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Review

Current development on the Operator 4.0 and transition towards the Operator 5.0: A systematic literature review in light of Industry 5.0

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A R T I C L E I N F O

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A B S T R A C T

Technology-driven Industry 4.0 (I4.0) paradigm combined with human-centrism, sustainability, and resilience orientation, forms the Industry 5.0 (I5.0) paradigm, providing support for the workforce and enabling the Operator 4.0 (O4.0) approach. The I5.0 focuses can face unforeseen challenges, as the applicability and readiness of I4.0 solutions are still not well discussed in the literature. Therefore, structuring existing knowledge of O4.0 to prepare for the smooth transition toward Operator 5.0 (O5.0) is crucial. A systematic literature review is performed in the Scopus database, considering publications up to 31 December 2022. Bibliography Network Analysis (BNA), text mining techniques (i.e., Latent Dirichlet Allocation (LDA), BERTopic), and knowledge graph (KG) were deployed on the retrieved abstracts. The full-text examination is carried out over papers matched by LDA and BERTopic. From the BNA result of 279 relevant papers, clusters of active researchers and topics were found, while text-mining results revealed trending and missing research directions. The extracted details from the full text of 81 papers reflected the coverage and development levels of O4.0 types with the preparation for resilience, human-centrism, and sustainability. Achieved results suggest that though the O5.0 transition is inevitable, I4.0 technologies are not ready with sufficient human factor integration. Missing research orientations including integrated sustainability from the human perspective, or system resilience, concerning drivers and restrainers for technology adoption. To prepare for O5.0, discussed O4.0 drivers can help to shape the favorable conditions, and the restrainers should be mitigated before adopting human-centric technologies. Further study including grey literature is necessary to exploit more industrial and policy-making perspectives.

1. Introduction

Industry 4.0 (I4.0) term was coined as an umbrella for modern exploitation of smart automation, data exchange and processing, and manufacturing technologies [1–3] based on increasing potentials of inter-connectivity [4]. I4.0 technologies revolutionized computer-integrated manufacturing and flexible manufacturing systems [5–9], created potentials on triple-bottom-line levels: Economically, Environmentally, and Socially [4,5]. Regarding the social dimension, I4.0 technologies are even well-employed at governmental levels [10].

However, with the technology-driven nature, I4.0 also poses threats [11] to the environment (i.e., electronic waste generation) and society (i.e., technophobia, unemployment fear) [12,13]. Considering manufacturing operations [14], usually economic and environmental bottom lines are considered first, in that order, as they occur earlier and are easier to measure and regulate. With associated effects often being delayed in time, the social dimension is underrepresented [15]. The same phenomenon happened with the invention of television [16] and video games [17], where the social aspect came last in the technology-process-people triangle, causing negative effects (i.e., addiction, social displacement) on an unforeseen scale. Therefore, I4.0 pros and cons should be assessed from environmental and, especially, social aspects before technical implementation, to avoid negative psycho-social effects on the workforce scale of the whole manufacturing society.

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I4.0 technologies enabled the integration of human operators with manufacturing processes (and equipment) into Human–Cyber–Physical Systems (H-CPSs) [18,19] as a new generation of workers (i.e., O4.0) [20], with different types corresponding to different core I4.0 technology gadgets [21]. Not only giving a tool-set to support human workers, this concept put them back at the center of manufacturing, as well-stated by Rosenbrock [22] as "Humans should never be subservient to machines and automation, but machines and automation should be subservient to humans". The I5.0 paradigm was formulated by the European Commission (EC), calling for a sustainable, human-centric, and resilient European industry [23], by utilizing rapid developments of sensors, wearables, actuators, and communication technologies [24,25]. Answering this call, the ideal symbiosis work system consisting of H-CPS and adaptive automation, which aims at a socially sustainable manufacturing workforce, is proposed as O5.0 [18,26], along with resilience requirements for human operators and human–machine systems. So far, O4.0 and O5.0 are the ongoing revolutions of operator-oriented paradigms [26].

Though the O4.0 is expected to naturally evolve into O5.0, both paradigms are still under development, since their common key element (i.e., human-centricity) is still underappreciated [27]. To prepare for unforeseen negative social effects, it is worth considering how the I4.0 smart technologies and the O4.0 paradigm could adapt to the I5.0 requirements, and how the smooth transition toward the O5.0 can create an impact on workplace sustainability, social issues, and resilience. As the field has newly emerged with only several granulated works of scattered topics, a comprehensive study providing an answer to this trans-disciplinary concern is critical. Therefore, this paper aims to address the following research questions (RQs):

- RQ1: What are the present research interests, active researchers, emerging trends, and development levels of the human-centric I4.0 and O4.0 solutions, regarding sustainability, resilience, and human-centrism?
- RQ2: What are the current readiness of human-centric I4.0 technologies and the O4.0 solutions for the I5.0 paradigm?
- RQ3: What can be expected with the O5.0 paradigm, inferred from the drivers, restrainers, and benefits of the technology adoption in the current human-centric I4.0 and O4.0 studies?

By answering these questions, the potential of the I4.0 technologies to achieve the I5.0 focus and create the O5.0 workspace will be highlighted. The synthesis from this study provides decision-makers insight into O5.0 enablers, while knowledge structuring helps scientists and practitioners discover covered applications and missing research directions. This work facilitates the transition toward I5.0 in general and motivates future research for O5.0 solutions in particular.

The paper is structured as follows: Section 2 describes applied strategy and methods. The analyzed results and findings then are delivered in Section 3. The discussion about the current development of O4.0 and the transition toward O5.0 are given in Section 4. The conclusion is drawn in Section 5, along with the future research agenda, which can be beneficial for researchers and entrepreneurs in the fields.

2. Research methodology

A systematic literature review approach was used in this work. Due to a large number of scattered studies, quantitative text-mining techniques were employed before in-depth qualitative full-text assessment. This section describes the review strategy, selected methods and tools, and the adjustment made in each step.

2.1. Review strategy

The selected database is Scopus, the most commonly used for literature searches [28], as it includes in-press papers that are important for emerging and multidisciplinary topics [29], suitable for field delineation [30]. It has advantages in comparison to Web of Science Core Collection (WoS CC) with more records [31] with good quality [32]. A generic query is constructed to start with a possibly great number of papers, its detailed descriptions are described in Appendix A. The PRISMA 2020 guideline [33] was applied in this paper. The records were limited to the following:

- Type: articles, conference papers, book chapters, reviews;
- Publication date: until 31st December 2022;
- Language: English.

The title and abstract screening phase was conducted with the inclusion criteria defined as follows:

- Irrelevant: studies that did not consider the manufacturing environment, or did not mention the use of the I4.0 technical solution, or the purpose of technology usage is not to support the role of human workers in their production tasks.
- Low relevant: studies that implied using the I4.0 technology to support human workers or partly mentioned the I5.0 objectives.
- Medium relevant: studies that explicitly proposed using the I4.0 technology to support human workers, with a detailed analysis.
- High relevant: studies that proposed using the I4.0 technology to support human workers and considered the I5.0 objectives.

Considering the fact that all papers are filtered based on the role of human workers in the manufacturing system, which is already human-centric, the I5.0 objectives for inclusion criteria are sustainability and resilience.

With a large amount of available literature that is impossible for manual or quantitative processing, researchers may seek another way to generalize and conceptualize. Since the literature is stored in the digital form of bibliometrics data, data mining, and machine learning methods can be applied for effective information retrieval, knowledge extraction, and document classification [34]. Various applications offer analysis and visualization tools to carry out bibliometric analysis [35]. Text processing built-in tools such as Cit-NetExplore and VOSviewer can provide citation-based clustering for complex cluster analysis [36]. Thanks to these results, topic modeling analysis and trend detection can be conducted to predict the emerging research direction in the future such as in modern economics [37], road safety [38], educational administration [39], tourism [40]. [41] proposed a combined approach that integrates AI and machine learning to process the literature data for a scientific review paper.

This study deployed a combination of techniques to analyze the relevant papers. After title and abstract screening, Global Citation Score (GCS) analysis and network analysis were developed with the VOSviewer tool. Next, quantitative text mining methods, i.e., Latent Dirichlet Allocation (LDA) and BERTopic, were applied to identify leading topics. The scheme of the study is following, with details mentioned in the next subsections:

- Quantitative method is used to check if keywords exhibit the expansion into more aspects of the I4.0, and awareness of the O4.0 and I5.0; The index keywords coming from publishers are examined for the same purpose;
- Quantitative text mining is applied to consider the research context and suggestions from the abstracts; Which allows for better predicting if one can expect a transition toward the I5.0; It is achieved by examination of the clusters of co-occurrence of these related keywords; It allows to see overlapping relevant topics and identify for further analysis prominent papers constituting mentioned topics;

Table 1
The most five popular publication sources from the included studies. The technical journals were the most favored.

No	Name of journal	Studies	Citations
1	Computers and industrial engineering	13	611
2	Sustainability (Switzerland)	12	476
3	ifip advances in information and communication technology	14	407
4	Annual reviews in control	3	365
5	Applied sciences (Switzerland)	12	238

- To further assess the readiness for this transition and foresee the possible restrainers and drivers, a closer look is taken by conducting in-depth full-text analyses and performing structured qualitative research; That allows for the extraction of searched data (details of proposed technologies, drivers, restrainers, benefits) from most seminal papers as defined via quantitative methods;

2.2. Methods and tools

A bibliographic network contains multi-typed, interconnected objects which enable an in-depth analysis with different procedures, such as exploring the author collaboration, citation communities [42], assessing research performance and the structure of research fields [43]. VOSviewer is a tailored tool for BNA [44–47] with distance-based visualization and other specialized features such as fractional counting methodology, association strength normalization, similarity-based mapping, and smart local-moving algorithm clustering [45–47]. By applying BNA with methods provided by van Eck and Waltman [44], the author's co-citation, term co-occurrence networks, and their clusters were employed in this research.

Topic modeling methods are deployed on the abstracts after the title and abstract screening phase to organize documents into respective groups. LDA is chosen as one of the most popular methods for this purpose [48–50], and is performed with the text mining module within KNIME analytic platforms [51]. A KNIME flow to process the text data is built with several principles applied during the word tagging process, as details provided in Appendix B.

To have a more interpretable, coherent topic representation with semantic relationships between words [52], BERTopic is performed to complement the LDA result, with a corresponding Python package [52]. The raw input for BERTtopic is extracted from the retrieved text on the KNIME platform, after the pre-processing step.

As KNIME returns the keywords from the LDA-discovered topics with the association metrics, a KG can be constructed with these keywords being the nodes and the weight of edges equal to the co-occurrence probability. A similar method is adopted with the combination of KNIME and Tableau software [53]. In this research, the combination of KNIME and Gephi [54] is deployed.

