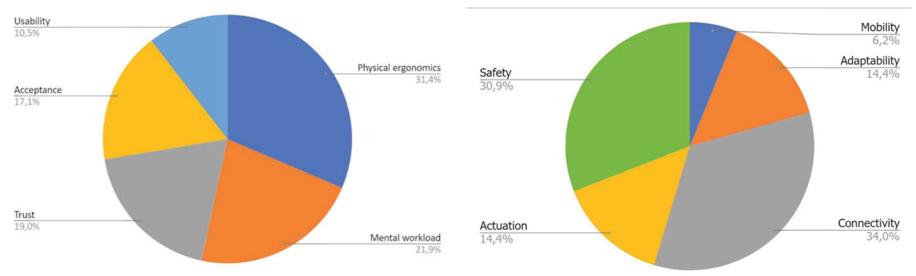
- As related to Human Factors (Fig. 2a), research has evenly analyzed all the different aspects, with a slight focus on physical ergonomics. Indeed, the respect of safety directive is not always sufficient to ensure optimal working conditions and, at worst, can result in downgraded working conditions, both physical and mental (Mühlemeyer, 2019). Moreover, physical ergonomics is usually considered alongside the mental workload. As observed by (Gualtieri et al., 2020a), better biomechanical conditions generate also a reduction of psychological stress.
- As related to cobots (Fig. 2b), safety and connectivity have been the most studied capabilities. These two factors are of particular importance in a collaborative system since they are directly related to the safety of the operator and the performance of the workcell. On the other hand, actuation has been considered for a fewer number of papers, even if it is related to operator safety. It is interesting to notice how the paradigm of traditional industrial robots is still present in the cobot paradigm: mobility has not been considered as a major topic, so the cobot is intended to be used as a still resource. This is reasonable since most of the robot task requires high precision, which can be ensured only by a proper workspace calibration, a time-consuming task to be performed each time the robot is moved (Comand et al., 2020).
- As related to modern production systems (Fig. 2c), cost-oriented and flexibility are the most studied features, which derive directly from the industrial world. However, agility, which is one of the main focuses of Industry 4.0, has been rarely considered in research if compared to other features. The demand for highly customized products in small batches should be of great interest to the research and could be addressed more in the future.

Another key aspect in the literature review discussion is to analyze which are the most popular research topics. In Fig. 3 the number of publications per year regarding the capabilities of the resources is outlined. In general, it can be noted that there is an increasing interest among all the aspects of HRC also in terms of Industry 4.0. Such interest is promising, because it suggests how many researchers aim at improving the performance of robotic systems while preserving both the human work and the flexibility of the production systems. The same trend can be found more generally if the number of publications per year for each dimension is depicted (Fig. 4). With this, we want to point out that this correlation of growth within the scientific community of the three factors, shows how these elements are related in the production research, moreover this shows that it makes sense to investigate the three dimensions together.

It is important to notice how this research interest in the topic has spread during the last 6-year period. In fact, before 2015 most of the literature has focused on improving the capabilities of the cobots in an industrial and safety perspective rather than its integration and influence on the human factors (Matheson et al., 2019).

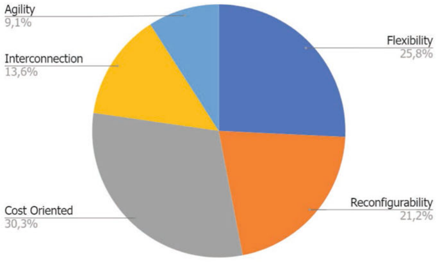
From the analysis of Fig. 3 other key points can be outlined:

- Mental workload and Physical ergonomics have always been considered in the research field since 2008 (Fig. 3a) and is yet a popular issue.
- Trust and Acceptance are considered similar from a research point of view since their growth has been parallel since 2015.
- In general, Human Factors are equally studied when connected to cobot and modern production systems.
- Huge interest in cobots has grown since 2017 (Fig. 3b).
- Cobot consistency is not of interest in the research field. This may be due to the mechanical efficiency of robots, which has developed for decades before the adoption of cobots. However, this can be open to questions towards different communities such as mechanics/control theory/automation.



