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Review

Exploring how new industrial paradigms affect the workforce: A literature review of Operator 4.0.

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ABSTRACT

The ongoing paradigm transition from Industry 4.0 to Industry 5.0 is driving toward a new industrial vision rooted in addressing human and planetary needs rather than solely focusing on innovation for profit. One of the most significant shifts that defines Industry 5.0 is the change in focus from technology-driven progress to a genuinely human-centric approach. This means that the industrial sector should prioritize human needs and interests at the core of the production process. Instead of replacing workers on the shop floor, technologies should enhance their capabilities, leading to a safer and more fulfilling work environment. Consequently, the role of industrial operators is undergoing a substantial transformation. This subject has garnered increasing interest from both researchers and industries. However, there is a lack of comprehensive literature covering the concept of Operator 4.0. To address this gap, this paper presents a systematic literature review of the role of Operator 4.0 within the manufacturing context. Out of the 1333 papers retrieved from scientific literature databases, 130 scientific papers met the inclusion criteria and underwent detailed analysis. The study aims to provide an extensive overview of Operator 4.0, analyzing the occupational risks faced by workers and the proposed solutions to support them by leveraging the key enabling technologies of Industry 4.0. The paper places particular emphasis on human aspects, which are often overlooked although the successful implementation of technologies heavily relies on who uses them and how they are utilized. Finally, the paper discusses open issues and challenges and puts forth suggestions for future research directions.

1. Introduction

The fourth industrial revolution is a widely discussed paradigm aimed at digitizing and automating manufacturing production systems. New tools and methodological approaches need to be developed to adapt to the new industrial scenario. However, in recent years, more attention has been paid to enabling technologies with which the operator interacts rather than his/her needs. The Industry 4.0 paradigm is bringing about significant changes in the role of workers, leading to an evolution in human-machine interaction. This transformation will reshape the industrial workforce and have significant implications for the nature of work [1]. Workers are now required to possess high flexibility and demonstrate adaptive capabilities in dynamic working environments [2]. In the factory of the future, human beings, with cognitive abilities that cannot be replicated by machines, will continue to play a central role in driving continuous improvement and providing real added value to maintain competitiveness. Although smart automation, robots, and other technological advancements have enhanced production systems, it is the human who ultimately makes the final decisions and remains responsible for creative work [3,4]. The operator remains at the core of the manufacturing system, even though their role is undergoing change [5].

Hence, it is imperative for industries to address human sustainability and adopt a human-centered production approach that aims to enhance workers' skills, health, and safety [6]. The efficiency and productivity of a manufacturing system are directly linked to human performance. Ensuring the well-being, safety, and health of workers has a positive impact on the entire industrial ecosystem [7,8].

In recent years, manufacturing companies have increasingly prioritized the safety and well-being of their employees. According to the European Business Survey on New and Emerging Risks (ESENER), approximately 25–30% of European industries have implemented appropriate procedures to manage psychosocial risks [9]. The absence of such measures leads to work-related illnesses affecting millions of workers, resulting in significant social costs and economic consequences. More than one in three workers state that their work negatively

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affects their health, and approximately three out of five workers report complaints of musculoskeletal disorders (MSDs), particularly in the upper limbs [10]. MSDs are the most prevalent occupational diseases in the manufacturing sector, causing both pain and a decrease in productivity [11].

Over the past few decades, significant changes in demographics, increased economic globalization, and rapid technological advancements have profoundly transformed the world of work. These transformations have led to the emergence of psychosocial risks, which have had a detrimental impact on the health and safety of workers [12]. Psychosocial risks are defined by Cox and Griffiths [13] as "those aspects of work design, the organization, and management of work, and their social and environmental contexts, which have the potential to cause psychological, social, and physical harm". ESENER [9] reported that over 40% of European industries perceive psychosocial risks as challenging to address compared to traditional risks. According to [14], 27.9% of employees reported that their exposure to these risks affected their mental well-being, corresponding to approximately 55.6 million workers.

In this context, the key enabling technologies (KET) of Industry 4.0, in addition to the inherent benefits of automation, are providing new opportunities for physical, cognitive, and sensorial assistance. Incorporating work processes into the Industry 4.0 concept emphasizes the importance of empowering workers to achieve enhanced productivity rather than replacing them [15]. The widespread utilization of advanced sensor-based systems and the application of artificial intelligence (AI) for analyzing large volumes of data are further expanding these opportunities by enabling real-time diagnosis and intervention. These developments offer tangible benefits in terms of productivity, quality, reliability, and even worker well-being. Dornelles et al. [16] proposed a shift in perspective, viewing Industry 4.0 not just as a collection of technologies aimed at improving process efficiency, but also as a suite of technologies capable of assisting the workforce within a company.

In this evolving scenario, the concept of “Operator 4.0″ emerges, referring to a smart and qualified worker who cooperates synergically with advanced human-machine interaction technologies toward a complete symbiosis between humans and automation [5]. The Operator 4.0 generation is supported by smart machines, interacts with collaborative robots and advanced production systems, and utilizes KETs, such as virtual reality (VR), augmented reality (AR), and wearable devices, exploiting their benefits. To ensure the success of the smart factory of the future, it is crucial to not overlook the interaction between the workforce and KETs, as well as the potential broader impacts these technologies may have on the operator. Considering the needs of the worker and the secondary effects that these technologies may impose on them is essential.

Romero et al. [17] presented a first comprehensive analysis of “Operator 4.0″, categorizing the types of Operator 4.0 based on the supporting technology. Subsequently, the scientific community has increasingly focused its research on the role of the smart operator, building upon this classification. However, the prevailing methodological approach is often technology-driven, neglecting the human aspects, despite the well-established knowledge that the successful implementation of technology strongly depends on who is using it and how they interact with it [18].

Several studies have emphasized the ongoing uncertainty surrounding the potential impact and enabling effects of advanced digital technologies on workers within the rapidly evolving domain of digital transformation [19]. These studies raise important questions about how these technologies will shape the future of work and the workforce. Meindl et al. [20] revealed a lack of clarity regarding the interface between Operators 4.0, the utilized technologies, and the multiple operational processes necessary for implementing a smart working approach. The intricate interplay among these elements remains unclear, posing challenges in effectively integrating advanced technologies into work environments and optimizing their benefits for workers. Further research is essential to comprehensively understand the relationships and dynamics involved in the impact of advanced technologies on operators to ensure the successful adoption and implementation of digital transformation strategies.

For these reasons, a comprehensive study of the current state of the art has been conducted to provide a clear and thorough analysis of Operator 4.0. The focus is on examining the different typologies of future operators and analyzing the impact of enabling technologies 4.0 on the performance and psycho-physical well-being of the operators. This analysis encompasses the evaluation of the stakeholders involved, the types of interaction, the required changes for operators, and the new benefits obtained by workers. Moreover, the study identifies and suggests future research directions to address the existing gaps in knowledge and understanding.

1.1. Motivation and novelty of the work

Concerning recent literature reviews on the topic of Industry 4.0, Human factors, and Operator 4.0, several studies can be identified. In Table 1 the identified papers are listed, highlighting the main topic discussed, future directions proposed by the authors, and the identified limits.

Some of the reviewed papers discussed topics unrelated to the specific area of interest, such as the aging workforce [32], risk management [33], manual smart assembly systems [34,35], and digital transformation [36]. Other literature reviews focused on specific aspects related to HF/E, including the relationship between Industry 4.0 and participatory ergonomics [30], safety and ergonomics in HRC [27], HF in production and logistics [25], and organizational and management aspects of HF/E [28]. Conversely, some reviews provided general overviews of the changing role of the operator before and after the emergence of Industry 4.0 [24], and the potential scenarios, hazards, and possibilities in the work of the future [26]. Nevertheless, both did not investigate how operators are actually coping with these changes.

Mark et al. [31] presented an overview of worker assistance systems used in industrial settings, focusing on the technologies and how to leverage their benefits to improve applicability in the industry.

Four reviews specifically discussed human aspects within the Industry 4.0 paradigm. Badri et al. [21] identified only eleven relevant papers and the review adopted a technological perspective; Leso et al. [22] limited their review to the impact of Industry 4.0 on occupational safety and health management systems. Kadir et al. [23] and Grosse et al. [29] conducted broader searches, considering HF/E in general related to Industry 4.0. The former followed a technology-driven vision and did not consider how the human role has changed; the latter performed a content analysis but analyzed only the keywords, disregarding the actual content of the papers. Nevertheless, all authors concluded that the literature on this topic is still limited and scarce, emphasizing the need for further research on Industry 4.0 with a stronger focus on HF/E.

In summary, there is still a lack of a detailed literature review focusing on the role of Operator 4.0 in the manufacturing context, as well as the research gaps and future directions in this area. The need for such a review arises from the new paradigm of human-centric production, which aims to prioritize humans and their needs. This work aims to contribute in several novel ways:

- Providing a clear and comprehensive overview of Operator 4.0 by analyzing the various typologies of future operators.
- Analyzing all the risks to which operators are exposed and how Industry 4.0 can help mitigate these risks.
- Investigating technological solutions that can support Operator 4.0 and assessing how these technologies impact the performance and psycho-physical well-being of operators.
- Discussing the emerging risks associated with the use of KETs and proposing strategies for researchers and industries to address the

Table 1
Identified previous literature reviews.

Paper	Year	Content	Future research directions	Main limits
[21]	2018	Considerations regarding the integration of Occupational Health and Safety (OHS) within the Industry 4.0 paradigm.	New measures based on a comprehensive vision of managing change to ensure a smooth and safe transition to the new paradigm	Only 11 papers are analyzed (only 4 are journal papers). It adopts a technological perspective, neglecting worker health and safety.
[22]	2018	Impacts of Industry 4.0 on workplaces in terms of practical effects and consequences on OHS	A proactive approach to risk assessment at the design or early stage of the new system implementationConsideration of different characteristics of workers for the job designFurther investigation for new learning modalities for workersThe development of international standards aimed at protecting workers from all potential risks	Only 22 peer-reviewed papers are analyzed, including journal papers and conference proceedings. It is not a systematic literature review.
[23]	2019	To what extent, what type of, and how do academic publications on Industry 4.0 integrate Human Factors and Ergonomics (HF/E) in their research	Focus on empirical dataTest of conceptual tools, methods, and designs in real industrial scenariosAdoption of a holistic research view on HF/E in Industry 4.0, including the three main domains (physical, cognitive, and organizational)	Few peer-reviewed papers (only 13 are journal papers). It adopts a technological perspective.
[24]	2020	How Industry 4.0 will change the role of the operator in production systems	Development of assistance systems (cognitive and sensorial aid)The production system needs to be designed to facilitate the physical work ergonomically and assist the operator in complex tasksBalance the workload of the Operator 4.0Understand the effects of Industry 4.0 in its practical implementation regarding the people involved	It is a general overview of the role of the operator that changes before and after Industry 4.0. However, it does not focus on how the operator deal with these changes and their impacts on him.
[25]	2020	Overview of the research challenges and opportunities in the field of Human Factors (HF) in production and logistics systems	Development of a human-centered perspective in production and logistics systemsNew human-centered approaches for the design, modeling, and management of these systems	It is mainly focused on the management and design of production and logistics systems. It analyzes only IFAC conference papers, and it is not a systematic literature review.
[26]	2020	Identification and characterization of scenarios and hazards in the future of work	Collaboration between scientific and industrial communities for the implementation of measures to guarantee a gradual and safe transition toward the futureResearch on psychosocial risks, prevention through design, and emergent risks at all levels of productionStrategic foresight to be prepared for the introduction of AI technologies to workers' safety, health, and well-being.Standards for specific training, reskilling, and upskilling of workers	It is a general overview of the future of the work in terms of all the possible scenarios, related risks, and recommendations to address them. However, it does not investigate how the operator faces this change.
[27]	2021	Description of the current state of the art of safety and ergonomics in collaborative robotics.	Balance of the developments of different research areas related to Human-Robot Collaboration (HRC). This will be necessary to create genuine and human-oriented potentials and not technological barriers. For these reasons, future developments should focus on the alignment of Human-Robot Interaction (HRI). Enhance safety and ergonomics research themes, especially in terms of sustainability, operator well-being, and related human-centered design, social, and psychophysical aspects of collaboration.	It is focused on a specific KET (HRC) evaluating aspects related to considers safety and ergonomics.
[28]	2021	Description of the state of the art of the HF/E aspects related to the Industry 4.0 paradigm focusing on organizational and management aspects.	Analytics of processes combined with HF/EUnderstand organizations' capabilities and their maturity in process analyticsUnderstand the maturity of technologies and the entire manufacturing process performance from the HF/E perspective	Few peer-reviewed papers (only 16 are journal papers). It is focused on organizational and management aspects, rather than on the operator's well-being.
[29]	2021	Which HF aspects and to what extent have been considered in the scientific literature on Industry 4.0.	Systematic integration of HF in future Industry 4.0 research and development	Content Analysis (CA) is limiting, since it analyzes only the keywords, ignoring the actual content of the paper. Moreover, the identified keywords (RU) can have ambiguous meanings.
[30]	2021	Literature review of the existing research works on the relationship between Industry 4.0 and Participatory Ergonomics.	The authors do not suggest future research directions to include participatory ergonomics in the context of Industry 4.0	Only 10 papers are analyzed in detail. It is focused specifically on participatory ergonomics and its relationship with Industry 4.0.
[31]	2021	Description of the current state of the art of worker assistance systems in manufacturing	Further industrial applications of worker assistance systems in manufacturing New methodologies for the choice of the most suitable system for a specific use caseNew methodologies for a structured evaluation of the suitability of worker assistance system	It is focused on a specific topic: worker assistance systems.