3. Findings from the included studies

3.1. Quantitative results from bibliographic network analysis and text-mining

3.1.1. Descriptive statistics of relevant studies

The search query returned 415 records, and three documents were excluded after technical screening (duplication, language). After title and abstract screening, 303 records were left for further quantitative analyses with BNA. Within these papers, the five most popular journals can be seen in Table 1. The two journals with the most frequent citations are "computers and industrial engineering" and "sustainability (switzerland)".

After conducting LDA and BERTopic techniques separately, four topics with 114 papers were matched with similar groups of terms, and eligible for the full-text scanning phase with the same inclusion criteria as in the title and abstract screening phase. The total number of included studies was 81 papers. The PRISMA flowchart is illustrated in Fig. 1. Details of the result from each analysis are described in the following subsections.

Fig. 2 shows the descriptive statistics of 81 included papers. Most of them were of medium relevance and were article papers, which inferred that the topic was not popular among researchers. Theoretical studies, conceptual frameworks, and studies with a statistical model or surveys contributed a larger ratio than the experimental ones and use cases. This reflects the fact that not all human-centric technology are well-defined in application contexts. Starting humbly with no publication from 2000 until 2015, the number of studies started to gain momentum in 2019, as the I4.0 has been proposed in this milestone. The peaks were in 2020 and 2022 with 22 and 35 studies, respectively. It can be expected that the interest in the social dimension of I4.0 will increase in the future.

3.1.2. Networks of author citation and keywords co-occurrence

Due to the large number of authors, only 147 authors possessing at least two publications were considered, and 103 of them cited the work of the others. With the fractionalization normalization method, the citation network is illustrated in Fig. 3, with the node scale as the citation number of each author.

The highest cited cluster gathered around Romero D. and Stahre J., respectively. Rauch E. and Gualtieri L. are the lead authors of the second most cited cluster. Peruzzini M. and Battini D., respectively, lead the rest third and fourth clusters. Details about four author clusters (CA) can be found in Appendix C.

From 2248 keywords from authors and the index of the publishers, non-contextual keywords (such as article, survey, case study, literature review, article, etc.) were excluded. Similar-meaning keywords were replaced by a single keyword (e.g., "collaborative robots", "collaborative robot", and "cobots" were replaced by "Cobot"). The co-occurrence network constructed by 82 keywords that appeared in at least five documents was illustrated in Fig. 4, with the node size representing the occurrence frequency. Interestingly, the keyword "Industry 4.0" occurred with the highest frequency, while "Industry 5.0" and "Operator 4.0" also appeared noticeably in different clusters.

The first cluster depicted in red color was the largest, with the most frequent keywords of "Industry 4.0", "Industry 5.0", "social sustainability", "engineering education", "human resource management" "economic and social effects" exhibited the transition of the sustainability aspect from I4.0 to I5.0, with the focus on a larger scale of workforce society. The second cluster is illustrated in green, with the keywords "ergonomics", "cobot", "human–robot collaboration", "man-machine system", "human–robot interaction", "accident prevention" and "machine design" appearing most frequently, representing the collaboration process between human workers and manufacturing systems. The third cluster represented the application of technology to support the human role in industrial work, with keywords such as "Operator 4.0", "CPS", "occupational health and safety", "wearable technology", "enabling technologies", "H-CPS", and "industrial hygiene". With hints from the keywords "human-centric", "well-being", "productivity", "risk assessment", "job analysis", and "behavioral research", the last cluster suggested the human factor consideration during the I4.0 technology consideration and adoption, to ensure the proper installation without any disruption. Details of recognized keyword clusters (KCs) were provided in Appendix C.

To take a deeper look at the difference between author and publisher keywords, two corresponding networks were constructed with the keywords that appeared in more than five documents. There are 36 keywords from authors and 77 from publishers, which overlapped. However, they formed different cluster structures.

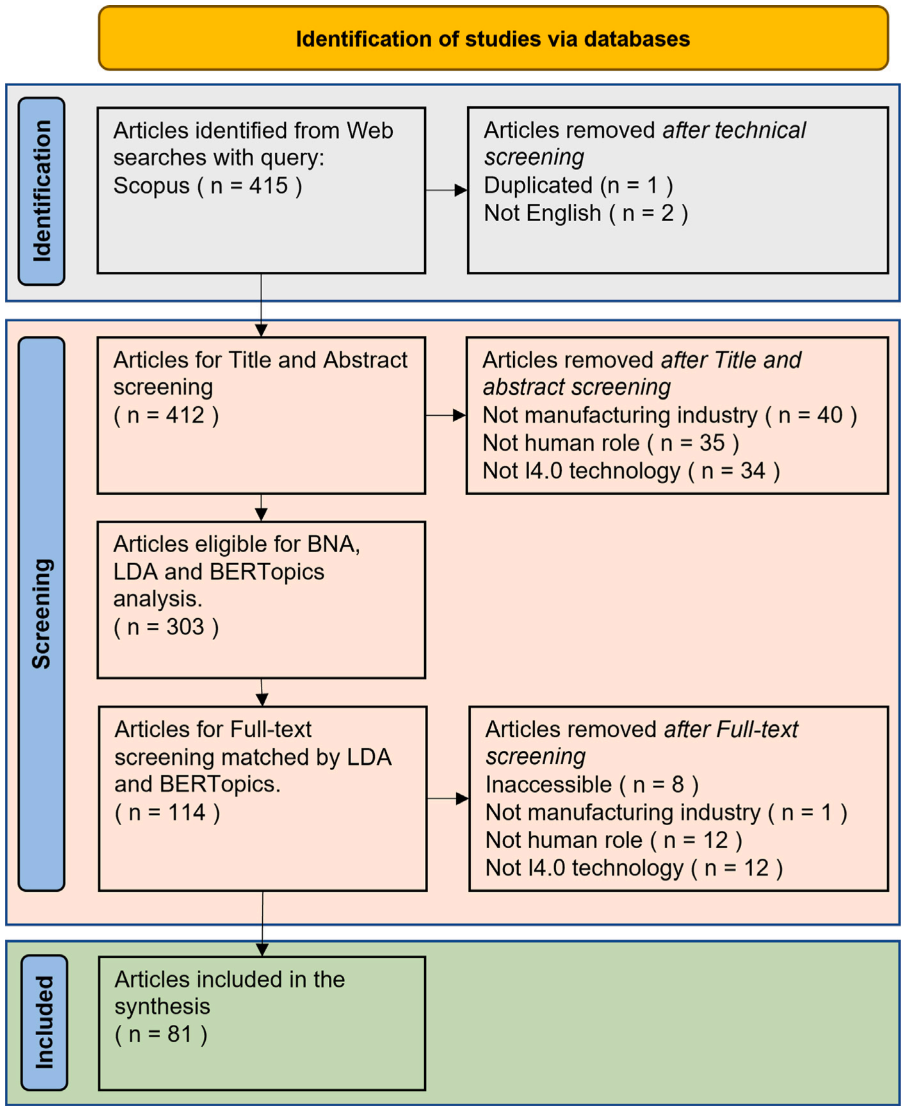

Fig. 1. PRISMA flowchart of the employed research method.

Four main clusters can be seen from the author keyword network in Fig. 5. Consider the two clusters: the red cluster illustrates the technical aspect of the O4.0 with AI, machine learning and digitalization, while the blue one represented the benefit of “human-centered manufacturing”, “ergonomics” and “productivity”. The third cluster in green color describes the transition into the I5.0, with “Industry 5.0”, and “human-centric”, while the fourth one in yellow mentions “Operator 4.0” and “social sustainability”. It can be seen that these clusters are not well-connected, as the meanings of the associated keywords were not convergent.

With more keywords from publishers, a clearer trend can be observed in Fig. 6. The first two largest clusters depicted in red and green colors reflect the technical and system collaboration aspects of I4.0 technologies, which are similar to the two main clusters from the network of all keywords. Noticeably, the “economic and social effects” emerged, connecting the technical aspect of the green cluster with the human–system collaboration aspect of the red cluster. Another significant difference is that the sustainability aspect now has a very well separately shaped branch with “sustainability”, “social sustainability”, and “sustainable development” with the “life cycle” and “supply chain”, while the O4.0 aspect is supported by “human-machine interface”, “artificial intelligence”, “real-time system”, which offers a more incisive meaning.

It can be concluded that the network of author keywords is not coherently structured, lacking supporting concepts within the same cluster, while the keywords from publishers are in contrast. However, the position of “Industry 5.0” is still in a technical cluster, not aligned with the sustainability aspect, showing that the keywords from publishers did not reflect the subtle intrinsic characteristic of I5.0 (meanwhile, this keyword was in the same cluster as “sustainable development” and “social sustainability” in the network of all keywords).

3.1.3. Latent Dirichlet allocation

Only 272 terms that occur at least in 10 documents are considered for LDA. Some terms occurring in fewer documents were included as they were important (e.g., “circular economy”), while too high-frequency terms which appeared in almost all documents (e.g., “human”, “Industry 4.0”) were excluded from the texts to avoid bias. The optimal number of topics returned after the PCA and the Elbow method was four. The 15 terms constituting each topic were depicted in Fig. 7, with the font size associated with the occurrence strength. The input set of terms and LDA result details are given in Appendix E.

The first topic (LDA 0) exhibited the trend of technical solution development to assist the work of operators and enhance their performance in manufacturing systems. The second topic (LDA 1) concerned the in-depth integration of the workforce into the future of smart

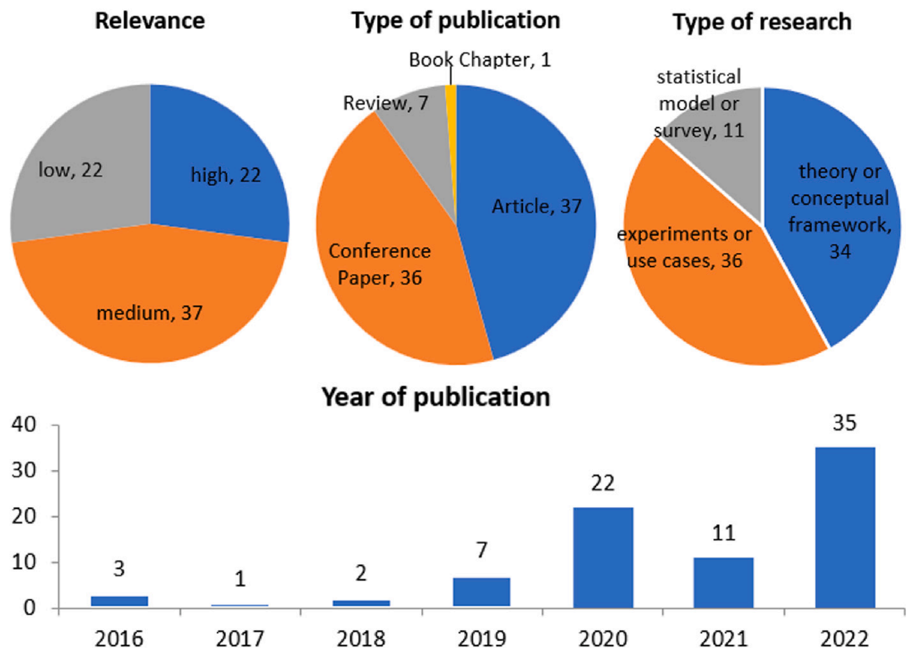

Fig. 2. Descriptive statistics of the included studies. Though the studies mentioned practical application and high relevance were still low, an increasing trend can be observed.