(a) Division of the research trends based on human factors

(b) Division of the research trends based on cobots capabilities



(c) Division of the research trends based on modern production systems

Fig. 2 Division of the research trends for each dimension

- Modern production systems show an interest trend very similar to the one of Human Factors (Fig. 3c).
- Agility has been highly considered in 2017–2018, but has not been researched since then. Instead, the economic aspect has been of great interest, especially in the last 3 years.

Since modern collaborative systems are the result of the combination of both human factors, cobot, and modern systems, it is interesting to analyze how the research has addressed the combination of couples of systems. As stated before, we have decided to avoid a three-terms direct comparison as it would have been messy and of difficult comprehension.

Figure 5 and Table 4 show the papers that join together Human Factors and Cobot capabilities. From the analysis, it can be found that two capabilities have not been studied extensively by previous works: mobility and consistency. In particular, mobility could be of great interest since mobile platforms are becoming more and more popular. In fact, there is extensive literature on mobile robots (Schneier et al., 2015), but very few papers do relate the mobility of the Cobot to actual Human Factors. Consistency, on the other hand, has been developed for traditional industrial systems, so it is clear how it is of little interest to the research field. However, cobots are equipped with additional sensors (which allow the manipulator to be effectively "collaborative"), which could be tested for consistency in future research studies.

On the contrary, great importance has been given to safety, connectivity, and intelligence in terms of ergonomics and mental workload. In fact, the latter two are of great importance both in the industrial field and in the research field. It is interesting to point out how literature has found a strong connection between safety and trust, pointing out how the safety features installed in the Cobots can be of great importance for a good HRI. Indeed, by improving the standard features required by regulations, it is possible to increase the production preserving the safety of human operators, making them feel more secure (Lucci et al., 2020). Similarly, a compliant joint or an arm in the robot has been proved to reduce injury that leads to better confidence of operators (She et al., 2020). Furthermore, (Savur et al., 2019) added that any potential physical collision with the robot decreases the human trust, and consequently the production benefits of the HRC. On the other hand, (Sauppé & Mutlu, 2015) found that the social features in industrial robots may reduce the safety of the interaction.

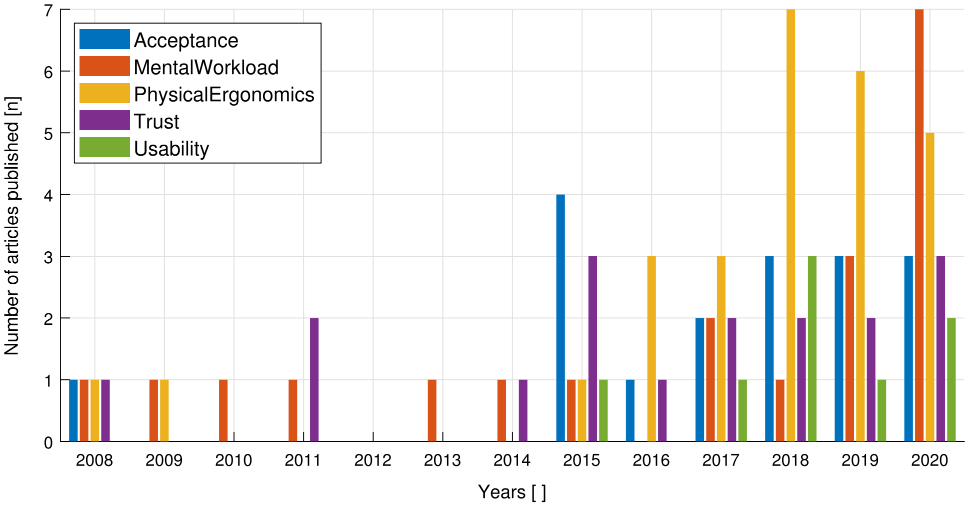
To our point of view, acceptance and usability should be further investigated for all the Cobot capabilities, since these have been analyzed only in a few works.

Figure 6 and Table 3 show the papers that join together Human Factors and modern production systems features.