identified research gaps and challenges by following the suggested future research directions.

2. Methodology

To achieve the objective of this paper, a systematic literature review was conducted, covering papers published until May 2021. The methodology employed follows the approach developed by Tranfield et al. [37], which enables the identification of relevant existing studies related to a specific subject or research issue. This systematic approach minimizes subjectivity and ensures the repeatability and transparency of the study's results [38].

The research involved searching for relevant works within the main online databases of scientific literature that collect academic studies published in indexed journals. The databases used for this research are Web of Science, Scopus, and Science Direct. These databases cover a wide range of academic disciplines, including industrial production management, human-centered manufacturing, and engineering. They also allow accurate and customized searches.

A set of keywords was defined to find a relevant range of papers. The following search keywords and Boolean operations were used: “Operator 4.0″ OR (“Operator” AND “Human Factors” AND “Industry 4.0″). The search was carried out using the title, abstract, and keywords. Since Operator 4.0 is the core of this analysis, all papers containing this keyword (or the synonym “Worker 4.0″) have been included. With "Operator" and its synonyms, the theme of the operator understood as a worker and as a person is included in the analysis. The "Human Factors" group considers aspects related to ergonomics and operator well-being, also including the themes of "Human-centered manufacturing" and "Human-centered design". Finally, within the keyword "Industry 4.0", both the concepts of the intelligent factory and the most widespread enabling technologies in the industrial environment, with which the operator can interact and from which he/she can be supported, have been included. For each of these groups, synonyms were chosen to cover as many papers as possible published in the existing scientific literature. The complete list of keywords is shown in Fig. 1.

To determine the most relevant papers in the scientific literature, specific inclusion and exclusion criteria were established. The focus was placed on papers published in academic journals, while other types of publications such as conference papers, periodicals, and working papers were excluded. These types of publications generally undergo a less rigorous peer-review process [39]. Additionally, papers that were not written in English and those that were not digitally available were also excluded from the review.

The methodology of the systematic research process is shown in Fig. 2. The electronic database research provided a collection of 1333 journal papers, excluding duplicates. After carefully screening the titles and abstracts, the number of papers was reduced to 195. The aim is to exclude papers not relevant to the topic of Operator 4.0. For example, papers focused on medical or educational aspects have been removed. Subsequently, a preliminary analysis of the entire paper was carried out to select only the relevant papers for the review topic. Finally, at a later stage in the process, and to ensure a thorough analysis of the topic, additional academic studies were identified through the manual cross-referencing screening. As a result, 130 scientific papers have been selected for detailed analysis, out of which 16 are review papers. The review papers have been thoroughly discussed and analyzed in the previous section. They have been included in the descriptive analysis but excluded from the detailed analysis and discussion.

3. Descriptive analysis

3.1. Journal and year of publication

To investigate the evolution and current significance of the topic, an analysis of the distribution of scientific papers over the years was conducted. Fig. 3 illustrates the temporal distribution of the selected papers. From 2018–2021, there has been a significant exponential increase in the number of academic contributions focusing on Operator 4.0, indicating a growing interest in this field. This surge in attention from the scientific community can be attributed to the widespread adoption of KETs within the industrial sector to support operators. However, the integration of these new technologies into work environments necessitates further research and the development of new methods and tools that prioritize the well-being of the operator.

The discussion surrounding Operator 4.0 encompasses various aspects, leading to a wide range of journals being involved in publishing relevant papers (68) with different scopes (Fig. 4). Most of the papers were published in Computers and Industrial Engineering and Applied Sciences (Switzerland) (11), followed by Journal of Manufacturing Systems (7), International Journal of Advanced Manufacturing Technology (6), Robotics and Computer-Integrated Manufacturing (6), Applied Ergonomics (5). Fig. 4 shows the distribution of the selected papers across the main journals. Journals with fewer than 2 papers were not included in the chart.

3.2. Category of research studies

The selected papers have been categorized based on their research study approach, as depicted in Fig. 5. The most prevalent research study category is the mixed approach, comprising 39 papers. This approach involves the development of a new method along with its validation through a case study, which can be conducted in a laboratory setting (18 papers) or a real industrial context (21 papers). There were 23 papers focused solely on experimentation, either in a laboratory or a real industrial environment, without proposing a new theoretical framework. Additionally, 21 papers presented the development of an application or tool, including its testing in either a laboratory or an industrial setting. Finally, 16 papers analyzed the context and the state of the art, followed by a group of papers proposing a new theoretical method (14 papers). Considering the papers that include a real case study, the main industrial sectors covered are metalworking and engineering industries, automotive and industrial vehicles, manufacturing companies (e.g., footwear, wood), and logistics.

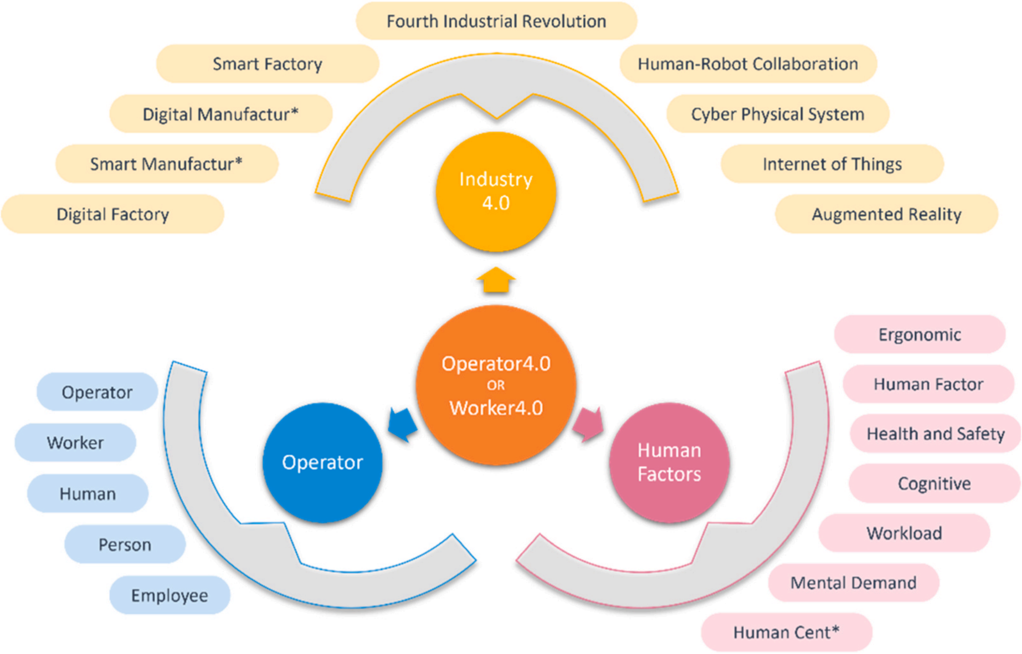

Fig. 1. Combination of research in the literature search.

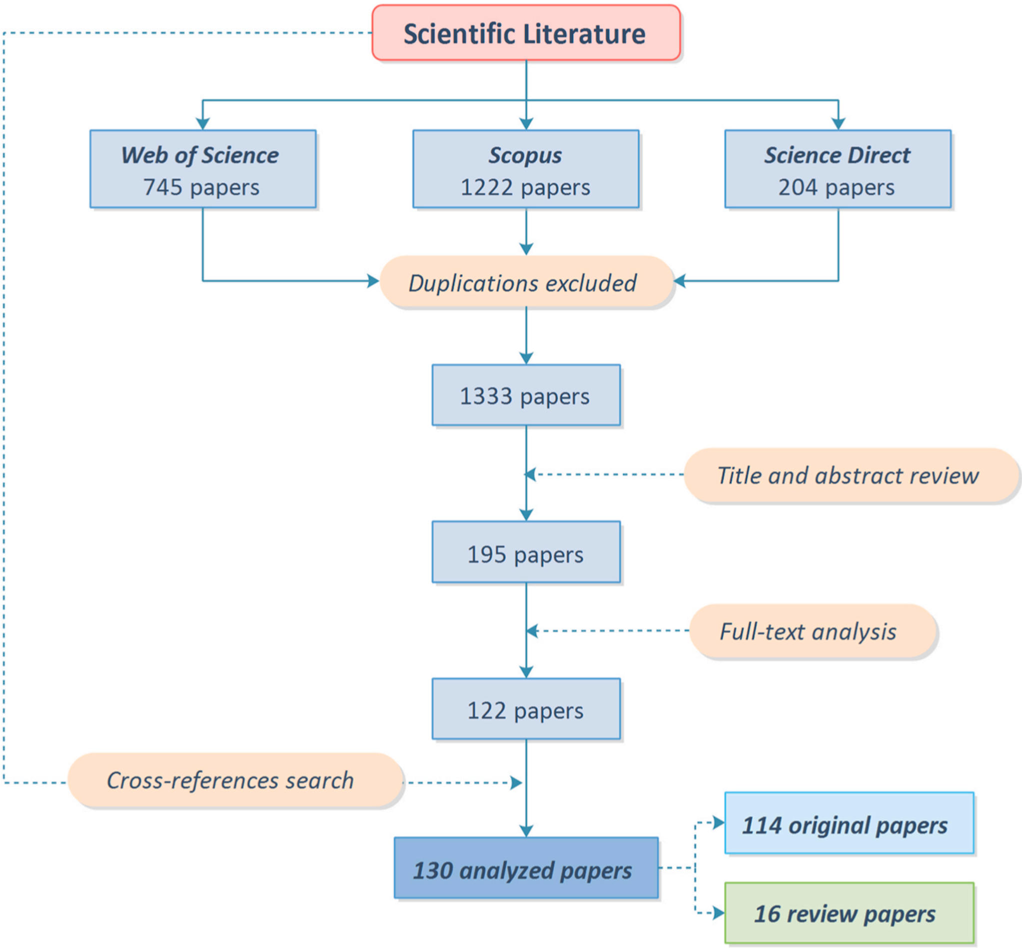

Fig. 2. Workflow of the scientific literature research process.