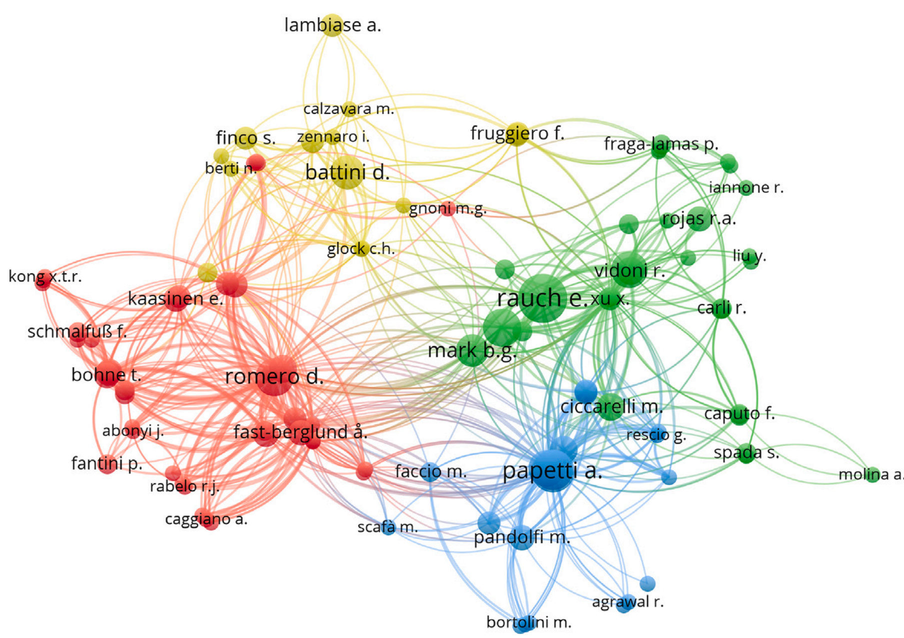

Fig. 3. Author citation network from the included studies, by the active authors possessing at least two publications. Four clusters can be recognized in red, green, blue, and yellow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

manufacturing by considering the cognitive and well-being aspects. The third topic (LDA 2) showed the growing concern about sustainability, not only in the manufacturing economic aspect but also in the social and environmental aspects, with the I5.0 appearing in this topic. The last topic (LDA 3) considered the collaborative work environment, in which human workers perform manual work along with cobots.

3.1.4. BERTopic

Four clusters were also discovered by BERTopic, with the first 10 most frequent terms shown in Fig. 8. Details of these clusters are provided in Appendix E.

The result from BERTopic confirmed the LDA result, but somehow they complement each other. The total number of papers that matched the results from LDA and BERTopic was 81, with relevant details given in Appendix E. This set of papers will be diagnosed in full text in the next section.

3.1.5. Knowledge graphs

Due to a limited number of terms that can be shown in the KG, only 65 terms with the highest co-occurrence in at least five documents will be included. The constructed KG is illustrated in Fig. 9, with the terms represented by nodes. The node size exhibited the connection of that node to other nodes, and the edge thickness showed their co-occurrences in documents.

From this KG, a closer look can be taken at a specific group of connected terms, to consider a broader meaning of current concerns in

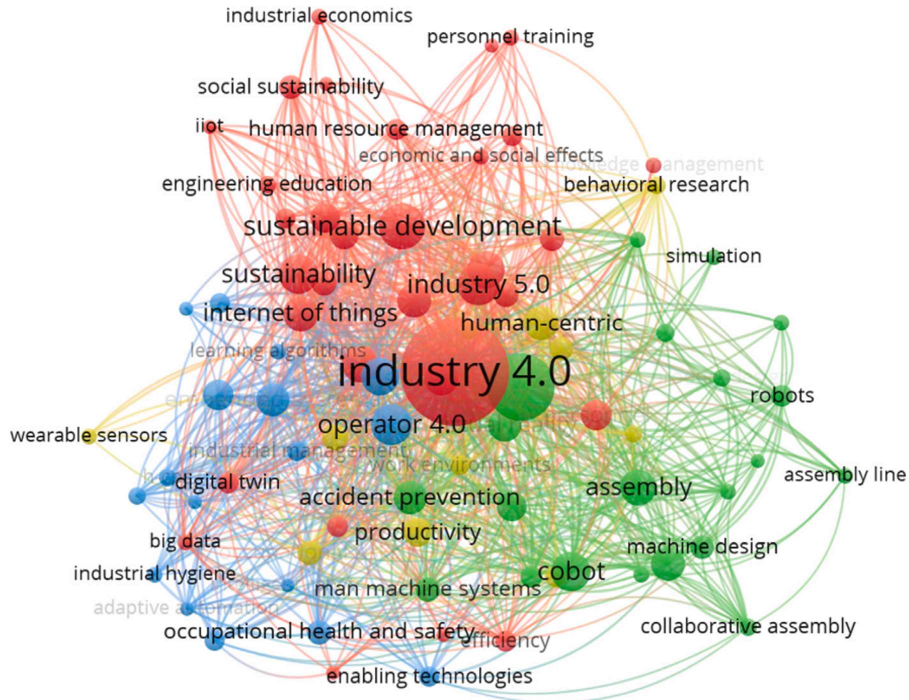

Fig. 4. Co-occurrence of keywords network — keywords from authors and publishers. The I5.0 and O4.0 themes can be seen in different clusters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

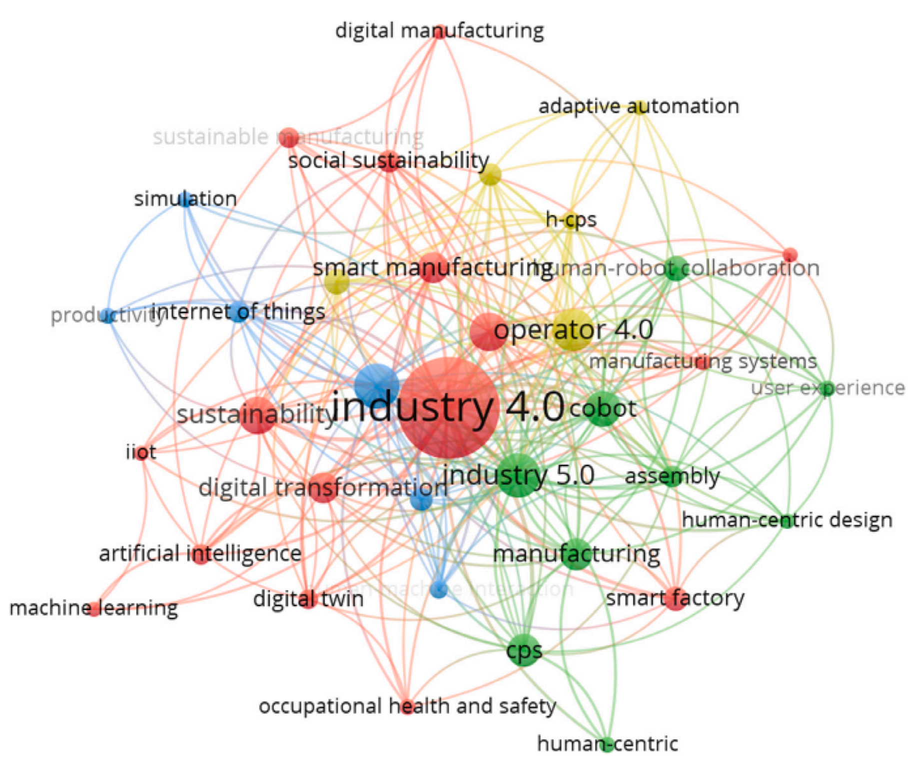

Fig. 5. Co-occurrence of keywords network — keywords from authors that appeared in at least five documents. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

included studies. The association characteristics between these terms can be seen clearly as follows, with the details of each group provided in the Appendix D:

- At first, the term “Industry_4.0” was associated with almost all the other terms, but most associated with the terms “health”, “sustain”, “safeti”, “age”, “social”, showing great concern about

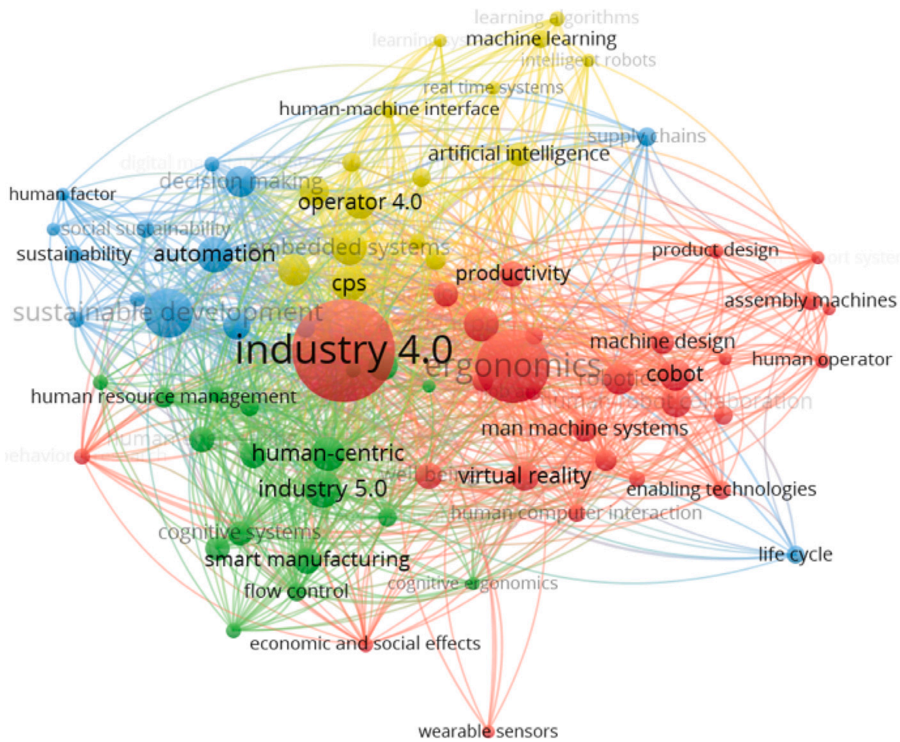

Fig. 6. Co-occurrence of keywords network — keywords from publishers that appeared in at least five documents. The "economic and social effects" aspect has emerged at the bottom. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

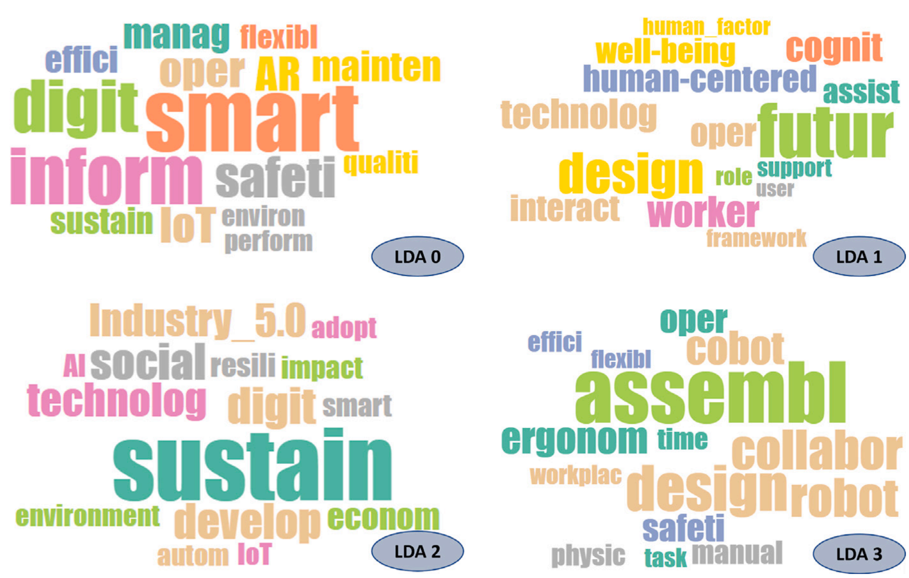

Fig. 7. The terms appeared in each LDA topic. The size reflects the occurrence frequency.