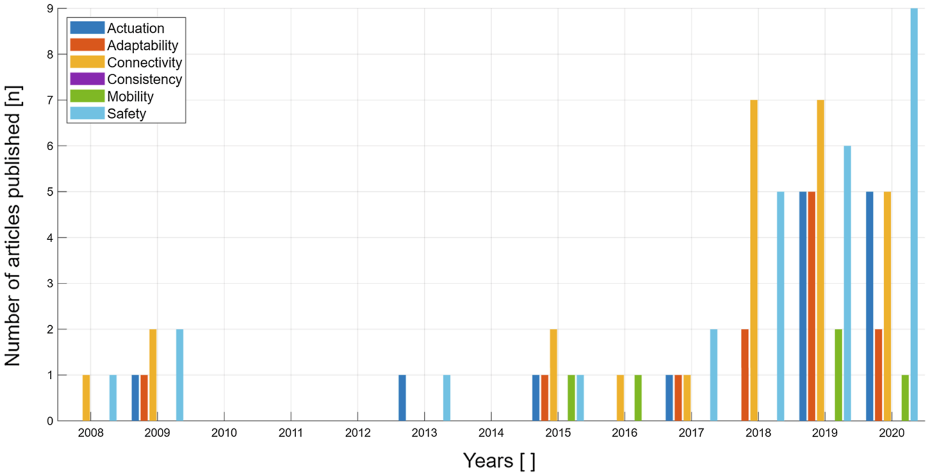
Among all these features, the Human Factor that has been considered the most is undoubtedly physical ergonomics. In fact, it is one of the main focuses related to Industry 4.0 and has been related to flexible and reconfigurable production systems (Bettoni et al., 2020).

In this scenario, however, trust, acceptance, and usability have been rarely considered. This is rather uncanny, since the new technology, to be properly efficient, has to be trusted, accepted, and easy to use for an operator, especially for SME, which are usually located in rural areas in which illiteracy is higher. As mentioned before, agility has been rarely con-

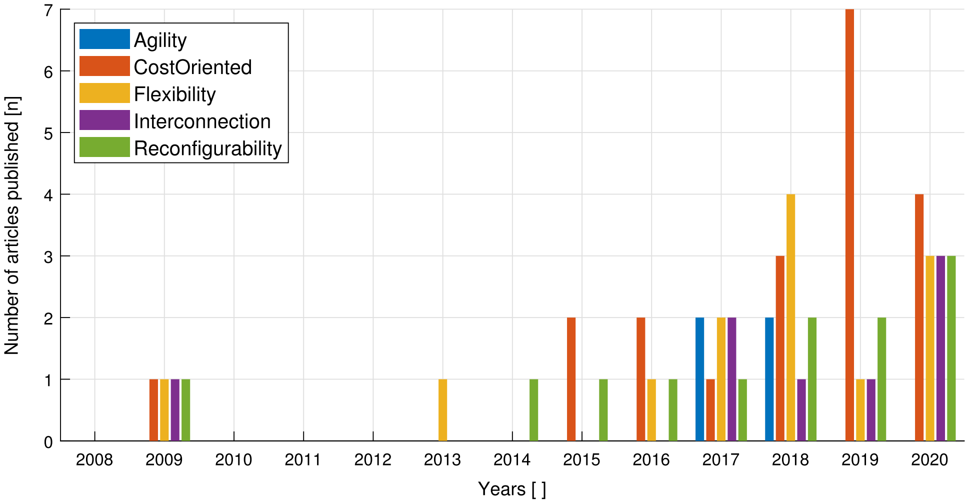
Fig. 3 Research trends per year



(a) Human Factors



(b) Cobot



(c) Modern Production Systems

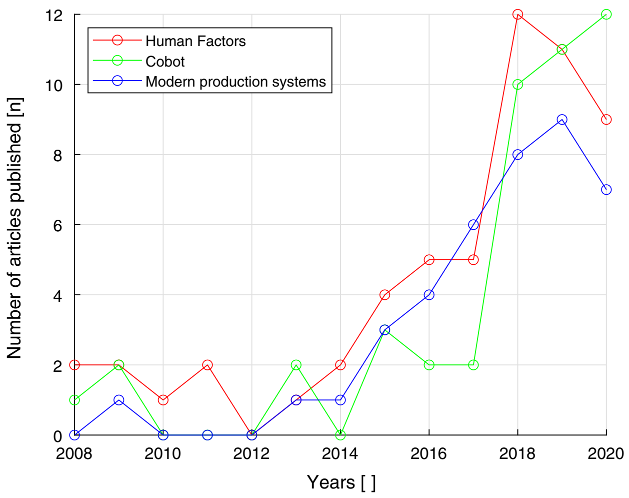


Fig. 4 Research trend of the three dimensions per year

sidered in literature, and it is particularly true if related to Human Factors: only a rather old paper (Chung, 1996) do relate agility to 4 of 5 Human Factors.