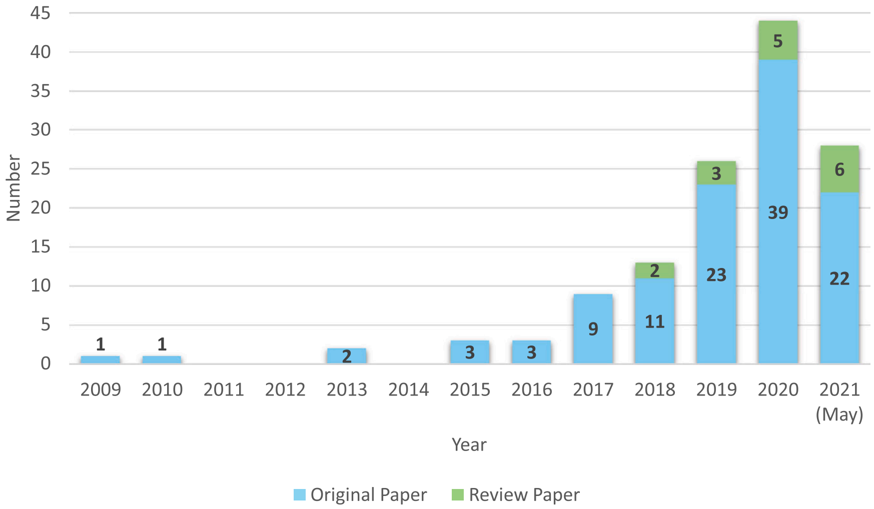

Fig. 3. Distribution of the selected papers across years.

3.3. Keywords analysis

The keywords provided by the authors of the selected papers were analyzed. Firstly, a co-occurrence analysis of the keywords was conducted using VOSviewer software [40], and the main results are shown in Fig. 6. A minimum of 3 occurrences was used for each keyword, resulting in a network map of 22 keywords and 155 links. Fig. 6 shows the co-occurrence network map of the keywords, along with a table indicating the frequency and total link strength for each keyword. The size of the nodes represents the frequency of keyword occurrences. The presence of a link between two nodes indicates that they have been used together in the same paper, and the thickness of the line represents the strength of the link, which indicates how frequently the two terms occur together. For example, in this case, the keywords "industry 4.0" and

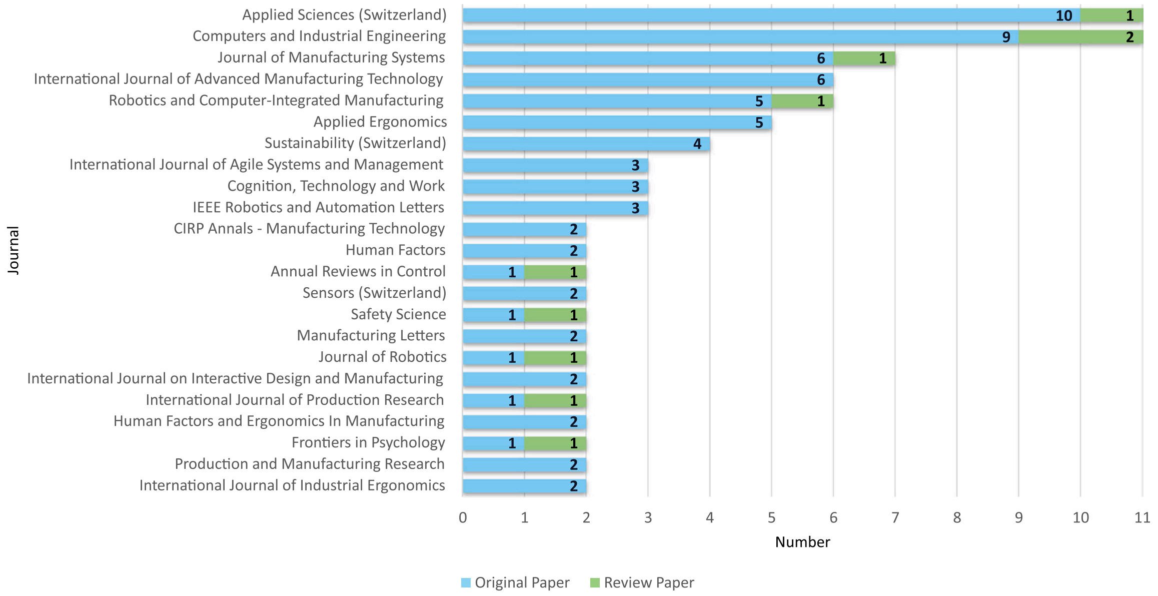

Fig. 4. Distribution of the papers in the main journals.

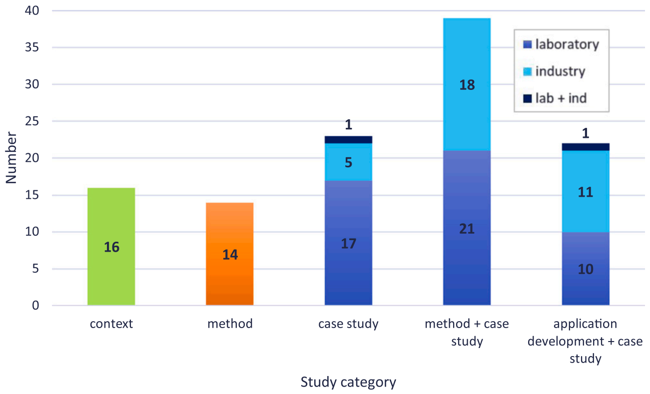

Fig. 5. Distribution of the papers considering the study category.

"human factors" are frequently used together. For example, in this case, the keywords "industry 4.0″ and "human factors" are frequently used together.

Additionally, for each keyword, the "total link strength" is calculated, which is the sum of all link strengths ending on that specific node. For example, the keyword "cognitive load" has one link with a strength equal to 1 and another link with a strength of 2, the total link strength of that node is 3. The color of the nodes corresponds to the average publication year of the keyword.

The analysis of the keywords in the selected papers has provided insights into the main topics discussed. The keyword "industry 4.0" had the highest frequency, indicating its significance in the literature. Among the technology-related keywords, "augmented reality" had the highest number of occurrences. In terms of human aspects, the most commonly used keywords were "human factors" and "ergonomics".

When examining the trends over the years, it becomes evident that the concept of "Operator 4.0" is more recent compared to "industry 4.0". "Digital transformation" emerged as a topic due to the widespread adoption of the new industrial revolution. On the other hand, "ergonomics" and "human factors" are more established aspects in the literature.

Analyzing the links between nodes, it is noticeable that the keyword "industry 4.0″ is frequently associated with "human factors", "ergonomics", "social sustainability", and "operator 4.0″. This finding highlights the increasing focus on social and human aspects related to the fourth industrial revolution. It also demonstrates that despite the close relationship between Industry 4.0 and technological advancements, there is a significant emphasis on humans.

However, the software used considers different words, even if they differ by only one letter but represent the same concept. Therefore, keywords with similar meanings have been grouped. For example, keywords related to occupational health and safety (OHS), such as "human factors," "ergonomics," and "well-being," have been aggregated into a group that is comparable in number to "industry 4.0". A similar approach has been applied to enabling technologies, where keywords like "augmented reality," "mixed reality," and "virtual reality" have been merged into the concept of extended reality (XR). Likewise, keywords related to human-robot collaboration, such as "human-robot interaction" and "collaborative robot," have been combined. The resulting graph in Fig. 7 shows the aggregated keywords. It can be observed that "industry 4.0" remains the most common keyword, followed by those related to human factors and ergonomics (HF/E). Among the chosen research keywords, XR and HRC are the most frequently mentioned technologies. The analysis also indicates that the topic of digitalization is relatively underrepresented in the literature. Finally, assembly is the most frequently cited activity, followed by maintenance.

4. Operator 4.0

The focus of this review is on Operator 4.0, the worker of the smart factory of the future. The new production paradigm is shifting from independent automated and human activities towards a human-automation symbiosis, characterized by synergic cooperation between machines and humans. Automation is not meant to replace human skills and abilities but rather to support and enhance them, leading to improved performance and efficiency. Over the years, operators have adapted their activities based on advancements in industrial and digital production technologies, giving rise to different generations of operators [41]. The Operator 1.0 generation primarily performs manual and dexterous work with the assistance of manually operated machine tools. Operator 2.0 is aided by computer tools and information systems. The third operator generation cooperates with robots, machines, and computer tools. According to [17], the Operator 4.0 generation is represented by "a smart and skilled operator, who performs not only cooperative work with robots but also work aided by machines as and if

Keyword	Occurrences	Total link strength
industry 4.0	52	100
augmented reality	24	27
operator 4.0	20	49
human factors	17	44
ergonomics	16	38
human-robot collaboration	13	22
assembly	10	20
collaborative robot	7	17
cyber-physical systems	7	19
internet of things	7	17
manufacturing	7	11
social sustainability	6	17
maintenance	5	9
cognitive load	4	3
cyber-physical production systems	4	12
digital transformation	4	10
digital twin	4	6
digitalization	4	11
human-centered design	4	9
human-machine interaction	4	14
human-robot interaction	4	5
mixed reality	4	8
safety	4	12
smart factory	4	12
automation	3	6
literature review	3	8
mental workload	3	1
smart manufacturing	3	8
systematic literature review	3	13

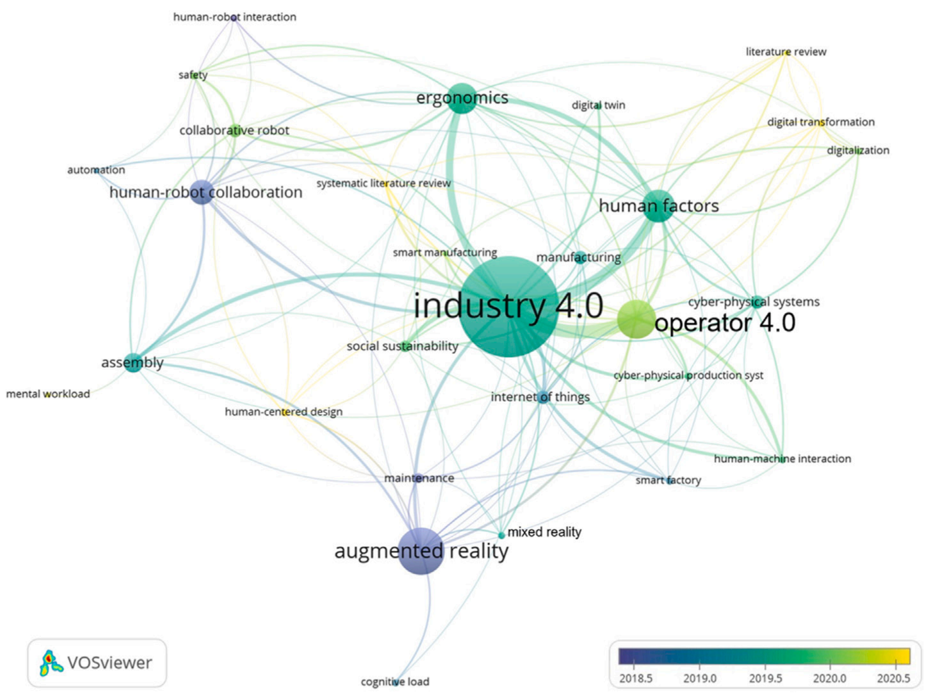

Fig. 6. Keywords co-occurrence trend using VOSviewer.