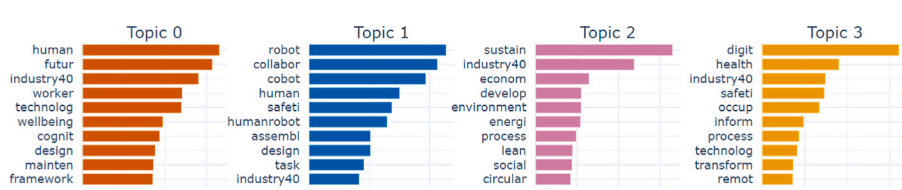

Fig. 8. The terms appeared in each topic after BERTopic. A similar set of terms can be recognized in comparison with LDA results.

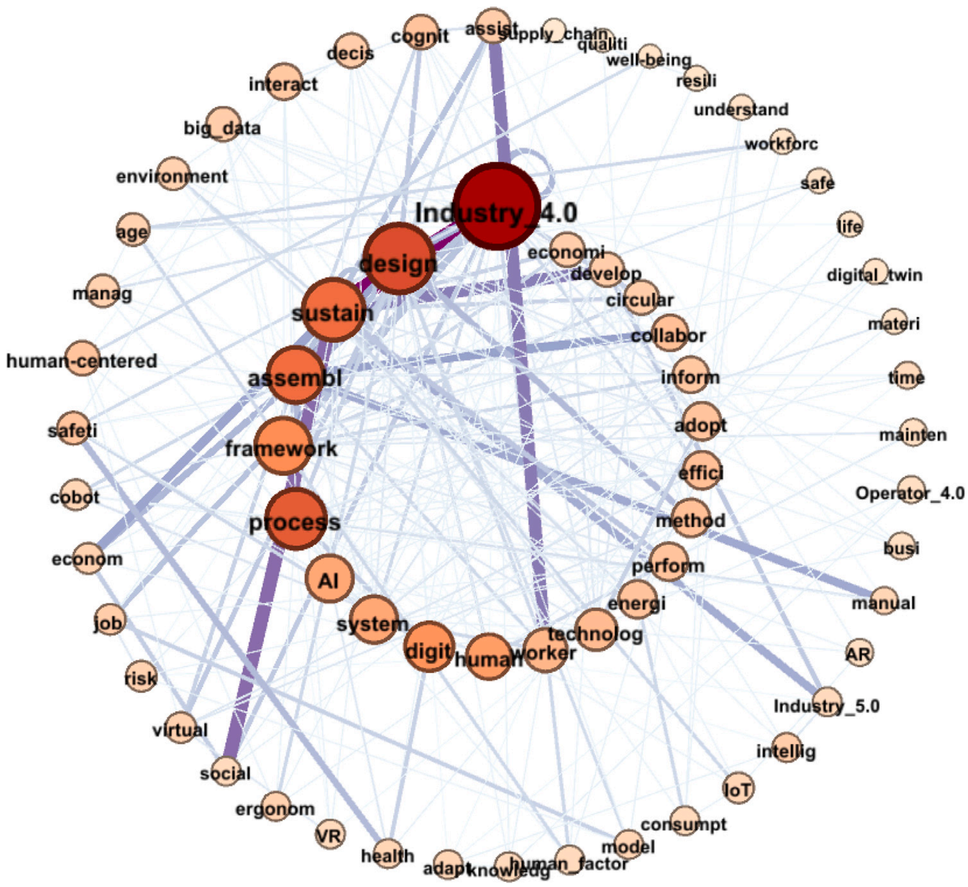

Fig. 9. Knowledge graphs of frequent terms. The I5.0 is strongly connected with sustainability but shows no association with resilience-, human- and social-related terms. The I4.0 and I5.0 are not connected.

the human factors in the industry. This fact is also reflected by the connection between the terms "life", "safe", "well-being", "worker" and "age".

- Secondly, there was a strong connection between the terms "Industry_5.0" with "sustain", "develop", "human", but not with "resili" and "supply_chain", suggesting that this I5.0 aspect did not attract adequate attention.
- Thirdly, concepts such as "Operator 4.0", "Industry 5.0" were hardly connected, as they did not have much co-occurrence with other terms.
- Last but not least, the term "sustain" was connected to terms such as "Industry_4.0", "Industry_5.0", "environment", "energi", and "consumpt", but did not show any association with technical terms such as "AI", "digital_twin", "AR", and "VR", which raise a concern about the lack of technology supporting the sustainable actions during manufacturing processes. Noticeably, the need for a profound understanding appeared as a requirement to guide human workers to an efficient consumption of energies from a sustainable viewpoint.

3.2. Qualitative results and discussion — cluster discovery

3.2.1. General characteristics of recognized clusters

From the citation network in Fig. 3, there were leading authors and their prominent works in each cluster, as discussed as follows:

- David Romero: this author is the founder of the O4.0 concept [18]. Despite a small number of publications (11 papers), he is the most cited author in the most cited cluster. His work focused on the engineering approach of integrating human factors into manufacturing systems [55,56], designing human–system collaboration workspace [57] with the integration of the I4.0 technology. Besides developing work analysis methods based on O4.0 concept [58], he also elaborated on the O5.0 concept to cope with the needs of the I5.0 era [26].
- Erwin Rauch: with 18 papers, his citation association defined another cluster, concerning the anthropocentric change under I4.0 effect from industrial workforce viewpoint [59], worker assistance system with different technologies for different user groups [60], and sustainable approach of human worker utilization in organizational level [61] as well as social level [62].
- Margherita Peruzzini: with ten papers, the work of this author defined the third cluster, with her research interests being human factors and ergonomics [63,64], human-centered adaptive system design [65], supporting tool and system design with a consideration of user experience [66,67].
- Daria Battini: from a multi-disciplinary operational management perspective [68], this author contributed 9 papers in the field, which focused on developing operational optimization models considering human factor [69–71] and ergonomics [72,73], which deals with workforce-scale problem such as aging [74], individual difference [75].

The co-occurrence of keyword clusters revealed vastly overlapping terms but differently distributed. Clusters found from co-occurrence networks do not form autonomous topics, and their boundaries were not sharp. That showed the relatively young nature of the general topic of O5.0, where research streams were not clearly defined by authors, and were still not well-recognized by publishers. However, keywords from publishers revealed the I5.0 (and its pillars different from sustainability, i.e. human-centrism and resilience), while that was not the case for keywords from authors. This is probably due to

Table 2
Discovered clusters and the match with keyword clusters, BERTopics and LDA.

Cluster	Name	Topics	Matched topics
Cluster 1	Human-centric enabling technologies	Micro-level: specific technologies and solutions Applications of specific smart technologies (AI, AR, automation, CPS, IoT, wearables) in manufacturing	KC 3; BERTopic 0; LDA 1
Cluster 2	Human–machine collaboration	Mezo-level: interactions within systems Creation to develop harmonious workplace for human collaborating with machines (robots)	KC 2; BERTopic 1; LDA 3
Cluster 3	Human factor integration	Micro-level: safety and health issues Support of smart technologies to fulfill human needs, adapting with human behavior and work preference.	KC 4; BERTopic 3; LDA 0
Cluster 4	General sustainability	Macro-level: general aspects of sustainability Social and environmental issues of humans within smart manufacturing environment	KC 1; BERTopic 2; LDA 2

the policy-driven nature of the I5.0 term, which policy was already recognized by publishers but still not widely accepted by the authors.

Interestingly, LDA and BERTopic revealed similar clusters (Table E.14) that overlap with clusters defined from the co-occurrence of all keywords (authors and publishers) networks (Table C.11). This similarity was summarized in Table 2.

Cluster 1 focused on specific technologies applied in smart manufacturing and their potential applications to supplement humans. The emphasis is on the potential for measurements and actions to increase worker productivity and performance. *Cluster* 2 specialized in the collaboration between humans and the system components, such as co-bot, and machines, with different techniques and methods to improve the collaboration performance. *Cluster* 3 considered the in-depth human needs, such as safety, instruction requirement, or human behavior and attitude. This cluster served the purpose of developing a better system based on human-factors-related understanding. *Cluster* 4 handled sustainability at different scales and levels, with technical proposals and platforms, and digitalization frameworks toward the sustainable transition.

3.2.2. Covered characteristics in recognized clusters

The four clusters mentioned above can appear explicitly or implicitly in the text from the included papers. To understand the cover characteristics and information depth in each cluster, a closer look at the four most relevant papers is done. The results were presented in Table 3. The context of the study (i.e., why the study was carried out and in which scenario) clarified more about research motivation. Each paper is examined to see if aspects such as the O4.0, sustainability, and resilience were considered. The information depth can be categorized into three levels:

- The study partly mentioned the idea as a foundation of an affecting factor of their research (•)
- The study proposed the idea as a suggested application or their future research interest (••)
- The study analyzes the idea in detail within its research scope (•••)

From the context of the relevant studies, four clusters were well distinguished. While the first cluster focused on developing technical solutions, the second concentrated on establishing effective human–robot collaboration. The third cluster considered different aspects of human factors, such as health, safety, and attitude, while the fourth was interested in different sustainable aspects.

Based on the information depth, different clusters showed different concerns over the covered aspects. Regarding the O4.0 concept, all the first three clusters had similar interest levels for this aspect. The second cluster has the highest level of O4.0-related, as the included research context already mentioned collaborative robotics, while the fourth only mentioned this aspect as part of the literature foundation. However, this trend was reversed with the sustainability aspect, which was hardly considered in the first three clusters. The concern about sustainability was tremendous within the research community, thus the fourth cluster was formed separately. The resilience aspect was not considered in the main research scope of any cluster.