Finally, Fig. 7 and Table 6 show the papers that join together Cobot capabilities and modern production systems features.

It is clear how, again, intelligence, connectivity, and safety are the main features that have been related to modern production systems. The former two are of great importance in the field of Industry 4.0 and IoT, while safety is of great importance for an efficient modern collaborative workcell. Moreover, cobots have been also presented as a way to introduce automation, and to an extent, Industry 4.0 to SMEs. This is achieved by taking advantage of the intelligence and connectivity capability of the cobot, which allows to quickly change the cobot task and adapt to the flexibility required by SMEs (Guerin et al., 2015). In addition, these features are also appreciated by operators without HRC expertise/confidence (Chowdhury et al., 2020).

However, there is a wide research gap if agility is considered. This may be due to the fact that agility is a very general concept, which may not be yet considered in collaborative applications, but it could be related to the cobot mobility. As a result, it is of great importance to further investigate this aspect.

Fortunately, as can be noted from Fig. 4, in the last years an increasing interest in these topics can be found in literature. As a result, this increasing interest presents wide opportunities for new works, since there are still many research gaps to be investigated, along with many challenges to face. In fact, new works may focus on studying how the cobot mobility may influence both Human Factors and modern production systems, or how the agility requested for Industry 4.0 affects human operators.

Other research gaps outlined in this work may not be of great interest in the future: the cobot consistency may be of greater interest in the industrial field rather than the academic field, since the mechanics of the robots have been defined many decades ago; cobot connectivity and modern production systems agility may not be correlated, thus there may not be interest in further developing the topic.

Comparison with other literature review

The novelty of this paper, already described in the previous sections, is the search of a relationship between these three different areas, which is remembered to be: cobots, human factors and industry 4.0.
Taking into consideration the other literary revisions we can highlight some deficiencies in each of these:

- in (Gualtieri et al., 2020c) only safety (as cobot capability) and ergonomics (as human factors) have been considered. The other HFs and the characteristics of Industry 4.0 were not included in the research;
- in (Hentout et al., 2019) safety and security and natural language were investigated but a classification of social factors wasn’t proposed;
- in (Matheson et al., 2019) an overview of human robot classification was carried out but this work fails in the analysis of the relation between human operations and cobots in terms of the features of Industry 4.0 technologies;
- in (Wang et al., 2019) human teaching and robot learning techniques were investigated, without considering the modern production systems repercussions;
- in (Zarte et al., 2020) the authors identified the notions for a human-centered architecture but cobot capabilities and Industry 4.0 characteristics were not included;
- in (Liu & Wang, 2018) a review on wereable sensor and contactless gesture control was carried out to improve the ergonomics in human robot collaboration: this means that all the other HF were not taken into account:
- in (Schneier et al., 2015) mobile manipulation, coordinated control and task architecture were the main themes without the consideration of HFs;
- (STEİN, 2020) is a review of cobots and Industry 4.0 but without HFs: the authors considered economic, technological and social dimension but only in relation with safety;
- in (Cohen et al., 2021) Cohen et al. presented cobot capabilities and peculiarities, useful features for the support in the realization of a workcell. HFs were not considered;
- Cardoso et al. (2021) is a review about physical and cognitive ergonomics and workload in a collaborative cell: modern production systems weren’t considered;

Fig. 5 Number of articles related to Human Factors divided for Cobot capabilities