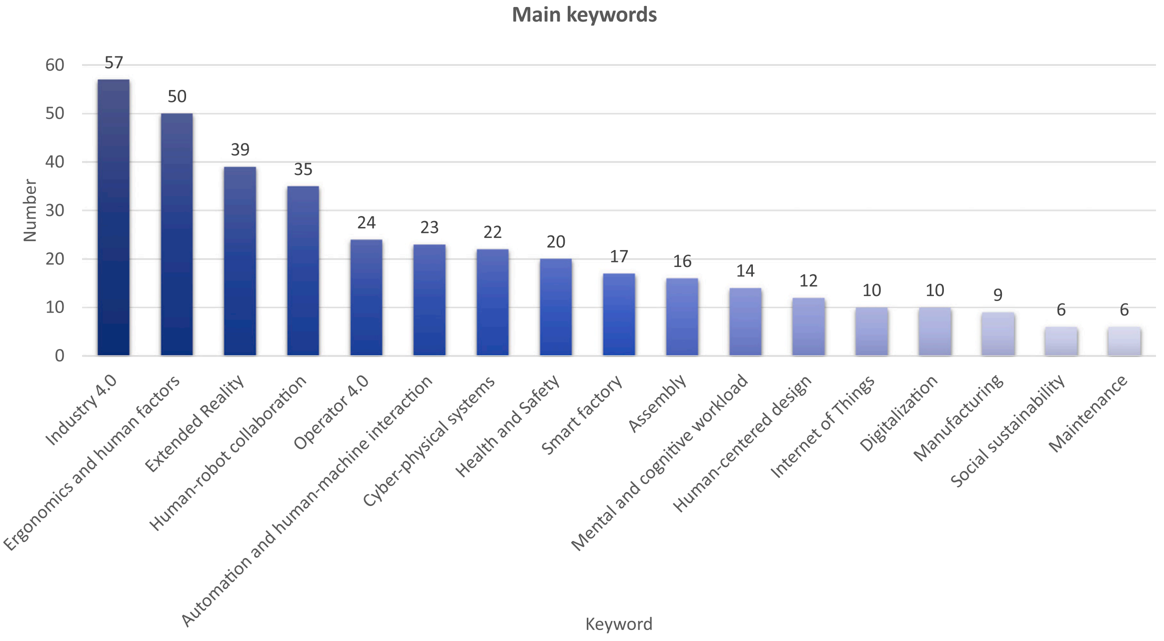

Fig. 7. Most common authors' keywords.

needed, employing human cyber-physical systems, advanced human-machine interaction technologies, and adaptive automation towards human-automation symbiosis work systems". Operator 4.0 introduces a new design and engineering philosophy for adaptive production systems, where automation is seen as a means to enhance humans' physical, cognitive, and sensorial skills by integrating human-cyber-physical systems (HCPS). This new generation of operators is capable of managing complex systems by leveraging and enhancing human skills and capabilities through the utilization of human-machine interaction technologies [42]. Operator 4.0 possesses superior knowledge that augments their skills and abilities within the working environment, utilizing information and guidance generated in virtual contexts. Di Nardo et al. [43] have highlighted the differences between traditional workers and Worker 4.0 in terms of competence and knowledge gaps. In this new context, smart companies need to invest in "re-skilling" or "skill revolution," which involves training and updating workforce competencies.

Since the definition proposed by Romero et al. [17], the concept of Operator 4.0 has been extensively investigated in the literature, leading to a significant increase in the number of scientific papers addressing it. 26 papers (approximately 23%) have specifically focused on the concept of Operator 4.0, providing detailed descriptions of their abilities, roles, and responsibilities. Many authors have adopted the description presented by Romero et al. [41] as a reference, adapting it to the specific context and objectives of their paper. This skilled operator of the future can and should be aided in various ways to create socially sustainable workplaces [44]. Kaasinen et al. [45] emphasized the need for socially sustainable factories that are well-suited for the Operator 4.0 generation. They discussed the importance of enabling workers to understand and develop their creative and innovative skills using digital assistance systems and technologies without compromising production performance. De Miranda et al. [46] defined Operator 4.0 as a cyber-physical system (CPS) with extensive connectivity capabilities at various scales and levels. They highlighted the operator's creative intelligence and expertise in the relevant knowledge domain, which enable analytical thinking, calculations, and simulations. Ruppert et al. [47] similarly emphasized the concept of Operator 4.0 as being based on HCPS, designed to facilitate synergistic cooperation and integration between humans and machines. Taylor et al. [48] presented a different perspective, envisioning the operator of the future transitioning from operators to makers, contributing to a better working life and socially sustainable factories. They referred to this as the "Maker 1.0" concept, where operators take on the role of product engineers rather than supervisors of production processes. In the changing paradigm of the smart factory, Cimini et al. [49] defined the roles of humans as data acquisition, state inference, state/system "influencing", and actuation. The proper integration between humans and CPPS requires the introduction of KETs to enhance human capabilities. Moreover, Operator 4.0 needs to establish a synergic symbiosis with AI, as AI primarily serves to improve and augment human capabilities [50]. To foster shared trust and minimize communication overhead between Operator 4.0 and AI, both entities should work together, leveraging and enhancing each other's complementary strengths.

The objective is to establish trusting and reliable relationships between humans and automation, empowering Operator 4.0 with new skills and technologies facilitated by the Industry 4.0 revolution. Table 2 describes all the Operator 4.0 typologies found in the selected papers. Different authors have defined distinct typologies that best characterize the Operator 4.0 figure they have considered. Mattsson et al. [51] described Operator 4.0 as a proactive operator capable of managing dynamic and flexible digitalized work, handling many different tasks, gathering information, and interacting with several technologies and systems. Mazali [52] defined the factory worker of the future as participative and proactive, in contrast to the resistant and reactive factory worker of the twentieth century. As mentioned earlier, Taylor et al. [48] proposed a significant shift in the role of humans, recognizing their creative potential as a complement to automated production systems. In this way, the operator becomes a creative operator. The growing attention to occupational health and safety in the factory of the future has led to the emergence of a new typology of Operator 4.0. Indeed, Nicoletti et al. [53] identified the Industrial Safety 4.0 Operator, who leverages KETs to ensure health and safety, even in emergency scenarios. Finally, Kong et al. [54] introduced the concept of the Empowered Operator, equipped with industrial wearable devices integrated with AI (similar to the smarter operator). This empowered operator is connected in real-time with other onsite operators and backend administrators, fostering effective communication and collaboration (similar to the social operator).

Among the selected papers, a majority (77 papers, 67%) categorized Operator 4.0 according to the classification described above. Fig. 8 shows the distribution of studies across the different types of operators. Most of the research works focused on augmented (29 papers, 38%) and collaborative (19 papers, 25%) operators. Healthy (10 papers, 13%) and smarter (6 papers, 8%) operators received less attention. Other typologies of operators, such as analytical and super-strength operators, were not identified in the papers analyzed. As shown in the figure, some papers considered multiple technologies, resulting in the combination of different operator typologies to describe their smart operator. For example, the operator who uses an AR device during the HRC can be defined as an augmented and collaborative operator [55,56].

Table 2
Operator 4.0 typologies.

Operator 4.0 Typology	Description	Reference
Super-strength operator	Powered exoskeletons represent a type of biomechanical system where the human-robotic exoskeleton works cooperatively with the operator to increase his/her strength and endurance for effortless manual activities.	[17]
Augmented operator	AR allows for enriching the real world with digital information and media that is overlaid in the operator's field of view	[17]
Virtual operator	VR allows the operator to interact with any object in interactive multimedia and computer-simulated reality with reduced risk and real-time feedback	[17]
Healthy operator	The operator uses wearable devices, which are designed to measure health-related metrics and other personal data, to monitor his/her state of health	[17]
Smarter operator	The operator uses an Intelligent Personal Assistant (IPA), equipped with AI, which helps the operator to interface with machines, computers, and all the production systems that are connected and integrated with all the others.	[17]
Collaborative operator	Collaborative robots directly cooperate with operators through intuitive interaction technologies, performing non-ergonomic and repetitive tasks	[17]
Social operator	The use of Enterprise Social Networking Services allows the operator to connect him/her on the shop floor with all the smart factory resources.	[17]
Analytical operator	Big Data Analytics, the process of collecting, organizing, and analyzing many data, allows the operator to predict failures, determine when to carry out preventive maintenance, and understand the smart factory performance	[17]
Proactive operator	The operator performs self-directed action, foresees or initiates change in the work system and work roles, and completes several different tasks, from monitoring and planning to verifying production strategies.	[51]
Creative operator	The operator is considered a maker, who works alongside automated production systems but in a creative role rather than simply monitoring non-discretionary workflow processes.	[48]
Industrial Safety operator	The operator exploits KETs to master procedures and safety regulations, and learn how to face emergency scenarios.	[53]
Empowered operator	The operator is equipped with industrial wearable devices, which can enhance his/her perception and communication ability thanks to AI. His/her decision-making ability is improved by human experience and multidimensional information support.	[54]

Contrary to the findings from the keyword analysis, where HF/E-related keywords were more prevalent compared to XR and HRC keywords, the literature mentions the healthy operator less frequently than the augmented and collaborative operators. This mismatch could be attributed to a tendency to associate Operator 4.0 with the technologies rather than his/her health. Thus, there is a need to shift the perspective and prioritize human health by adopting a thoroughly human-centric approach, placing humans at the center of the production process rather than being driven solely by technology.

4.1. Work-related risks

The Occupational Safety and Health Administration (OSHA) has categorized occupational hazards into five main categories: safety hazards, chemical hazards, biological hazards, physical hazards, and ergonomic hazards. In recent years, another category has been added to the

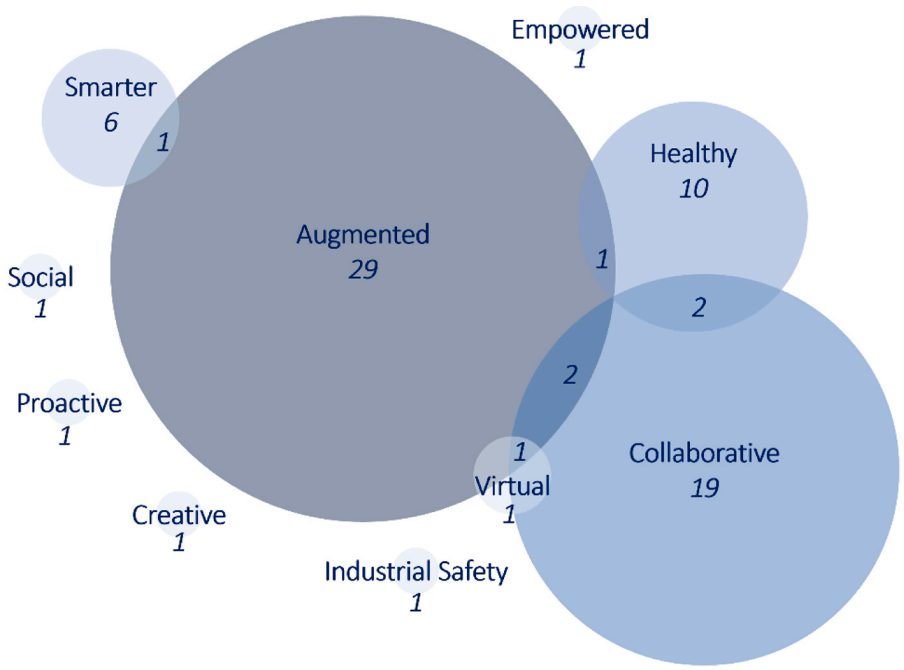

Fig. 8. Presence of different operator's typologies in the analyzed papers.

classification, which is psychosocial and organizational hazards, reflecting the increasing recognition of psychosocial aspects. Safety hazards encompass potentially dangerous situations that can lead to injuries, accidents, and illnesses in the workplace. These hazards are more likely to affect operators who directly work with machinery and include risks such as slips, trips, falls, electrical hazards, and operating dangerous machinery. Chemical hazards pose a threat to workers who are exposed to hazardous liquids, solvents, gases, or acids. Exposure to these substances can cause illnesses, skin irritations, breathing problems, and in severe cases, even death. Biological hazards include any biological substance that could harm humans, such as viruses, bacteria, or molds, generally associated with working with animals, people, or infections plant materials. Physical hazards affect workers in extreme weather conditions or harmful working environments. They encompass various factors present in the work environment that can harm workers without direct physical contact. Examples include continuous loud noise, high or low temperature, radiation, or high exposure to sunlight/ ultraviolet rays. Ergonomic hazards arise from manual activities, body positions, and working conditions that strain the worker's body. These risks are not always immediately apparent, making their identification challenging. Short-term impacts may result in muscle soreness, while long-term exposure can lead to musculoskeletal injuries. Ergonomic hazards include activities that involve awkward postures, manual handling of heavy objects, repetitive movements, excessive force, and excessive vibrations. In recent years, the recognition of psychosocial and organizational aspects has grown, necessitating their consideration in the analysis of operator risks. These hazards have negative effects on individual (e.g., health and well-being) and/or organizational (e.g., low productivity) outcomes [57]. They are primarily attributed to work organization and psychological factors, including high workload demands, intense work pace, and social relationships.