3.2.3. Theoretical and conceptual studies

Considering O4.0 and I5.0 are new research concepts, the authors took a separate look at the theoretical and survey studies to assess the information depth of these concepts. The characteristics of the studies with theoretical, conceptual work, or review were summarized in Table 4. Mostly the studies were aware of the O4.0 concept, however, only a few analyzed the O4.0 in detail as their research focus. The rest of the studies mentioned O4.0 as a small factor in their literature review without any recommendation for future application. Sustainability was the dominant factor to be scrutinized in many studies than the O4.0 aspect. The fact is sustainability was more well-developed during the last decade. Resilience was scarcely mentioned in four studies; only one integrated this aspect into the main research purpose. It can be concluded that the literature and conceptual works were not balanced between the three pillars of the I5.0 hallmark. This may lead to the obstruction of updating the O4.0 into O5.0.

3.2.4. Survey studies

The characteristics of the studies with surveys were summarized in Table 5. The surveys or interviews in these studies were conducted with industrial managers, experts, or researchers, to shape their visions about the manufacturing requirement of the future. Most of them were designed to assess sustainability, which showed special concern about this aspect. Only a few studies consider the O4.0 and resilience aspects.

3.2.5. Experimental studies

General characteristics of experimental studies

Experimental studies were conducted with an experiment or a use case to validate the technological application. The technological readiness levels in these studies were categorized as follows:

- Concepts & Proposals: The authors suggested, or proposed a possible usage for the introduced technology, without any validation or evidence.
- Enabling technologies: The proposed usage was validated by the use case, and the technical solution proved its applicability.
- Adoption Initiatives & Framework: Not only the technology was validated by the use case, but the authors generalized their approach into an adoption initiative or a framework, to enhance scalability.

The data extraction from these studies revealed their considered aspects and the current technology adoption status:

- Human-centric technological development: the development factors or scenarios that considered human behavior, and human needs.

Table 3
Cluster formation with four most relevant papers, their research context, and coverage level regarding the I5.0 focus.

Cluster	Study	Context of the study	Considered aspects		
			O4.0	Sustainability	Resilience
Cluster 1: Human-centric enabling technologies	Bances et al. [76]	Review the benefits and challenges of exoskeleton connectivity within a smart factory.	•••		
	Kurschl et al. [77]	Propose different scenarios to use Mixed Reality in Intralogistics.	•••		
	Siew et al. [78]	Propose a network to enhance human involvement in disassembly and maintenance operations.		•••	
	Szajna et al. [79]	Review the tools related to AR and AI to overcome employee turnover and shortages in pandemics and war times.	•	•	••
Cluster 2: Human-machine collaboration	Gualtieri et al. [80]	Evaluate cognitive ergonomics variables in different human–robot collaborative assembly scenarios.	•••		
	Ronzoni et al. [81]	Propose a support-design framework for the layout and task scheduling design of a cooperative robot system in a labor-intensive manufacturing process.	•••	••	
	Nourmohammadi et al. [82]	Propose algorithms to balance and schedule assembly lines with human–robot collaboration tasks.	•••	••	••
	Gervasi et al. [83]	Evaluate the use of human physiological responses in human–robot collaboration.	•••		
Cluster 3: Human factor integration	Damiani et al. [84]	Propose the multi-purpose application of AR for safety measure.	•••		••
	Adam et al. [85]	Study the attitude of employees toward digitalization in the manufacturing workplace.		••	
	Johansson et al. [86]	Identify the information needs in manual assembly system.	•	••	
	Simeone et al. [87]	Propose a healthcare monitoring platform for workers.	•••		
Cluster 4: General sustainability	Bag et al. [88]	Review the influence of the I4.0 technology on sustainable manufacturing and circular economy capabilities.	•	•••	
	Margherita et al. [89]	Diagnose the support of the I4.0 technology for sustainable organization values in flexible manufacturing.	•	•••	••
	Bordel et al. [90]	Propose an I4.0 sensing platform to increase the global production process efficiency and the well-being of workers.		•••	••
	Colla et al. [91]	Propose a platform with Machine Learning and Artificial Intelligence to optimize steel production toward socio-economic and environmental sustainability.	•	•••	

Table 4
Coverage level regarding the I5.0 focus in the included theoretical, conceptual, and review studies.

Study	Considered aspects			Study	Considered aspects		
	O4.0	Sustainability	Resilience		O4.0	Sustainability	Resilience
Gualtieri et al. [92]	•••	•		Yilmaz et al. [93]		•••	
Sgarbossa et al. [70]	•	•••		Arun et al. [94]	•	••	
Perez et al. [95]	•	••		Zizic et al. [96]	•••	•••	•••
Segura et al. [97]	•	••		Kong et al. [24]	••		
Gualtieri et al. [98]		•••		Mark et al. [60]	•••	••	
Vysocky et al. [99]	•		•	Panagou et al. [100]		•••	
Tortora et al. [101]	•	•		Proia et al. [102]	•	••	
Cunha et al. [103]	•••	••		Jamwal et al. [104]		•••	
Aivaliotis et al. [105]	•	•		Bozkucs et al. [106]	•	•	
Matt et al. [62]	•	•••		Lu et al. [107]	•	••	••
Golan et al. [108]	••	••	•	Zarte et al. [109]	•••	•	
Gualtieri et al. [110]	•	••		Javaid et al. [111]		•••	
Turner et al. [112]	•	••		Alves et al. [113]	•	•	
Ruppert et al. [114]	••	••		Nagy et al. [115]	••	••	•
Kalateh et al. [116]	•••	•••	•				

Table 5
Coverage level regarding the I5.0 focus in the included studies with statistical model and surveys.

Study	Considered aspects			Study	Considered aspects		
	O4.0	Sustainability	Resilience		O4.0	Sustainability	Resilience
Kaasinen et al. [117]	•••	•••	••	Fruggiero et al. [118]	•	•	
Narwane et al. [119]		•••		Pasi et al. [120]		•••	
Ghobakhloo et al. [121]		•••	•	Welfare et al. [122]		•	
Paulikova et al. [123]	•	•••		Jongprasithporn et al. [124]		•	
Viles et al. [125]		•••					

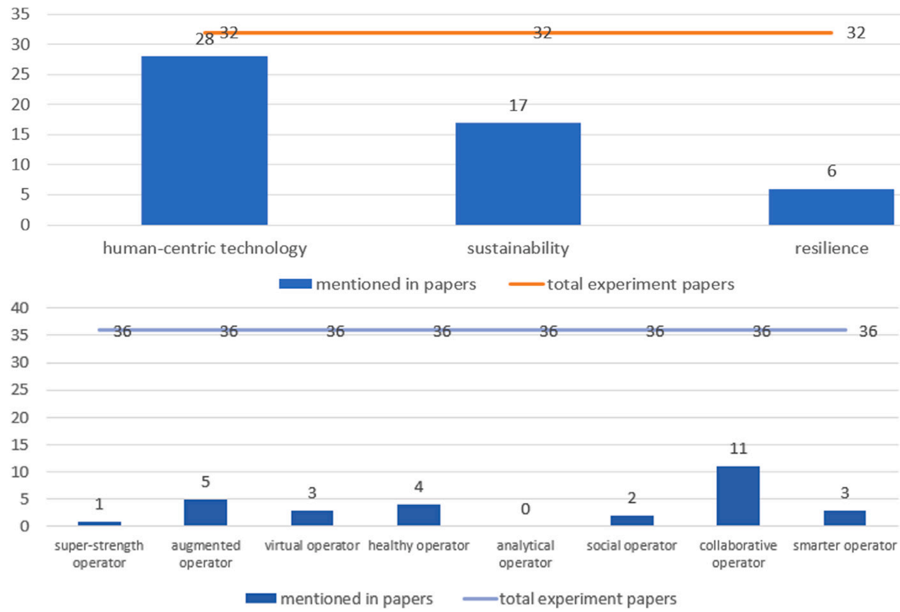

Fig. 10. Characteristics of included experimental studies that mentioned the I5.0 focus. Resilience does not gain interest, while the O4.0 types were not equally developed.

- Sustainable development: the sustainable effects expected from the technology adoption.
- Resilience preparation: the resilient-oriented design intention from the authors to cope with disruption during operation.
- Drivers: factors that facilitate the technology usage and adoption, coming from the nature of the approach or recommended by authors.
- Restrainers: factors that obstruct or reduce the effectiveness of the technology usage and adoption, coming from the nature of the approach or recommended by authors.
- Benefits: the advantages or competitiveness achieved from the technology adoption.

Details of these aspects were described in the following subsection.

Human-centric technological development

Within the included experimental studies, the developments of human-centric technologies were categorized according to the O4.0 types. Besides the O4.0 types, there were other aspects of human-centric technology development as described as follows:

- Human-centric system-integration: This aspect considered the deep integration of human factors in the manufacturing systems by studying the needs, behavior, or characteristics of human beings during work context.
- Human-centric system-modification: This aspect considered modifying the existing system, changing its structure or design for better human utilization.

As can be seen in Fig. 10, human-centric technology development was mentioned in almost every included experimental study (28 over 32). This ratio was highest among the other aspects, i.e., sustainability and resilience. Within these studies, the number of studies that mentioned the O4.0 concept showed the asymmetry between pillars. A majority of studies focus on the "collaborative operator", while "augmented operator", "healthy operator", and "smarter operator" were followed. The "analytical operator" type was not considered in any study.

As seen in Table 6, the technologies related to the O4.0 types were mostly at enabling level. The associated recommendation for new concepts and proposals were in high numbers. Considering each O4.0 type, the associated adoption characteristics of its core technology can be revealed:

- Super-strength operator: the scarcity of research about this type showed that exoskeleton was not yet popular in the industry.
- Augmented operator: augmented reality technology was popular in the market nowadays, resulting in various use cases in different scenarios, utilizing on-the-shelf equipment.
- Virtual operator: virtual reality was not well-introduced, as the most of studies were limited at the concept phase.
- Healthy operator: thanks to the abundance of health sensors and wearables, this type gained a high momentum for customizing different tracking solutions.
- Analytical operator: due to the fact that there was no study considering this type, big data usage was not sufficiently incorporated into manufacturing processes.
- Social operator: the use of social networks within a manufacturing context was still in doubt, given that the suitable scenario for using it was not well established.
- Collaborative operator: this is the most developed type, with many enabling technologies for different aspects. The most frequently mentioned adoption framework was transitioning from a manual working process into a collaborative one with robots.
- Smarter operator: the development of personal assistants for industrial operators was immature. Currently, the research activities were related to human–machine voice and text information exchange.

Other aspects of human-centric technological development were described in Table E.13. From the human-centric system-integration viewpoint, a significant trend can be observed, with many studies focused on considering the human physical and psychological reaction to enhance the human–system symbiosis. Other forming trends were individual optimization (i.e., assigned workload based on the consideration of the physical and physiological status of each worker), and natural and ergonomic interaction.