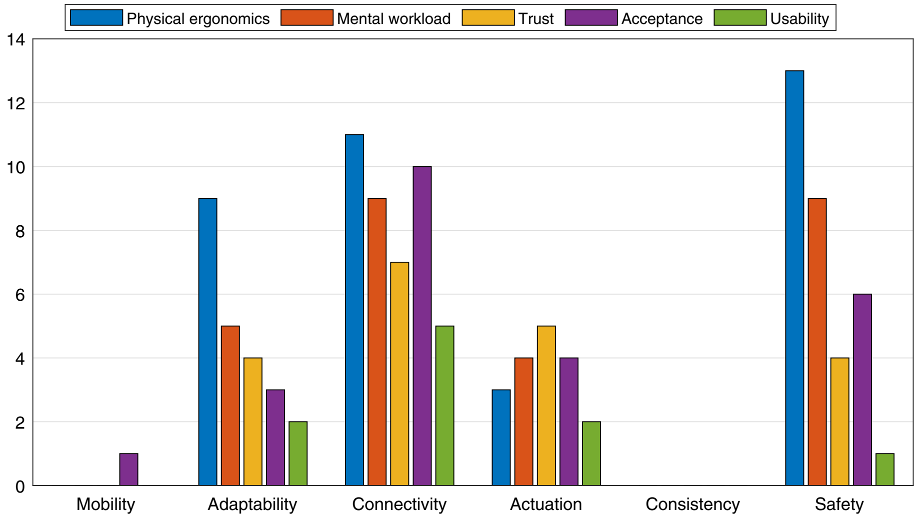


Fig. 6 Number of articles related to Human Factors divided for modern production systems features

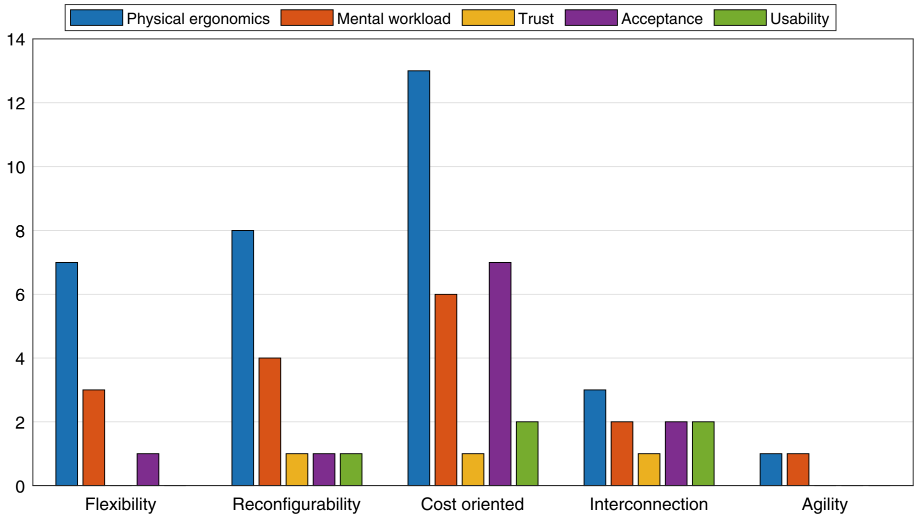
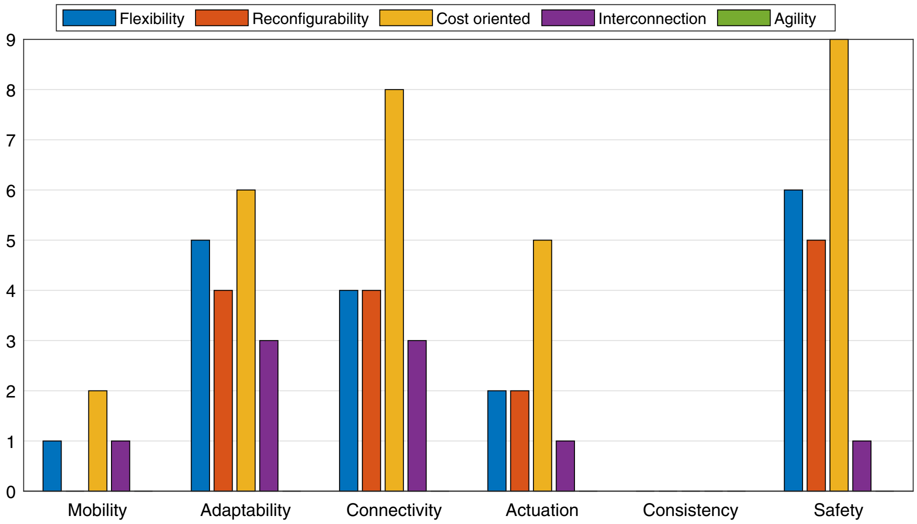