Although the terms "hazard" and "risk" are frequently used interchangeably while debating health and safety aspects, their meaning and function are different. A hazard is typically defined as something that has the potential to cause harm, while risk takes into account the probability of exposure and the potential severity of the harm [58]. Hazards are associated with the intrinsic ability of a situation to cause negative effects (e.g., electric wiring). On the other hand, risk considers the likelihood of a damaging event occurring and its potential impact (e.g., the exposed electric wiring puts it in the "high-risk" category if it was entangled with a sharp object). However, in scientific papers, the authors often identify the risks that operators are exposed to in specific conditions. For this reason, going forward, we will use the term “risk”.

The selected papers were analyzed to identify the main risks to which the operator is exposed and the associated risk factors. Papers that mentioned certain risks for the operator in the introduction and did not address them further in the rest of the paper were disregarded. From the analysis, it emerged that 36% (41 papers) identified specific risks for the worker that need to be mitigated and reduced. The risks have been categorized according to the previous classification. Some authors identified multiple risk categories in their papers: 20 papers (approximately 49%) addressed ergonomic risks, 20 papers (approximately 49%) discussed psychosocial and organizational risks, and only 11 papers (approximately 11%) identified safety risks. No papers highlighted chemical, biological, and physical risks since they pertain to specific working environments. For each category, the effects and impacts that the risks may have on the operator were also reported if specified by the authors in their papers. Specifically, the following effects have been identified:

- Ergonomic risks: biomechanical overload, MSDs, occupational illness
- Psychosocial and organizational risks: detrimental effects on operators' mental well-being, and human errors
- Safety risks: injuries, and accidents.

However, it has not always been possible to identify one or more effects in all the analyzed papers. In some cases, authors did not specify the impacts within the risk category (e.g., MSDs in ergonomic risks), but they referred to it in general (e.g., “not defined ergonomic risks”). Additionally, since understanding the causes of risks is essential for risk mitigation, all the possible risk factors identified in each paper have been included in the analysis. In literature, risk factors are defined as actions or conditions that increase the likelihood of injury [59].

To present the correlations between risk category risks effects, and risk factors, a Sankey diagram has been realized, shown in Fig. 9. The diagram depicts the flow between causes and effects, and the width of the arrow represents the magnitude of the flow. This allows for an

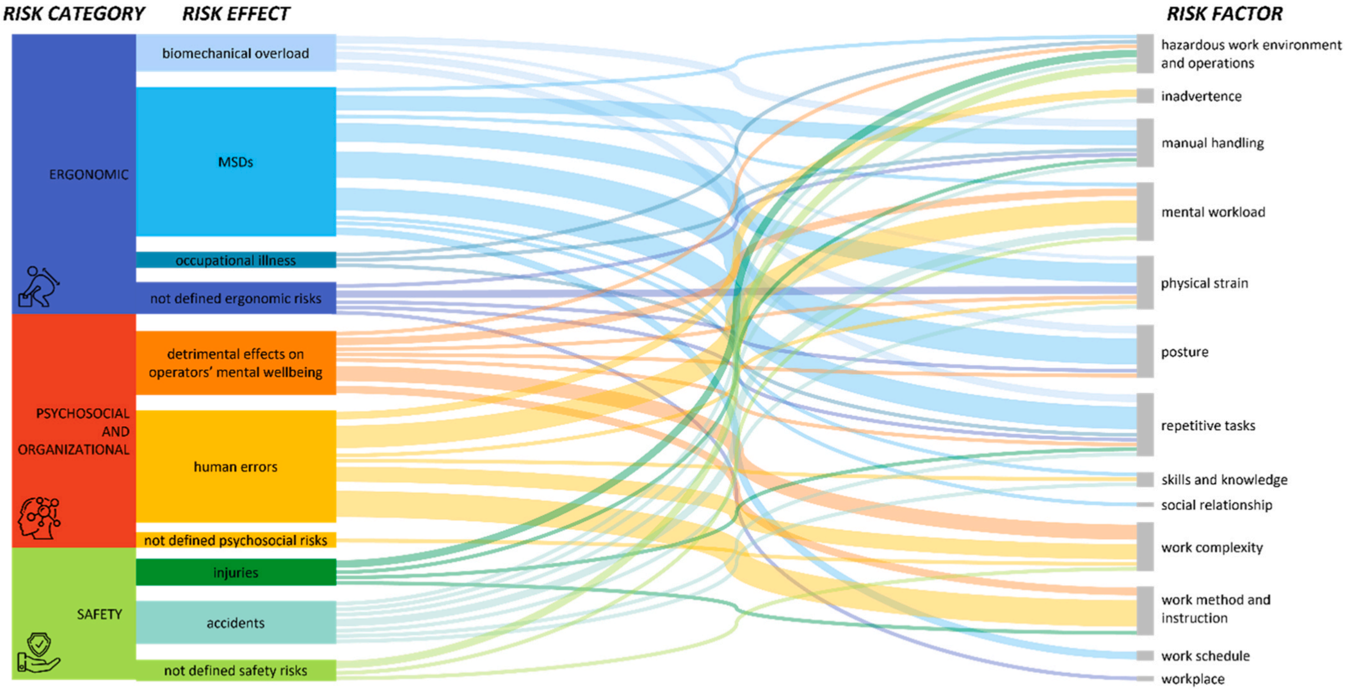

Fig. 9. Sankey diagram of the relation between risk factors, risk effects, and risk categories.

analysis of the most common factors leading to ergonomic, psychosocial, or safety risks, as well as the main effects and impacts within each risk category. Since ergonomic risks are more widely recognized within the scientific community, it is easier to specify an ergonomic risk compared to a psychosocial risk. As a result, there is a greater number of identified ergonomic effects compared to psychosocial effects, even though the number of papers that have identified these two risk categories is the same.

The analysis showed that ergonomic risks are mainly caused by prolonged exposure to uncomfortable and awkward working postures [60], manual handling of heavy objects (i.e., lifting, pushing, carrying, etc.) [61], repetitive manual work operations [62], and physical strain, which includes physical fatigue, forceful and sustained movements, and excessive exerted forces [63]. These factors can result in biomechanical overload, MSDs, and occupational illnesses that require long-term treatments. As a result, workers may need to take absences from the production process, leading to productivity loss for the company. While MSDs are commonly associated with high physical workloads, psychosocial and organizational factors have gained increasing importance in recent years in the insurgence of MSDs [64]. For example, an increase in work pace and a lack of recovery time have been linked to higher musculoskeletal strain [65]. The way work instructions are displayed and the layout of the workplace can also impact the worker's ergonomics, potentially forcing them to adopt uncomfortable postures [66]. A survey conducted by Wixted et al. [64] pointed out that psychosocial factors, such as poor social relations and low job control, are linked to an increase in self-reported musculoskeletal complaints, particularly in the upper back and upper limbs.

One of the significant factors contributing to psychosocial and organizational risks is excessive mental workload, which refers to the level of cognitive engagement and effort required when performing a task [67]. High mental workload and excessive concentration can have negative effects on operators' mental well-being, leading to stress [68], dissatisfaction [42], decreased productivity, and increased errors [69]. Additionally, various aspects related to work instructions and the complexity of operations can impact workers' health and performance. Manual activities now require higher precision, and the trend of mass customization has led to an increase in product variants, placing a significant demand on working memory [70]. Traditional work and procedural instructions (i.e., paper-based) are often difficult to understand, confusing, redundant, and inflexible, requiring significant time and effort to memorize [71,72]. Inadequate training sessions can also contribute to an increased likelihood of errors as they fail to provide sufficient skills and knowledge. In some cases, mistakes made by operators can be attributed to inadvertence, such as omission, misunderstanding, or distraction [73]. Furthermore, physical strain, particularly fatigue, can also pose psychosocial and organizational risks. Excessive physical and mental fatigue can lead to an increased likelihood of errors and can compromise the overall production process [63].

Finally, research has shown that a majority of accidents and injuries occur in hazardous work environments, particularly in specific manufacturing industries [74,75]. Studies have indicated that accidents often result from inadvertence, omissions, and misunderstandings [73]. Improper training systems or work instructions have also been identified as contributing factors to accidents and injuries [76]. Physical and mental fatigue can further increase the incidence of accidents as short-term effects [77]. Additionally, there is a link between exposure to safety hazards and increased mental demand, further highlighting the interconnectedness of psychosocial and safety risks.

5. Technological solutions to support Operator 4.0

In this section, the papers were categorized based on the solutions they proposed to address the identified risks and the KETs that were used. The solutions were classified into three different categories:

1. Design: it encompasses papers that presented a methodology or a framework to design workstation, work, process, plant, and collaboration between humans and robots/machines
2. Application/System: it includes papers that described the development of an application or a system using specific technologies, without necessarily defining a theoretical framework
3. Evaluation: it comprises papers that presented assessments or evaluations.

Fig. 10a depicts the correlation between the categories of solutions

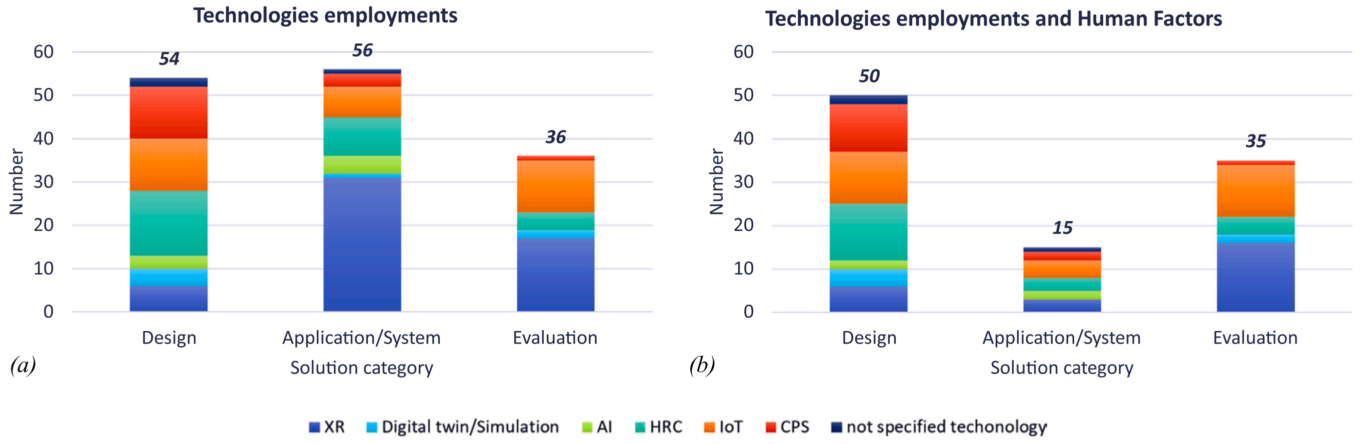

Fig. 10. Correlation between technologies, solutions, and human factors.

and the technologies, acknowledging that each article may encompass multiple KETs. Thus, each solution's category can be associated with more than one KET. The majority of the works focused on design methodologies or system development. The used technologies were categorized into six main groups: XR, HRC, AI, CPS, Internet of Things (IoT), and Digital Twin (DT)/simulation. The XR category encompasses all X-Reality technologies, including AR, Mixed Reality (MR), and VR. The IoT category also includes wearable systems and devices. The analysis revealed that CPS and CPPS were generally employed together with other technologies. In the *Design* category, the most frequently used KETs were HRC, IoT, and CPS. For *Application/System,* XR prevailed, whereas for *Evaluation,* IoT and wearable devices were the most used technologies, as indicated in the graph.