From the human-centric system-modification viewpoint, system design with human consideration gained the most interest, with multiple frameworks and approaches proposed. Enhancing manufacturing systems with situational awareness was another emerging direction, with tracking and recognizing human activities and behavior. Service orientation, interactive visualization, and retrofitting were less developed.

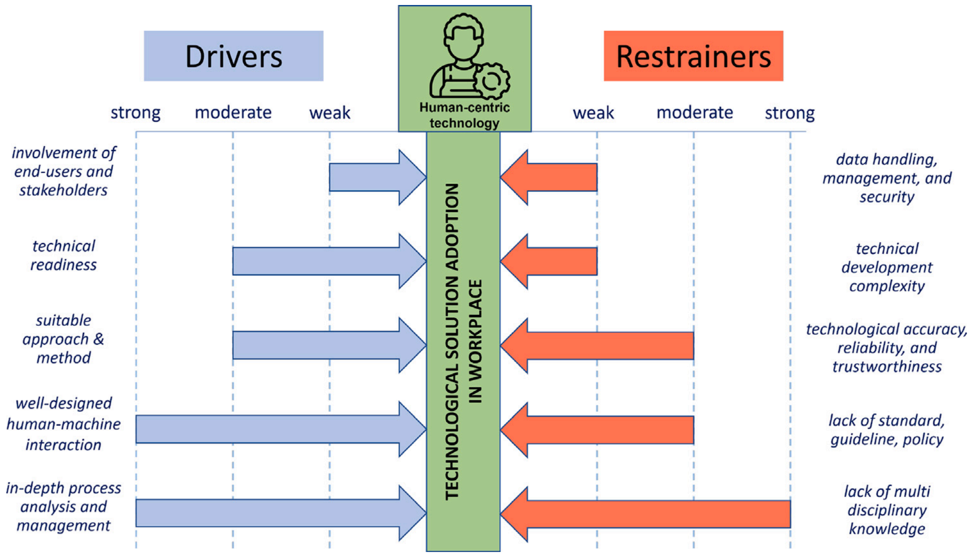

Fig. 11. Drivers and Restrainers of adopting human-centric technology.

Table 6
Human-centric technology developments: the O4.0 types in the included experimental studies.

Aspect	Consideration and pillars	Considered context [Study] with readiness level		
		Concepts & Proposals	Enabling technologies	Adoption Initiatives & Framework
O4.0 types	Super-strength operator		Communication architecture for exoskeleton network [76]	–
	Augmented operator	Real-time feedback and optimized work instruction [78]	Enhanced learning [126], Work instruction for maintenance and warehouse tasks [77]; Safety application with Glass-Up F4 VR glasses [84]; AR application for warehouse picking process [127]	Modular framework to use haptic gloves for gesture recognition and machine interaction [128]
	Virtual operator	Human–robot teamwork performance in a virtual environment [129,130], Collaboration with a co-bot in a virtual environment [131]	Participatory design with a virtual factory [132]	–
	Healthy operator	Real-time medical application with exoskeleton network [76]	Movement and heart rate variability tracking [126]; Personal well-being tracker [132]; Physiological stress measurement in repetitive task [133]; Online cognitive load assessment [134]; detect mental and physical fatigue [135]	–
	Analytical operator	–	–	–
	Social operator	Social interaction during maintenance procedure [136]	Contextual knowledge sharing platform for work-related discussion [132]	
	Collaborative operator	Incorporating cognitive ergonomics variables from workers [80,137]	Enhance human–robot collaboration with human pointing gesture [138]; Multi-criteria robot trajectory planning with smoothness and speed [139,140]; Improve human performance with physical assistance of co-bot [131]; Human–robot collaboration in repetitive assembly [133]	Convert manual assembly workstation into a collaborative one [61,137,141]; Framework for collaborative robot system in labor-intensive manufacturing [81]; Cobot integration for supporting monotonous tasks in SMEs [142]; Axiomatic design for workstation with cobot [143]
	Smarter operator	Vocal assistance for maintenance operation [144]	Dialog system for human–system information exchange [145], Voice-enabled digital assistance during maintenance [126]	–

Sustainable development

The use case conducted within the included experimental studies were categorized into different levels of sustainability:

- Economic level: the sustainability consideration resulted in better economic effects on the operation of the manufacturing company regarding productivity, quality, and system utilization, up to a larger scale of the whole supply chain.

- Social level: this level considered the effect on a single worker or the whole workforce.
- Environmental level: the development at this level helped to optimize resource usage and reduce production waste.

Details of these developments were provided in Table 8. Most studies concerned the economic level, with many concepts, enabling technologies, and adoption frameworks. Social and environmental levels gained similar interest.

However, these technologies were elaborated from the system viewpoint, such as designing the system, working procedures, or tracking human activities to change the behavior of the system. There was no technology to help human workers proactively enhance sustainability or understand the sustainability effect within their work procedure.

Resilience preparation

The included studies incorporated the resilience preparation as categorized in Table 9. Depending on the countermeasure for inevitable events, different levels of engineering resilience can be listed as avoiding disruption, withstanding disruption, adapting to unexpected change, and recovering from the unprecedented situations proposed by Romero et al. [26].

The resilience aspect was not popular, as only a few studies considered incorporating it in their use cases. The readiness levels were low, mainly in the concepts and suggestion phase. Avoiding disruption was the most frequent initiative deployed during preparation and system design. Withstanding disruption was not mentioned in any studies, showing a lack of concern for this level. A scarcity was observed with the "adapting to unexpected change" and "recovery from the unprecedented situation" levels.

Technological solution adoption: Drivers and Restrainers

Based on the characteristics of the employed approach and recommendations from authors, the five most frequently mentioned drivers and restrainers of technological solution adoption of included experimental studies were illustrated in Fig. 11, with the arrow size reflecting the appearance frequency of the factor in the included experimental studies. The more frequently a factor appeared, the stronger effect that factor posed on the technological solution adoption. The most significant driver was the in-depth analysis and management of a manufacturing process. Equally important was the well-design interaction between humans and machines. Since human factor study in the manufacturing context required the incorporation of many disciplines, the lack of multi-disciplinary knowledge was the strongest restrainer obstructing the technology adoption. Lack of standards and guidelines and technological accuracy posed the same negative impact. Data-related concern, with associated handling, management activities, and security, was the least mentioned factor. Details of these drivers and restrainers can be found in the Appendix F.

Technological solution adoption: Expected benefits

From the improvements validated by the use cases, the included experimental studies suggested various benefits from the organizational, system, and human worker viewpoints. These benefits can be categorized into four types as illustrated in Fig. 12:

- Sustainable operation: the technical adoption yielded benefits in efficient operations of the organization and the supply chain.
- Human–system collaboration: enhanced the efficiency and convenience of the collaboration.
- Human-centric consideration: bringing benefits for human workers based on their needs and individual status
- Social resilience: larger-scale benefits for the workforce and society

Details of proposed benefits and their occurrence in included studies are provided in the Appendix G. The enhancement of operational effectiveness was mentioned most frequently. The second popular benefit was a "safer and healthier working environment" for human workers. The other anticipated benefits were "better system autonomy and human synchronization" and "improved work experience". Supply chain effectiveness, workforce sustainability, natural human–system interaction, and advanced intervention were new emerging benefits that appeared in a few studies.

4. Discussion of the main findings

The conducted systematic literature review has covered a vast interest area from scientific publications with a carefully selected set of keywords. By applying a combination of BNA and text mining techniques, the hidden trends and perspectives are revealed from granulated and scattered studies. While the BNA result helped us to grasp the general awareness of clusters of researchers and topics, the text-mining result formulated more details of the topics. The selection of informative terms and special adjustments (the coined terms, occurring frequency) were discussed and agreed upon by all authors, considering the keywords suggested by authors and journal indexes. As non-contextual terms can diverge the coherence, these modifications during the text-mining process heavily affect the convergence of the topics, therefore, they were painstakingly conducted in an iterative manner during execution.

Based on the discovered findings, this section discusses the direct answer for introduced RQs and raises topics that are worth discussing. The first subsection is devoted to answering the RQ1 and RQ2, while the second subsection explained the RQ3. To better assess the current favorable policy and institutional environment, grey literature will be considered at the end of this section.

4.1. Current development of Operator 4.0 and transition toward Operator 5.0

In addressing RQ1, the findings in this paper reflected the currently scattered and intermittent development of O4.0. From a human-centric viewpoint, the increasing number of related studies exhibited a growing interest in human factors in manufacturing systems. Nevertheless, the research was stemming from an engineering standpoint, with prevalent engineering researchers and journals. The low number of relevant studies and disruptively connected keywords inferred that not all of the studies are aware of the O4.0 concept nor aligned with the I5.0. The O4.0 concept was mentioned in several studies but was only considered as the main interest in only a few. The majority were confined to theoretical and statistical studies, showing that new concepts are still in an immature phase and technical adoption contexts were not well-defined. Within the experimental studies, the O4.0 types experienced an imbalanced development due to different readiness levels and customization possibilities of the respective core technologies. Noticeably, sustainability, resilience, and human-centrism keywords appeared in single separated clusters showing that they were not well-constructed by the authors, and the I5.0 pillars were not well embedded in the research yet. Instead of a holistic view, authors rather focused on how to leverage workers' productivity and minimize ergonomic pain, e.g. [61,76,81,90,91,127,131,133,136,141–144,149]. However, the BNA result exhibits an expansion into the I5.0 aspects, and relevant research interests have been triggered in the scientific community. The publisher index keywords formed a better vision for new research directions with more sophisticated leading details. New research themes, e.g. "social effect", linked the traditional engineering approach with the social dimension and will be crucial for the I5.0 preparation, which affects the manufacturing workforce on a larger scale (i.e., demography [113]).

Regarding RQ2, though the transition toward the I5.0 is inevitable with many appearing signs, a lack of foundation and technical readiness for the transition toward O5.0 can be observed. Besides the scattered development, the technical readiness of the O4.0 solutions in particular, and the I4.0 human-centric technologies in general, was not ready for the I5.0 application. There are missing links between the I5.0 with

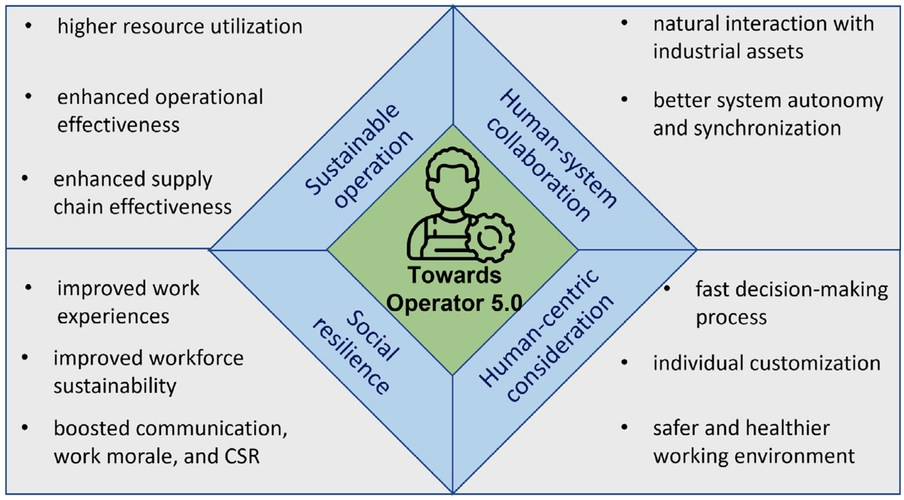

Fig. 12. The expectable benefits toward the Operator 5.0.