Fig. 7 Number of articles related to Cobot capabilities divided for modern production systems features



– in (Hashemi-Petroodi et al., 2020) wasn't considered how the interaction of human operators and cobots affects the features of Industry 4.0;

– in (Kadir et al., 2019) the authors explained how modern production systems integrate human factors but not how the cobot capabilities influence them;

- (Neumann et al., 2021) is a survey on how integrate human factors in the development and implementation of modern production systems without considering cobot peculiarities;
- in (Sgarbossa et al., 2020) human ergonomics, manufacturing management and support system production for Industry 4.0 were highlighted. Cobot capabilities and the other human factors were not analyzed;
- in (Reiman et al., 2021) a review of Industry 4.0 in relation with HFs was conducted but cobot capabilities weren't studied.

As previously mentioned, human factors were mainly considered from the point of view of the ergonomics (both physical and mental) in relation with safety issues, without including the featuring of the Industry 4.0. All the other factors were only partially considered in relation to cobot capabilities or modern production systems characteristics. So, in summary, a lot of literature reviews have been made in the last decade but none of them considered all three dimensions above mentioned together. This paper, instead, provides an overview of the characteristics of these fields, highlighting the links between them and in which areas the literature is not yet complete.

Conclusions

Collaborative applications are more complex than traditional industrial robot applications, since not only two completely different resources are included in the same workspace, but they also interact, so the interaction leads to some advantages and disadvantages. In fact, how the operator feels the installed workcell influences the overall performance of such industrial application.

As a result, human factors must be considered in the design of model collaborative applications. Moreover, human factors and cobot capabilities must be linked to all the modern production systems features that characterize the Industry 4.0 paradigm, so that the resulting workcell can express its full potential.

This paper has provided an overview of how human factors, cobot capabilities, and modern production systems features interact, showing that research has already addressed the problem. However, as described in Sect.“ Introduction”, there are some research questions for which we have sought an answer, already provided in Sect.“ Discussion” and summarized here briefly:

- The most considered human factors are physical ergonomics and mental workload, in relation to safety, intelligence and connectivity as cobot capabilities, as shown in Fig. 5. No human factor was studied in relation to cobots consistency and only one article focused on acceptance in relation to mobility. Similarly, reconfigurability and cost oriented as modern production systems characteristics were extensively analyzed in relation to ergonomics and mental workload, Fig. 6, while other factors (for both fields) have been poorly considered. Finally intelligence, connectivity, safety and actuation were largely studied with regard to cost oriented, reconfigurability and flexibility as production systems features as shown in Fig. 7.
- The study of these iterations has led to an increase of the production guaranteeing however the necessary level of safety and consequently making the operators feel safer in the collaboration, (Lucci et al., 2020). Similarly, a compliant joint or an arm in the robot (so the analysis of cobot features) has been proved to reduce injury that leads to better confidence of operators (She et al., 2020). Moreover, taking advantage of the intelligence and connectivity capability of the cobot, allows to quickly change the cobot task and adapt to the flexibility requested by moder markets, (Guerin et al., 2015).
- There is a wide research gap if agility is considered. This may be due to the fact that agility is a very general concept, which may not be yet considered in collaborative applications, but it could be related to the cobot mobility. As a result, it is of great importance to further investigate this aspect: new works may focus on studying how the cobot mobility may influence both Human Factors and modern production systems, or how the agility requested for Industry 4.0 affects human operators.

We can expect collaborative applications to become more and more popular with the introduction in the industrial setting of the knowledge coming from research. This could lead to further improvement in automation which can result in new challenges to overcome in the future.