The *Design* of human-centered frameworks and/or methodologies is crucial before developing systems and applications to support Operator 4.0. The majority of works proposed a framework to assist in the operator's decision-making processes by using CPS and AI [50]. These frameworks aimed to address operators' inquiries regarding tasks, procedures, and tools through intelligent personal digital assistants such as AR and CPS [2]. Additionally, they focused on responding intelligently to operators' cognitive and physiological states using CPS and wearable sensors [78]. However, to perceive the advantages of introducing CPS and IoT technologies in the production systems and achieving suitable performances, it is necessary to properly integrate humans in this new environment. Therefore, some papers presented frameworks to integrate humans and technologies leading to dynamic and efficient cooperation [49,79]. Similarly, studying the interaction between humans and smart machines [80] and collaborative robots [81]. Highly adaptive and fast-reconfigurable systems are also necessary to establish efficient cooperation with smart systems [62]. Thus, the interest in designing systems that enable adaptive collaborative robots or smart machines based on human states or actions is highly increasing [62,82]. Other works presented methodologies for integrating technologies, such as IoT, DT, VR, and CPS, into the design of workstations [83], manufacturing processes [84], and work configurations [85]. This novel approach not only helps reduce design costs but also ensures the incorporation of HF from the early stages of the design process. Finally, the remaining papers in the *Design* category focused on HRC, specifically on the design of new collaborative workstations [86,87] and the definition of task allocation [88,89].

In the *Application/System* category, the development of XR applications is prevalent (31 papers). As depicted in the graph, the human-centered design approach for XR technologies is mostly overlooked, and the focus is directly on the development phase. Specifically, AR and MR devices are commonly employed to support and assist operators in manual activities [90], and enhance the interaction between humans and robots [55,56,91], or machines [92], while ensuring operator safety and productivity. Moreover, VR is utilized as an effective tool during the training phase, creating highly immersive and interactive virtual environments where HRC can be studied and evaluated without exposing operators to any risks [93,94]. The remaining papers focused on the implementation of wearable devices, IoT systems, and CPS without proposing a theoretical framework [54,95].

Papers that concentrated on the assessment of operators' well-being are classified under the *Evaluation* category. The majority of these papers employed wearable devices to measure and evaluate both the physical [61] and cognitive [96] ergonomics of shop floor operators. In some specific cases, the assessment was conducted within a virtual environment [97,98], during HRC [99–101], or while using AR applications [102,103] to monitor fatigue, mental stress, physical effort, and postural risks.

Considering the significance of HF, an analysis was conducted to determine the number of works that incorporated human aspects such as ergonomics, well-being, and social sustainability in their proposed solutions. To emphasize this aspect within each defined category, the graph in Fig. 10b only included papers that considered HF. It is immediately evident that theoretical frameworks and assessments consistently integrate human aspects, whereas they are often neglected in the development of applications or systems. By incorporating HF into the design of work environments, companies can create more inclusive and resilient systems that support the well-being of their employees, thereby contributing to social sustainability [104]. This would also promote the adoption of a proactive and preventive approach to work-related risks rather than a reactive one.

The implementation of a smart solution can be driven by different factors. Analyzing the selected papers, the following drivers were identified:

- *D1: Increase social sustainability*

  Social sustainability in production plants embraces various aspects, including the quality of working activity, workers' empowerment, individual/collective learning, employee participation, work-life balance, workers' rights, preventive occupational health and safety, and human-centered design of work [105,106]. The operator's well-being is encompassed within the concept of social sustainability, as it can be defined as a state characterized by satisfaction and positive emotions [107]. Common terms used to describe operator well-being include job satisfaction, motivation, good working conditions, and health and safety at work [70,108]. The aim is to preserve or build up human capital, promoting sustainable prevention and encouraging greater participatory efforts.
- *D2: Reduce physical ergonomics risks*

  Physical ergonomics risks are thoroughly described in section 4.1.

The prevention, reduction, and elimination of these risks result in a safer and healthier work environment.

- *D3: Reduce Psychosocial risks*

  Psychosocial risks are deeply thoroughly in section 4.1. Supporting the operator with advanced technologies during working activities leads to a reduce mental demand and cognitive workload.
- *D4: Increase safety and reduce accidents and injuries*

  Safety risks are deeply described in section 4.1. Ensuring operator safety is the first aspect that a manufacturing environment should ensure, according to the Industrial Human Needs Pyramid [109].
- *D5: Improve interaction and collaboration between human and machine/robot*

  The Industry 4.0 paradigm demands a deeper consideration of the modality of interaction and collaboration between humans and advanced production systems. The aim is to establish efficient, satisfying, and even enjoyable cooperation, always guaranteeing operator safety and awareness [110].
- *D6: Face work change*

  The paradigm shift from mass production to mass customization, along with the growing demand for more and more product variants and the rising cognitive tasks for operators, require a change in the organization of work [111]. To remain competitive and profitable, companies need further production flexibility, efficiency, and sustainability [86]. On the other hand, the new production paradigm changes the role and the work of operators, who must cope with the increasing amount of information and product complexity [51,112].
- *D7: Increase human performance and company productivity*

  The enhancement of human performance includes the reduction of human errors and competition times [72], while the improvement of company productivity means production efficiency, the reduction of time-to-market, and the improvement of product quality [69]. The introduction of new technologies to support the operator can be driven by improving these aspects.
- *D8: Reduce Costs*

The integration of the Industry 4.0 paradigm and the development of digital technologies can result in more efficient and flexible processes able to manufacture high-quality products, reducing costs and time, and providing a considerable competitive edge [113].

Fig. 11 illustrates the identified drivers and displays their corresponding count in the articles, allowing for the inclusion of two or more drivers in a single paper. The most prevalent driver is the desire to increase human performance and company productivity, followed by the aim to reduce psychosocial and physical ergonomic risks. Notably, there is greater attention towards psychosocial aspects compared to physical ergonomics, highlighting the growing interest in mental health. Nevertheless, considering both domains, physical and cognitive, ergonomics remains the prevailing driver that motivates companies to introduce and implement new technologies to support operators. The necessity to face the work change encompasses aspects related to performance and productivity. Similarly, efforts to enhance collaboration and interaction between humans and machines or robots are aimed at improving performance (e.g., right workload distribution), safety, and human awareness. Social sustainability includes ergonomics but also encompasses other aspects that focus more specifically on human well-being and satisfaction. Lastly, the reduction of costs is mentioned relatively infrequently as a driver, although it is likely often implicit and not explicitly stated.

Fig. 12 illustrates the relationship between the identified drivers and the utilized KETs, considering the possibility that papers may address multiple drivers and multiple KETs simultaneously. The use of XR technologies can significantly enhance cognitive and performance outcomes in operational settings by reducing cognitive load, eliminating the split-attention effect, and thereby reducing errors [68,114]. In comparison to traditional instructions, which are often complex, redundant, and physically distant, digital instructions provided by XR devices enable a decrease in demands on working memory [72]. Moreover, AR-based assistance systems can support spatially dispersed teams, optimizing their temporal coordination and consequently overall company performance [115]. In complex environments, accidents are a recurring problem, and the use of XR technologies for maintenance tasks can enhance safety, maintain availability, reduce errors, and decrease the time needed for scheduled or ad hoc interventions [73,116]. XR can rapidly provide relevant information to help resolve specific tasks, thus improving occupational safety measures [65]. Additionally, VR presents significant advantages for training operators in safety-critical environments and during collaboration with robots [94]. The work change and the increasing pace of innovation can be addressed by employing XR devices to transfer knowledge to employees in a faster and more efficient way [76]. Finally, the implementation of XR technology can have a positive impact on social sustainability by reducing the time spent on operations, enhancing worker health, improving well-being and motivation, developing user skills, and increasing overall job satisfaction [105].

The implementation of HRC is primarily driven by the aim to improve physical ergonomics, with a focus on reducing biomechanical overload [86], muscle efforts [99], manual handling of bulky objects [117], and awkward postures [118]. HRC can also be employed to alleviate the mental strain experienced by operators during complex assembly tasks [119]. As HRC involves a shared workplace, safety

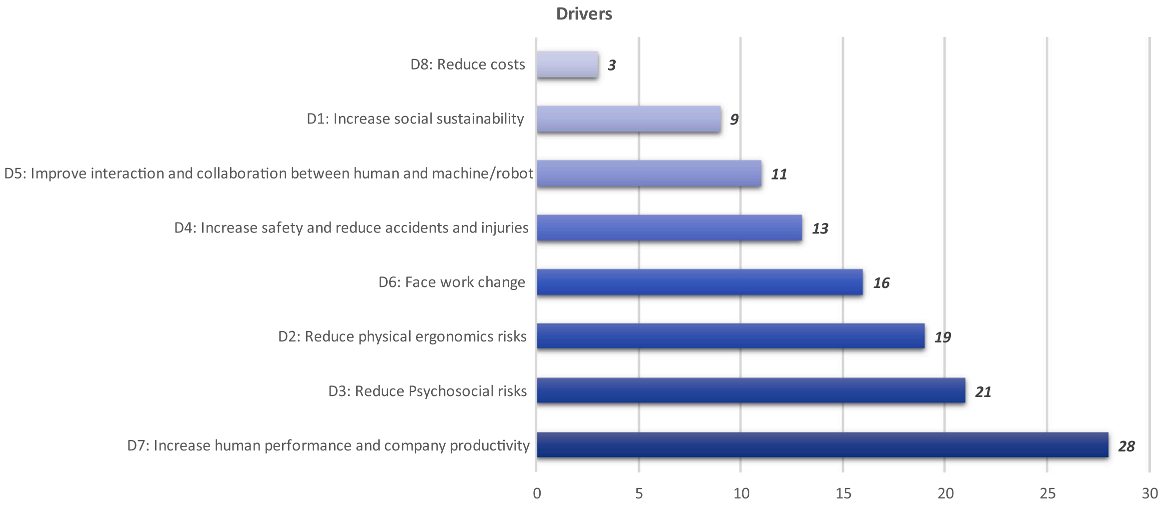

Fig. 11. Drivers.