Table 7
Human-centric technology developments: other aspects in the included experimental studies.

Aspect	Consideration and pillars	Considered context [Study] with readiness level		
		Concepts & Proposals	Enabling technologies	Adoption Initiatives & Framework
System-integration	Individual optimization.	Individual cognitive load according to demands and characteristics of workers [134]; tune the adaptive behavior of system according to human status [135]	–	Individual optimization with ergonomics score [78]
	Natural and ergonomic interaction.	Natural communication dialog system [145]; Use interconnected visual-based sensors to recognize human natural gestures [138]	Recognize hand gesture by the natural working movement [128], monitor postural stability by smart soles [146]	–
	Human physical and psychological reaction.	Effect of robot appearance on human performance virtual environment [129,130]	Adjustable smoothness of robot trajectory according to human cognitive stress [139,140]; Measure human performance with eye tracker [131]; Subjective and physiological response during human–robot collaboration [133]; Human attention tracking for online cognitive load assessment [134]	–
System-modification	Retrofitting	–	–	Human-centric retrofitting with low cost technical improvements [147]
	System design with human consideration.	–	–	Multi-disciplinary design framework for labor-intensive manufacturing [81]; Workstation design to improve physical ergonomics and production efficiency of operators [61]; Axiomatic design for a workstation with cobot [143,148]
	Service orientation.	Service-oriented function for safety engineering [149]	Service-oriented digital twin [144]	–
	Enhanced system with situational awareness	Bi-directional information flows between operators and robots by sensors and interactive HMI [137,141]; Modify robot trajectory according to human movement tracking and action prediction [150]	Low-cost scalable people tracking system [150]	–
	Interactive visualization.	–	Human–Machine interface with 3D digital twin [151]	–

other technical aspects of the I4.0, and with social aspects of the O4.0. Lack of multi-disciplinary knowledge urges for studies that scrutinize the scientific foundation and applicability of human integration into H-CPS [152]. Though each of the I5.0 focus should be elaborated

Table 8
Different levels of sustainability in the included experimental studies.

Level	Sustainable consideration	Considered context [Study] with readiness level		
		Concepts & Proposals	Enabling technologies	Adoption Initiatives & Framework
Economic level	Improve operation performance.	Reduce error by the data from exoskeleton network [76]	Optimize task allocation between human and robot [137,141]; Reduced operation time and error rate with co-bot assistance [131]	Remove quality control-related cost [90]; Reduce production time, maintenance cost and enhance quality with Ubiquitous Knowledge [144]; Re-design collaborative assembly workstation for cycle time reduction [61]
	Better resource planning.	–	Information sharing within the exoskeleton network [76]	–
	Optimized End-of-Line product recycling.	–	Enhance performance of workers in the disassembly process [78]	–
	Increased system modularity, flexibility, and availability.	–	Flexible Human–Machine interfaces architecture [151];	Increase system availability [90]; Modular safety assurance process for re-configurable application [149]
	Legacy systems utilization.	Human-machine interface as a retrofitting solution [151]	–	Human-centric retrofitting [147]
	Supply chain integration	Service-oriented Digital Twin for maintenance operation [144]	–	–
	Enabled circular economy.	Digitalization with AI and Machine Learning in the steel industry [91]	–	–
Social level	Work condition improvement.	Adjust human–robot collaboration based on human reaction [129,130,135]	Safe human–robot interaction with people tracking system [148,150]	Re-design collaborative workstation for better ergonomics [61]
	Improved workforce well-being.	Prevent future injuries based on historical data [76]; Different optimized sequences for different operators [78]	Support the detection of incorrect postures while working [146]	Reduce thermic discomfort, lung infection, health problem, and intoxication in the bakery industry [90]; Enhance ergonomics in monotonous tasks [142]
	Enhanced social cohesion, integrated ethical aspect.	Modelling and assessing human activities during maintenance procedure [136]	–	Framework to assess ethical issues in human-machine symbiosis [126]
Environmental level	Optimized resources usage.	Reduced power consumption with Human–Machine interface architecture [151]	Modified production plan based on the I4.0 platform [90]	–
	Reduced production waste.	–	–	Reduced waste in quality control [90]
	Enabled environmental footprint.	–	–	Scrap tracking and identification system in steel factory [91]

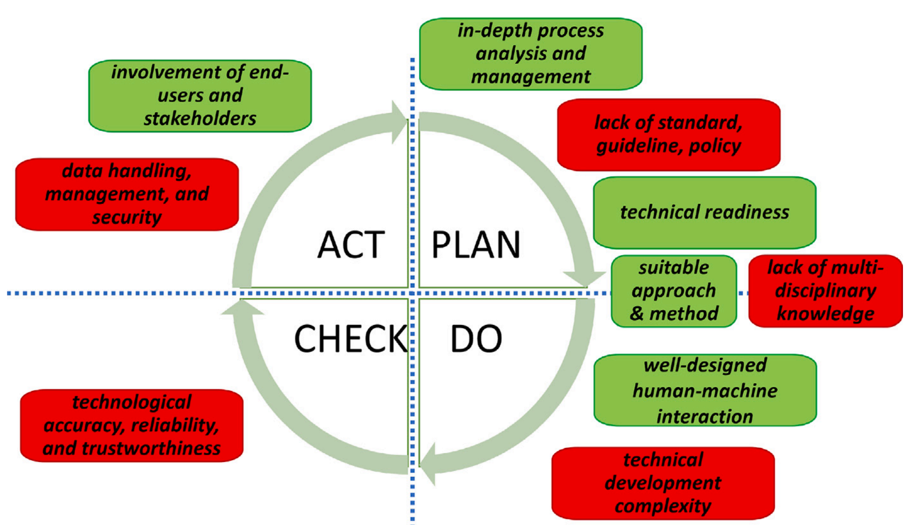

Fig. 13. Drivers (green) and Restrainers (red) in PDCA phases of the O5.0 transition project. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 9
Different levels of resilience in the included experimental studies.

Level	Resilience preparation	Considered context [Study] with readiness level		
		Concepts & Proposals	Enabling technologies	Adoption Initiatives & Framework
Avoiding disruption	Adaptable technology with dynamic use for different users.	Wearable devices for healthy operator [126]; Automatic adaptation of system elements according to psychophysical work condition, need and want of operators [61,135]	–	–
	Preparation during training.	Experience industrial accidents during training periods with simulation-based VR [126]	–	–
	Systemic robustness design.	–	–	Identify ethical rules with Value Sensitive Design approach [126]
	Dynamic task allocation.	Flexible tasks based on the needs and wants of workers [137,141]	–	–
With-standing disruption	–	–	–	–
Adapting to unexpected change	Quick safety measures after unexpected events.	–	Fire prevention and emergency evacuation with AR and QR code technique [84]	–
Recovery from unprecedented situations.	Reduction of reaction time against malfunctions.	–	–	Reaction time against malfunction in supply infrastructure [90]

equally to cope with the new industrial challenges, unfortunately, not all aspects of sustainability and resilience were analyzed, and most of the solutions were in the concept and proposal phases (see Tables 6–9). Though the need for a human-in-the-loop Life Cycle Assessment was well-stated by Turner et al. [112], there was no technology for sustainability from the human viewpoint, such as providing instruction for sustainable activities, or training for a sustainable mindset during production work. A further suggestion of Socio-Ecological sustainability [153] also calls for technical innovation, with the combination of social and natural science perspectives. Additionally, there was no preparation for the resilience requirement, which will soon play an important role in a robust supply chain of the future, especially after the pandemic. This underdevelopment poses a hurdle to future elaboration.

Noticeably, the human-centric focus of I5.0 aims at building a sustainable workforce. However, current studies are rather technology-oriented and more focused on specific solutions and applications. Ergonomics and safety aspects attracted more work than the social effect, regarding the application of new technology in the workplace. This lack of consideration for the social dimension may pose a severe aftermath for later development, as a natural consequence of the I4.0 technology-driven policy that policymakers have seen holistically for a relatively short period.

4.2. Prepare for the transition toward the Operator 5.0

The RQ3 is answered through the full-text scan and qualitative research in this study, in which the drivers and restrainers from the technical adoption of the O4.0 and human-centric I4.0 solutions in the included experimental studies are recognized. These possible factors and associated benefits that are inferred from the current I4.0 reflect the expectable circumstances for the forthcoming I5.0. Fostering the O5.0 transition is necessary for industrial stakeholders and requires knowledge of the favorable context and corresponding enablers. Therefore, industrial managers and practitioners can refer to this work for better preparation.

The transition from O4.0 to O5.0 can have the same characteristics as a retrofitting-based development project for the I5.0 solutions suggested by Tran et al. [154]. The drivers and restrainers can be expected to appear during the famous Lean-related PDCA phases [155] of the project as in Fig. 13.

During the *Plan* phase of the transition, an in-depth analysis of the intended process or work contributes a strong foundation for the to-be picture of the expected system. A clear vision of which human tasks should be assisted, the ideal process requirements, which collaboration level between human–system should be established, etc. are pointed out. If the existing in-house technologies are ready, or on-the-shelf solutions are available, the planning will be easier. On the contrary, the project team members experience ambiguity due to a lack of standards, guidelines, or policies when they look for a specific direction of technology adoption. Considering the I5.0 is recently pronounced to encounter the social negative effect of the I4.0, this lack of knowledge is reasonable and will not be solved in a short time.

Suitable approach and method is the crucial driver during both the *Plan* and *Do* phases. As the focus of O5.0 is not merely technical-oriented, integrated effort from a cross-functional team is necessary. Generally, a comprehensive and systematic approach should be considered. To utilize the smart sensors and equipment that monitor human physiological parameters, and recognize their physical and mental status, life science knowledge is necessary. Social science provides a vital perspective to further assess the social effect of supporting technologies on the workforce. The lack of multi-disciplinary knowledge will greatly undermine the success of the transition.

During the technical implementation, or *Do* phase, the technical solution should be customized before field application takes place. The technical development complexity may pose a huge challenge, as this option selection step will define the future system, and need thorough market research, feature comparisons along with detailed use case studies. For efficient human–system communication and collaboration, well-designed human–machine interaction in every aspect should be accounted.