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Appendix 1

Table 4 Comparison between cobot capabilities and human factors

	Physical ergonomics	Mental workload	Trust	Acceptance	Usability
Mobility				Cohen et al. (2019b)	
Adaptability	Liu and Wang (2018), Prati et al. (2021), Bragança et al. (2019), Gualtieri et al. (2020d), Krüger et al. (2009), Faber et al. (2017), Peternel et al. (2018), Bettoni et al. (2020), Kim et al. (2021),	Prati et al. (2021), Bragança et al. (2019), Gualtieri et al. (2020d), Faber et al. (2017), Bettoni et al. (2020)	Prati et al. (2021), Bragança et al. (2019), Lasota and Shah (2015), Savur et al. (2019)	Prati et al. (2021), Cohen et al. (2019b), Lasota and Shah (2015)	Prati et al. (2021)
Connectivity	Liu and Wang (2018), Tang and Webb (2018), Prati et al. (2021), Bragança et al. (2019), Gualtieri et al. (2020d), Gualtieri et al. (2020c), Krüger et al. (2009), Ogorodnikova (2008), Salunkhe et al. (2019), Realyvásquez-Vargas et al. (2019), El Makrini et al. (2018), Bettoni et al. (2020), Kim et al. (2021)	Prati et al. (2021), Bragança et al. (2019), Gualtieri et al. (2020d), Rojas et al. (2020), Landi et al. (2018), Ogorodnikova (2008), Tan et al. (2009), Eimontaite et al. (2019), Bettoni et al. (2020)	Prati et al. (2021), Bragança et al. (2019), Terzioğlu et al. (2020), Gualtieri et al. (2020d), Maurtua et al. (2017), Nordqvist and Lindblom (2018), Savur et al. (2019), Sauppé and Mutlu (2015)	Prati et al. (2021), Terzioğlu et al. (2020), Gualtieri et al. (2020c), Cohen et al. (2019b), Kildal et al. (2018), Ogorodnikova (2008), Elprama et al. (2016), El Makrini et al. (2018), Pohlt et al. (2018), Sauppé and Mutlu (2015)	Tang and Webb (2018), Prati et al. (2021), Terzioğlu et al. (2020), Kildal et al. (2018), Pohlt et al. (2018)
Actuation	Bragança et al. (2019), Gualtieri et al. (2020d), Krüger et al. (2009)	Bragança et al. (2019), Gualtieri et al. (2020d), Rojas et al. (2020), Bortot et al. (2013)	Terzioğlu et al. (2020), Gualtieri et al. (2020d), Maurtua et al. (2017), Lasota and Shah (2015), Savur et al. (2019)	Terzioğlu et al. (2020), Gualtieri et al. (2020d), Cohen et al. (2019b), Lasota and Shah (2015)	Terzioğlu et al. (2020),
Consistency					
Safety	Liu and Wang (2018), Bragança et al. (2019), Gualtieri et al. (2020d), Gualtieri et al. (2020c), Krüger et al. (2009), Heydaryan et al. (2018), Ogorodnikova (2008), Galin et al. (2020), Gualtieri et al. (2020a), Realyvásquez-Vargas et al. (2019), El Makrini et al. (2018), Faber et al. (2017), Kim et al. (2021)	Bragança et al. (2019), Gualtieri et al. (2020d), Gualtieri et al. (2020c), Rojas et al. (2020), Ogorodnikova (2008), Galin et al. (2020), Gualtieri et al. (2020a), Tan et al. (2009), Eimontaite et al. (2019), Faber et al. (2017),	Bragança et al. (2019), Gualtieri et al. (2020c), Maurtua et al. (2017), Savur et al. (2019)	Gualtieri et al. (2020c), Kildal et al. (2018), Ogorodnikova (2008), Galin et al. (2020), El Makrini et al. (2018)	Kildal et al. (2018)