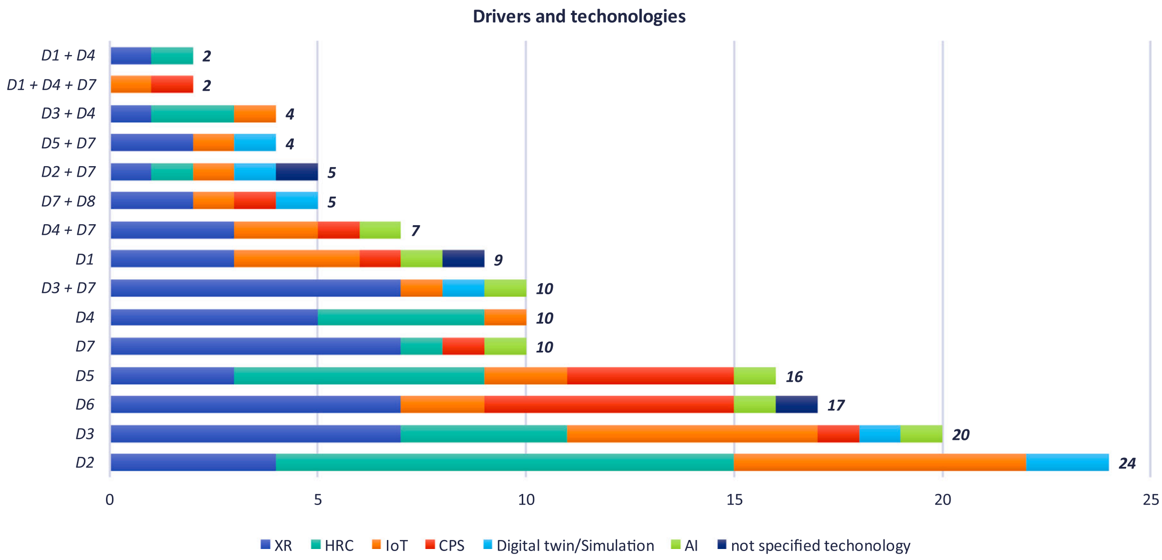

Fig. 12. Correlation between technologies and solutions' drivers.

considerations are always paramount [56]. One approach to ensure safety is by designing trajectories that balance both safe and psychologically less stressful movements, without excessively limiting robot performance [120]. The realization of HRC workstations also requires the definition of an efficient, intuitive, and satisfying collaboration and interaction between the two co-workers [121]. For instance, this can be achieved through dynamic task allocation based on human monitoring [88,122] or task complexity [89], or by providing the operator with an AR device [55].

IoT sensors are typically used with other technologies, such as HRC, XR, and CPS, to collect and transmit a large amount of real-time data. Wearable sensors are mainly employed to evaluate the operator's mental and cognitive load [123,124] as well as physical ergonomics [61,125], even during HRC [99,101]. Similarly, IoT can be used to create a specific infrastructure for capturing human-related parameters from the shop floor and assessing and enhancing workers' well-being [106]. Additionally, CPS and IoT can be leveraged to support the operator and intelligently respond to their cognitive needs [78]. In the same way, IoT can be employed to dynamically adapt AR user interfaces based on acquired contextual data about the activity, operator, and environment [126].

The increasing complexity of products and processes necessitates the enhancement of operators' capabilities, competencies, and flexibility. The adoption of CPS and CPPS can support operators in value-added activities, including decision-making, problem-solving, and creative actions [50,85]. Moreover, CPS can facilitate the establishment of a human-cyber-physical symbiosis enabling real-time, trustworthy, and dynamic interaction among operators, machines, and production systems by integrating IoT systems and AI algorithms [54,80].

Computer-based simulation and the creation of a DT are employed to assess physical ergonomic risks and identify potential hazards during the workstation design phase [83,113,125]. Additionally, IoT and DT can be used to monitor and evaluate physical ergonomics even during manufacturing production [97,127].

In the following paragraphs, the technologies chosen as research keywords (XR, HRC, CPS, and IoT) will be discussed in detail. Additionally, considering that AI has emerged as a prominent component integrated with these technologies, it will also be included in the in-depth analysis.

5.1. *Extended reality*

XR technologies have predominantly been deployed to assist and support the operator in various manual activities, such as assembly [68,71,74,128], repair and maintenance [129,130], quality control and visual inspection [69,105,131], and training [76,111]. To cope with the increasing amount of information and the complexity of products and production processes, it is essential to enhance the capabilities and skills of operators by empowering them with smart technologies [42,112]. Most research studies have focused on determining the benefits of XR systems in terms of competition times, error rates, and mental workload [72]. However, it is also crucial to evaluate user acceptance, perceived complexity, physical efforts, and frustration associated with the use of XR technology to ensure its ease of use in daily work [68,132]. Different XR devices have been tested and compared based on users, tasks, and contexts [129]: head-mounted display (HDM) (e.g., HoloLens 2), hand-held device (e.g., tablet), projection-based AR system, and Spatial Augmented Reality (SAR). The results indicated that the use of XR systems improved worker performance, reduced workload, and increased user awareness compared to paper-based instructions. However, there are differences among the devices used. While projection-based technology may yield inferior results compared to HDMs [68], some users preferred projectors due to the technical limitations of HMDs in real industrial scenarios (e.g. high weight, low battery, poor ergonomic design) [56]. Hand-held systems have proved to reduce errors and completion time, but they can have a negative impact on skill and memory preservation, and prolonged use can lead to physical exhaustion for operators [114]. The use of SAR can help reduce errors, especially for challenging tasks, but it does not allow displaying virtual objects in mid-air [133]. Simões et al. [134] investigated the combination of different devices, such as Microsoft HoloLens, projectors, and mobile tablets. This approach allows skilled workers to ignore digital instructions while receiving alerts about potential errors from the systems. In contrast, novice workers can utilize all the systems for comprehensive assistance. Overall, XR applications can be particularly helpful and convenient in specific use cases, potentially in unclear and demanding scenarios [135]. However, the application of XR in the industrial field remains in the exploration and prototype stages, due to technological limitations of devices, ergonomics issues, limited user acceptance, and cognitive aspects [135,136]. Therefore, attention should be given to the compatibility and optimization of user cognition and technology-integrated systems [103]. Moreover, objective measures to evaluate operators' stress levels during interaction with XR devices should be investigated [68]. It is essential to gain a better understanding of how humans interact with virtual objects in an XR environment in terms of cognitive demand, to design and develop systems that effectively enhance human performance by addressing cognitive needs rather than relying solely on user-driven behaviors.

5.2. Human-robot collaboration

Collaborative robots are implemented in a shared space to work "shoulder-to-shoulder" with humans [75], helping with repetitive and strenuous tasks and reducing their workload. Most of the research works investigated new methods to enhance collaboration and interaction between two co-workers. Authors have addressed several significant topics, including human safety [87], task allocation strategies considering task characteristics and the skills of humans and robots [60,121], and robot adaptation based on human behavior during collaboration [82,110]. Most studies revealed that HRC successfully improved task efficiency and accuracy, resulting in higher performance and reduced effort, although it may require increased temporal demand [137]. However, it is worth noting that many of these studies have been conducted in laboratory settings under controlled conditions and may not fully comply with safety regulations. There are still several open issues that need to be addressed to ensure a safe and effective HRC. Physical ergonomics is consistently considered in the HRC and HRI design, while cognitive aspects are often overlooked or receive less attention. Few works analyzed the physiological risks that could emerge during collaboration and the operators' acceptance of working alongside robots without barriers [120]. Pollak et al. [101] examined the levels of physiological stress of operators in different collaboration modalities. The results indicate that the autonomous modality generated more stress appraisal than the manual one. Establishing effective communication between humans and robots is crucial for ensuring safe collaboration, and the potential of brain-robot interactions to enhance HRC in industrial settings lies in their ability to directly convey intentions and commands from the human operator's brain to the robot, leading to improved efficiency, assistance in complex tasks, and a reduced cognitive load on the human operator. Overall, HRC can involve improvements in productivity, ergonomics, and safety in manufacturing environments, but only if HF issues are adequately considered [94].

5.3. Cyber-physical system

The term CPS is often used to contextualize rather than describe a specific innovation; it is typically supported by other technologies enabling Industry 4.0. In this new factory of the future, the concept of HCPS is emerging to develop symbiotic relationships between humans and AI within CPS environments [50]. The main goal of HCPS is to leverage the unique capabilities of humans and AI to create systems that are more intelligent, adaptable, and reliable. By integrating humans into the loop, HCPS aims at addressing the limitations of fully autonomous systems and benefit from human cognitive abilities, creativity, intuition, and ethical considerations. Many of the analyzed works highlighted the low consideration of HF in CPS. They mainly focused on methods or frameworks for human-oriented design to successfully integrate workers into CPPS [85,138], the evolution of interactions between humans and non-human agents [43,80] also enabling the human-in-the-loop approach [49,139], and models to enhance the decision-making process [50,140]. Kumar and Kumar [141] also suggested reconsidering industrial efficiency measures to include human cognitive efficiency. In this context, the highest expression of the CPS can be found in the design and development of an adaptive work environment. The system must be context-aware and able to change its behavior according to process parameters, events, and operators' needs. The importance of considering human-related data in the definition of adaptive algorithms is emphasized due to the aging workforce [142]. Currently, adaptivity is mostly limited to the user interface [138], but it should be extended to the HCPS as a whole. Healthy operator 4.0 should be supported by HCPS to intelligently respond to his/her cognitive and physiological state [78,143].

5.4. Internet of things

IoT systems provide an opportunity to collect and manage data that can be used to evaluate variables that define a specific environment, process, or system in which a person lives, works, or is physically present. This data can be utilized to gain insights and improve the overall efficiency and effectiveness of the system [106]. Many research works proposed frameworks and systems for ergonomic assessment using wearable sensors. Some studies focused on the detection of physical fatigue [77], while others developed tools for real-time calculation of the ergonomic risk index [61]. Wearables can measure and collect physiological data, thus they have the potential to support occupational health and safety for factory workers [70]. Several papers proposed IoT frameworks to evaluate cognitive or mental workload by collecting physiological parameters, such as Heart Rate (HR), Heart Rate Variability (HRV), Respiratory Rate (RR), Electrodermal Activity (EDA), electroencephalography (EEG), and pupillometry [96,107,123,124]. However, experimentations were mainly conducted in controlled laboratory environments, as measuring cognitive workload in real manufacturing contexts can be challenging [96]. Some works presented IoT frameworks to design and re-design manufacturing processes, plants, workstations, and tools to promote social sustainability and workers' well-being [83,84]. The aim is the creation of a human-centered connected factory using an IoT framework that enables data acquisition and analysis.

5.5. Artificial Intelligence

AI has revolutionized the field of smart manufacturing, empowering advanced automation, predictive analytics, optimization, and decision-making capabilities throughout the manufacturing processes [50,131]. By leveraging AI technologies, such as machine learning (ML) and computer vision, smart manufacturing systems can enhance productivity, quality control, and operational efficiency, leading to improved production outcomes and reduced costs [144]. In the context of smart factories, the integration of IoT, HCPS, and AI is transforming various aspects of manufacturing. Thanks to this strong synergy, communication and collaboration between humans and machines are more effective. Moreover, AI-based systems can learn and adapt to human preferences, making interactions more intuitive and personalized [80]. Additionally, AI can enhance machine capabilities to understand human emotions, needs, and intent, leading to more effective and seamless human-machine interactions [142]. Furthermore, the integration of AI with XR systems holds immense potential for enhancing productivity, reducing errors, and unlocking new possibilities. AI, particularly ML and deep learning, has revolutionized XR by enabling advanced data analysis from sensors and cameras. This integration empowers AI algorithms to optimize worker and factory performance, detect anomalies, and provide real-time insights to operators [128]. Additionally, AI enhances XR systems through object recognition, scene understanding, and natural language processing, expanding their capabilities and potential applications.

6. Discussion and conclusions

The literature reflects a growing interest in Operator 4.0 and his/her evolving role within the manufacturing context. An in-depth analysis of these papers has provided several key findings and insights.

The Operator 4.0 paradigm represents a shift towards leveraging and enhancing human competencies and skills to handle complexity, rather than replacing human workers [5]. Research predominantly focuses on human cognitive aspects and capabilities augmentation. When innovative technologies are integrated properly into the work environment, they have the potential to improve the physical and mental health of workers [145,146].