Table 5 Comparison between modern production systems features and Human Factors

	Physical ergonomics	Mental workload	Trust	Acceptance	Usability
Flexibility	Gualtieri et al. (2020d), Krüger et al. (2009), Michalos et al. (2018), El Makrini et al. (2018), Faber et al. (2017), Bettoni et al. (2020), Kim et al. (2021)	Gualtieri et al. (2020d), Faber et al. (2017), Bettoni et al. (2020)		El Makrini et al. (2018)	
Reconfigurability	Prati et al. (2021), Gualtieri et al. (2020d), Krüger et al. (2009), Johannsmeier and Haddadin (2016), Pearce et al. (2018), Weckenborg and Spengler (2019), Heydaryan et al. (2018), Bettoni et al. (2020)	Prati et al. (2021), Gualtieri et al. (2020d), Dombrowski and Wagner (2014), Bettoni et al. (2020)	Prati et al. (2021)	Prati et al. (2021)	Prati et al. (2021)
Cost Oriented	Gualtieri et al. (2020d), Grosse et al. (2015), Krüger et al. (2009), Weckenborg and Spengler (2019), Galin et al. (2020), Salunkhe et al. (2019), Gualtieri et al. (2020a), Peternel et al. (2018), Realyvásquez-Vargas et al. (2019), El Makrini et al. (2018), Owen-Hill (2016), Mühlemeyer (2019), Bettoni et al. (2020)	Gualtieri et al. (2020d), Grosse et al. (2015), Galin et al. (2020), Gualtieri et al. (2020a), Eimontaite et al. (2019), Mühlemeyer (2019), Bettoni et al. (2020)	Lasota and Shah (2015)	Grosse et al. (2015), Cohen et al. (2019b), Kildal et al. (2018), Galin et al. (2020), El Makrini et al. (2018), Lasota and Shah (2015), Eimontaite et al. (2019)	Grosse et al. (2015), Kildal et al. (2018)
Interconnection	Prati et al. (2021), Krüger et al. (2009), Bettoni et al. (2020)	Prati et al. (2021), Bettoni et al. (2020)	Prati et al. (2021)	Prati et al. (2021), Kinzel (2017)	Prati et al. (2021), Kinzel (2017)
Agility	Peruzzini and Pellicciari (2017)	Peruzzini and Pellicciari (2017)			

Table 6 Comparison between cobot capabilities and modern production systems factors

	Flexibility	Reconfigurability	Cost Oriented	Interconnection	Agility
Mobility	D'Souza et al. (2020)		Cohen et al. (2019b), Fast-Berglund et al. (2016)	D'Souza et al. (2020)	
Adaptability	Gualtieri et al. (2020d), Krüger et al. (2009), Faber et al. (2017), Bettoni et al. (2020), Kim et al. (2021)	Prati et al. (2021), Gualtieri et al. (2020d), Krüger et al. (2009), Bettoni et al. (2020)	Gualtieri et al. (2020d), Krüger et al. (2009), Cohen et al. (2019b), Peternel et al. (2018), Lasota and Shah (2015), Bettoni et al. (2020)	Prati et al. (2021), Krüger et al. (2009), Bettoni et al. (2020)	
Connectivity	D'Souza et al. (2020), Gualtieri et al. (2020d), Krüger et al. (2009), El Makrini et al. (2018), Bettoni et al. (2020), Kim et al. (2021)	Prati et al. (2021), Gualtieri et al. (2020d), Krüger et al. (2009), Michalos et al. (2015), Bettoni et al. (2020)	Gualtieri et al. (2020d), Krüger et al. (2009), Cohen et al. (2019b), Kildal et al. (2018), Salunkhe et al. (2019), Realyvásquez-Vargas et al. (2019), El Makrini et al. (2018), Eimontaite et al. (2019), Bettoni et al. (2020)	D'Souza et al. (2020), Prati et al. (2021), Krüger et al. (2009), Bettoni et al. (2020)	
Actuation	Gualtieri et al. (2020d), Krüger et al. (2009)	Gualtieri et al. (2020d), Krüger et al. (2009)	Byner et al. (2019b), Gualtieri et al. (2020d), Krüger et al. (2009), Cohen et al. (2019b), Lasota and Shah (2015)	Krüger et al. (2009)	
Consistency					
Safety	Gualtieri et al. (2020d), Krüger et al. (2009), Malik (2019), El Makrini et al. (2018), Faber et al. (2017), Kim et al. (2021)	Gualtieri et al. (2020d), Krüger et al. (2009), Malik (2019), Heydaryan et al. (2018), Michalos et al. (2015)	Byner et al. (2019b), Gualtieri et al. (2020d), Krüger et al. (2009), Kildal et al. (2018), Galin et al. (2020), Gualtieri et al. (2020a), Realyvásquez-Vargas et al. (2019), El Makrini et al. (2018), Eimontaite et al. (2019)	Krüger et al. (2009)	

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