A value-oriented approach is essential to shift the perspective from a technological one to a human-centric one [147]. This shift aligns with the principles driving Industry 5.0. Inclusion and interaction are key topics within the new socio-technical systems. It is increasingly important to empower and support operators with disabilities and address the needs of an aging workforce to promote an inclusive work environment. In the factory of the future, a synergic human-machine symbiosis should be enabled, making humans, cyber systems, and physical systems work together in perfect harmony, leveraging the strengths of all resources [50]. Nagy et al. [148] proposed the utilization of hypergraphs to analyze and design an intelligent collaborative manufacturing space with sensors, aiming to enhance collaboration by providing valuable performance and system state information and identifying critical elements and interactions. The symbiosis must be reached even from an ergonomic perspective considering both physical and cognitive domains [81]. Traditional techniques for ergonomic assessments are beginning to be complemented by objective assessments exploiting sensor-based or vision-based systems.

The successful adoption of technological advancements requires individuals to unlearn old technologies and practices and embrace new ones [149]. However, many manufacturing industries, especially small and medium-sized enterprises, often lack the necessary knowledge and resources to practically implement Industry 4.0 solutions. In such situations, smart retrofitting can be a fast and cost-effective way to enhance productivity and competitiveness, yet the limited technical knowledge of employees often hinders its implementation. Ruppert et al. [150] argued that addressing this knowledge gap should start with students' education, and they propose a demonstration laboratory to support skill development aligned with the goals of Industry 5.0.

Moreover, innovative technologies offer effective tools for learning and adapting to the rapidly changing demand for skills. For example, Longo et al. [151] proposed investigating whether it is possible to train industrial workers specifically for upcoming scenarios rather than preparing them for a broad range of unlikely situations. They suggest a structured on-the-job training strategy for non-routine tasks, where a prescriptive analytics module schedules training sessions shortly before they are needed. Since technological progress is constantly evolving, a continuous learning approach is essential for the establishment of a learning society.

Even if technological capabilities represent the basis for making the implementation, the organizational changes result have a greater impact [90]. Clear leadership and a well-defined vision of top management are essential in promoting innovation. The existing organizational culture may need to evolve to embrace the changes brought by Industry 4.0. This includes fostering a culture of innovation, adaptability, and cross-functional collaboration. Effective change management practices should be employed to minimize resistance, address concerns, and ensure a smooth transition. Awareness and acceptance of the implemented changes are crucial [152]. Human awareness and context awareness enhanced the interaction with new systems (e.g., robots, machines, and devices) [110,126]. Humans need to be aware of systems' conditions and activities and at the same time systems should be able to perceive and understand the surrounding environment allowing for adaptation, personalization, and proactivity. However, frameworks and methods for adapting robots and machines based on human states are mostly tested in the laboratory. Moreover, robust data governance practices need to be established to ensure data integrity and security.

6.1. Emerging risks

Although the growing, rapid, and global spread of the Industry 4.0 paradigm supports workers with advanced digital systems and practical solutions, it also gives rise to new emerging risks that need to be analyzed and addressed.

Deploying XR solutions in a manufacturing environment pursues the concept of the augmented operator; however, it can give rise to safety risks due to the user being largely isolated from its near surroundings [153]. MR may be less problematic due to the partial view of the real environment but also requires care if used in industrial scenarios [48]. XR technologies have proven to have a positive influence on performance and do not seem to negatively impact cognitive load [154]; however, it is essential to conduct further research to examine their potential psychosocial risks and their influence on mental well-being.

Particular attention must be paid to the acceptance and cooperation of workers with advanced production systems; for example, by investigating the impact of collaborative robot movements and modalities on human stress [101]. Some preliminary experimentations of mental strain assessment during HRC by objective physiological measurement demonstrated that high speed, lower predictability, and robot proximity increase demands on the operator. These increased demands may lead to higher risk perception, anxiety, and workload, and potentially have detrimental effects on the operator's mental well-being. Additionally, these factors may also contribute to a decrease in task performance [94,100]. A way to consider cognitive stress during the trajectory design is proposed by Rojas et al. [120]. They defined a multicriteria approach to planning robot trajectory considering a trade-off between two constraints: smoothness and speed. The former is related to human cognitive stress, while the latter is related to safety requirements. In this way, the planned trajectory is safe, ergonomic, and efficient.

These new types of multi-agent collaborations, between human agents, organizational agents, software agents, hardware agents, and artificial (machine), will generate new systems integration and interoperability problems to face [155]. The deployment of indoor localization and tracking, which are vital for human-centric technologies, can encounter significant challenges in industrial complexes due to electromagnetic interference that directly impacts production or communication devices [156]. Sufficient and robust telecommunication technologies are essential to support the practical implementation of technological innovations in smart manufacturing environments.

6.2. Research directions and future challenges

This section provides insights into the future research directions to enhance Operator 4.0 well-being and performance while using new technologies. HF should be considered to enable predictive and proactive approaches, rather than exclusively preventive or even worse reactive.

(i) Physical ergonomics evaluation.

Even if physical ergonomics has been deeply addressed over the years and several standard methods have been developed for its assessment, there are still some challenges to face:

- Inertial sensors and magnetometers can suffer from drawbacks such as magnetic disturbances that hinder data collection for objective ergonomics assessments. These limitations could be overcome by using additional video signals [61]. However, also these systems have some drawbacks related to the human-tracking system, more specifically to the use of a depth camera-based tracking method [60]. Combining cameras placed at different locations around the human could improve the human-tracking system and reduce occlusion issues.
- To leverage the potential of the DT and enable a real-time analysis the motion capture system must be able to process and transfer data in real-time [97].
- Real-time feedback about the risk index, considering all the ergonomic domains, should be provided to the operator [84]. Moreover, the suggestion of corrective actions could be automated and specifically designed by using AI and ML.

  (ii) Psychosocial risks evaluation

  There are still significant research gaps for operator mental workload (also known as stress or cognitive load) evaluation during working activities. Although the use of wearable devices could be extremely simple, the collection, elaboration, and analysis of measured health-related parameters and personal data require a significant effort in terms of research and study. The main issues are the following:

- Identification of the labels for AI techniques such as supervised ML models to be used in real industrial environments [67].
- Investigation of universally valid methods to determine mental workload that can be applied to any operational scenario.
- Definition of ground truth for field data.
- Use of multiple sensors to increase the consistency of measurements and reliability of the system.
- Elimination of inaccurate readings caused by the wearable device’s poor placement or the user’s rapid movements. Even vision-based systems, such as facial thermography, present multiple challenges related to the depth of field, the accuracy of tracking, and interferences [124].
- Study of different data fusion techniques and weighting strategies to calibrate the model for each subject.
- Investigation of the emotional response based on human psycho-physical response monitoring [125].

(iii) Industrial human needs.

A human-centric approach must meet industrial human needs, ranging from the basic ones (safety) to personal growth. The introduction of new technologies raises security, ethical, and privacy concerns that require careful attention to ensure industry acceptance [139]. It is crucial to ensure that confidential information regarding the operator’s personal, mental, and physical state remains inaccessible to unauthorized individuals, and the operator should have control over and monitoring capabilities of their own data [78].

Engaging workers in the implementation of new digital technologies plays a vital role in how they perceive upcoming changes. Workers need to be informed about the benefits and opportunities that technology usage can bring. Kadir et al. [157] confirmed that during the initial implementation of advanced solutions, both operator well-being and system performance may be negatively affected. However, after successful implementation, both aspects tend to improve. Additionally, further investigation into participatory ergonomics approaches for successful workstation and process design and redesign is necessary.

Future efforts should focus on designing and developing new instrumental prototypes of active-power assistive equipment to support aging workers. New training methods should be explored to effectively train robots starting from workers’ experience to guarantee ergonomic movements [32]. One of the main challenges lies in capturing and modeling workers’ knowledge and expertise. Job design, with a focus on health, safety, satisfaction, and performance, needs to be reevaluated considering the complexities arising from individuals’ aspirations, hopes, and personal backgrounds [158].

(iv) Operator augmentation.

Although XR technology is mainly focused on system development (Fig. 10), the practical implementation of XR in the manufacturing industry remains in the exploration and prototype stages. Wearable XR devices require still more technical maturity, in design, safety, comfort, and software aspects, to be considered suitable for industrial environments [54,66]. Improvements in tracking accuracy in manufacturing environments should be obtained, by examining and exploring marker-less recognition techniques [69]. Moreover, XR turns out to be more beneficial to novice learners, since the advantages of using this technology reduce as more assembly attempts are performed, and the operator begins to master the activity [68]. Experienced workers usually tend to ignore digital instructions, but they considered the system useful for its alerts about potential errors. Finally, the greatest potential of this technology currently is for teaching and learning activities [76].

(v) Human-machine symbiosis.

Dynamic adaptation of production systems to human states and process performances is the basis for a symbiotic collaboration and needs to be deeply investigated [142]. Online adaptation and dynamic task allocation are crucial in flexible and reconfigurable production processes involving HRC and smart machines [63]. A task allocation based on the individual human being with their capabilities, comparing them with the specific requirements of a given task will allow for designing an inclusive workplace, which is ergonomically adjustable and accessible to disabled people [159]. Moreover, Cimini et al. [160] proposed a job profile design tool aimed at comprehending the changes in certain jobs and the need for their redesign, particularly in terms of task allocation, following the adoption of new smart and digital technologies and associated tools. To successfully implement dynamic adaptation during HRC in industrial environments, some practical implementation challenges need to be further investigated. Firstly, the system needs to be compliant with the current international regulations on safety [82]. Other technical challenges should be addressed, such as the choice of practical, low-cost, but reliable sensors to record human states, and the training of detection algorithms, which can be time-consuming and not in real-time.

6.3. Limitations

There are some limitations of this paper that need to be addressed. The review provides a present overview of the current state of scientific research, despite being continually updated.

(i) Lag times.

A systematic literature review often fails to capture the latest research on a specific topic due to the time delay between the final systematic search and the submission/publication of articles. This delay has led to the omission of emerging concepts and terms that have acquired significance since the start of the search. For instance, one such concept is Operator 5.0, which was not widely recognized at the beginning of the research, resulting in the exclusion of keywords associated with this term from the study. However, given the impending shift towards the Industry 5.0 paradigm, it becomes crucial to enrich the analysis by incorporating the concept of Operator 5.0, which introduces the notion of a Resilient Operator [161,162]. It involves two aspects: addressing workforce vulnerability through enhancing "self-resilience" and enhancing the "system resiliency" of human-machine systems. It empowers individuals to adapt and cope with challenges while optimizing collaborative human-machine systems to withstand disruptions, adapt to change, and recover efficiently.

The context is shifting towards what is known as HCPS [163], aiming to establish security-engineered systems that actively involve humans in decision-making. These systems leverage advanced communications, adaptive control technologies, and context-aware approaches to ensure fault tolerance and seamless interactions.

(ii) Keywords selection.

The selection of research keywords has affected the results, even if the identification of search terms was very careful and aware. For example, the KETs included in the search words have been limited to those by which humans can be supported during working activities, neglecting others. The criteria employed might have potentially excluded pertinent studies from the review, particularly those related to big data and analytics, and simulation. In addition to the existing keywords, it is recommended to consider incorporating new keywords related to the emerging paradigm. These could include terms such as resilience, social sustainability, adaptability, workforce agility, and more.

(iii) Quality of included studies.

The focus of this systematic literature review was to incorporate high-quality studies by exclusively selecting journal articles. However, this approach inadvertently overlooks valuable papers published in conference proceedings, leading to the omission of significant studies and introducing a potential source of bias. Therefore, it is recommended to include papers presented at relevant conferences in further analysis to provide additional insights into recent research. For instance, Romero et al. [164] present a vision for the future of work in smart resilient manufacturing systems within the emerging Industry 5.0 paradigm. Their work proposes achieving optimal resilience in smart manufacturing systems from a human-centric perspective, employing the Operator 4.0 typology and its associated technical solutions. Incorporating such conference papers can enhance the comprehensiveness and timeliness of the analysis, ensuring that recent advancements and perspectives are considered.

Declaration of Competing Interest

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

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jmsy.2023.08.016.

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