As most current human-centric technologies are in an immature phase, accuracy, reliability, and trustworthiness are under great concern. During the *Check* phase, any defects and errors from the deployed technologies should be calibrated to ensure an effective application. In the last step of the *Act* phase, before the tested system is put into daily operation, data handling, management, and cyber security measures should be integrated to prevent any data leakage and future cyber attack. Though the cross-functional team is gathered from the beginning of the transition project, the involvement of the end-user (in this case, human workers who use the supportive technologies) and other stakeholders should be informed about technical deployment, familiarized with new environment and system interaction, so an appropriate usage can be yield. As PDCA is a continuous cycle, these two last factors also prepare for another PDCA cycle for large-scale installation, adjustment, and modification during later operation.

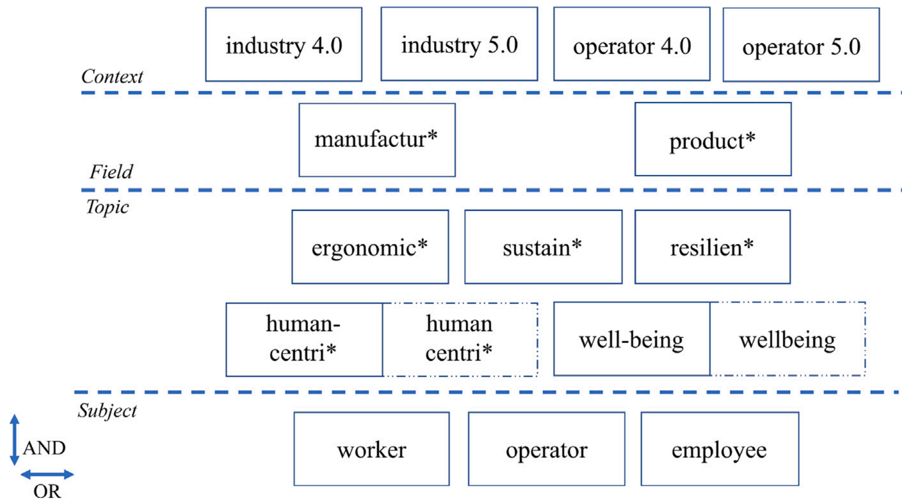

Fig. A.14. Keyword matrix for the query.

Table C.10
The author clusters with six most cited authors.

Cluster	Color	No. of author	Most cited authors (No. of documents/citations)
CA 1	Red	40	Romero D. (11 – 817); Stahre J. (6 – 733); Bernus P. (2 – 634); Noran O. (2 – 634)
CA 2	Green	30	Rauch E. (18 – 443); Gualtieri L. (10 – 312); Vidoni R. (6 – 300); Matt D.T. (11 – 196)
CA 3	Blue	19	Peruzzini M. (10 – 179); Papetti A. (14 – 141); Germani M. (12 – 138); Faccio M. (3 – 109)
CA 4	Yellow	14	Battini D. (9 – 225); Sgarbossa F. (4 – 210); Neumann W.P. (2 – 106); Glock C.H. (2 – 103)

Table C.11
The clusters of all keywords from authors and publishers.

Cluster	Color	No. of keyword	Ten highest-weighted keywords (No. of occurrence)
KC 1	Red	33	industry 4.0 (203); sustainable development (43); industry 5.0 (36); sustainability (32); human factor (29); smart manufacturing (27); internet of things (25); augmented reality (24); digital transformation (24); personnel (20)
KC 2	Green	21	ergonomics (85); cobot (32); assembly (26); human–robot collaboration (24); accident prevention (23); virtual reality (23); robotics (19); man-machine systems (13); machine design (12); human–robot interaction (11)
KC 3	Blue	17	operator 4.0 (34); CPS (29); embedded systems (23); sustainable manufacturing (20); occupational health & safety (13); enabling technology (9); industrial management (9); machine learning (9); wearable technology (9); h-cps (7)
KC 4	Yellow	11	human-centric (24); productivity (18); well being (15); occupational risks (13); human-centric manufacturing (12); risk assessment (10); work environments (9); employment (8); behavioral research (7); job analysis (7)

4.3. Consideration from grey literature

Considering the highly industrial and practical nature of the discussed domain, an analysis of grey literature will enrich and complement the result from the literature review. Industrial-oriented white papers from global key stakeholders would be used in this section. Fostering the transition toward the I5.0 will be the key objective of every modern economy, and favorable policy plays a critical role. With this overview, policymakers can project necessary contributions from their roles, sketching an early vision of a supportive institutional environment.

Besides the European Union (EU) official announcement site [156], other grey literature sources considered in this work were the international perspective provided by UNIDO [157] and World Economic Forum [158]. The Industrial IoT Consortium [159] represents the United States (US) point of view, while Platform Industrie 4.0 [160] and Acatech [161] are key stakeholders within the German manufacturing industry. Additionally, the Sino-German Cooperation on Industrie 4.0 offers an English summary of the Chinese 14th Five-Year Plan on Intelligent Manufacturing [162]. Recent publications on the websites of these key stakeholders were screened. Relevant papers were selected based on their title relevance for the O5.0 concept and in accordance

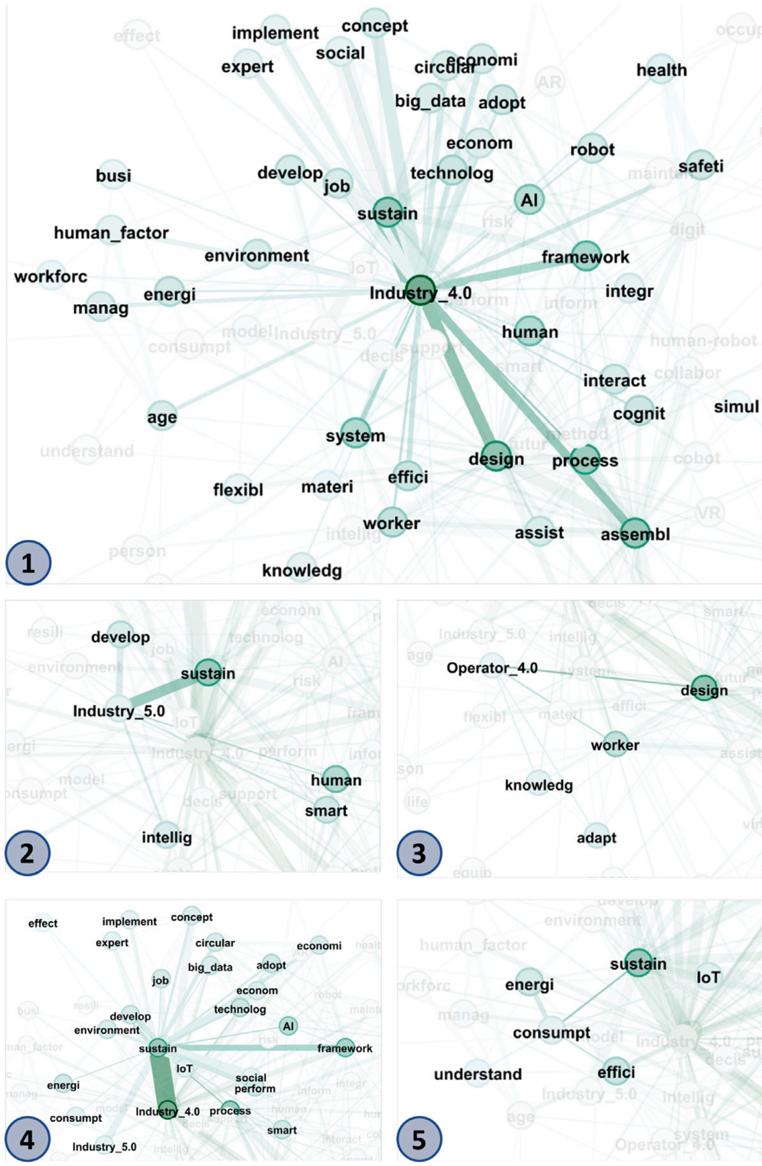

Fig. D.15. Discovered association in the extracted knowledge graphs of frequent terms.

Fig. E.16. The input set of frequent terms that appeared in more than 10 documents were employed for LDA topic extraction.

with the expert opinion of the authors [26]. Eventually, eight papers were selected and analyzed in-depth.

From organizational contribution, the EU is the first player in the field with tremendous corporate efforts to establish and facilitate the transition. One kind of such activity is the direct inclusion of the I5.0 paradigm into Horizon Europe calls, which reorients previous focus (mainly technological and economic sustainability) to include human-centrism, resilience, and a holistic sustainability approach. Other international stakeholders were mainly focused on augmented, collaborative, social, and resilient aspects of the O5.0 concept [163–165]. Other linked focused areas were leadership, trust, and transparency [163]. The most urgent topic was increasing learning and teaching efficacy, which also is reflected by the augmented-workforce-initiative [163].

On the national level, the German manufacturing industry generally focuses more on the virtual, collaborative, healthy, smart, and resilient aspects of the O5.0 concept [166]. Other aspects in consideration were design principles, ethics, and regulations that linked to Human–Machine-Interaction, the creation of the so-called team robotics and the human digital twin, and the development of mobile work approaches, i.e., the “home workbench” [166,167]. For shaping resilient manufacturing systems, education, competence, and work organization becomes essential factors [166]. In the US, the O5.0 approach does not have much practical relevance, as the human operators are rarely addressed in employed activities [168,169]. Only the application of augmented reality (AR) headsets for supporting the worker was discussed [169]. The 14th Five-Year Plan on Intelligent Manufacturing in China essentially promoted the application of AR, virtual reality (VR), and mixed reality (MR) for facilitating production and the work of operators [162].

5. Conclusion and future work

Though using I4.0 technologies to support human workers has gained attention through a growing number of research lately, not any generalized structuralization was constructed. This paper summarizes the current status of the field from an interdisciplinary perspective, in an attempt to avoid severe social negative consequences from non-guided developments. The O4.0 concept is still in the immature phase, its types need more time for the corresponding core technologies to be elaborated and circulated in the market, with the application context to be well-established. More practical studies are required to materialize the current technical concepts and proposals.

The transition toward O5.0 is inevitable, evidenced by many signs of research interest expansion. However, missing links between the current O4.0 development and I5.0-related topics pose a challenging hurdle. Inter- and multi-disciplinary efforts should be conducted to link knowledge from different fields, creating a trustful and solid scientific foundation for future improvements. As technical readiness for O5.0 was inadequate, more research and development should be done in both the I4.0 application and social effect aspects. Though the sustainability aspect was popular within academia, sustainability implementation from a human viewpoint is missing, and enabling technologies are rarely available. The resilience aspect was underrated and needs more definition as guiding calls for pilot scientific research.

Table E.12
The topics from LDA analysis with the included number of studies.

Topic	No. of study	Lowest probability	Highest probability
LDA 0	78	0.3653	0.9958
LDA 1	64	0.3735	0.9964
LDA 2	75	0.3474	0.9952
LDA 3	86	0.3926	0.9950

Besides the unbalance practice in industrial research, a similar asymmetric development can be observed in grey literature. Among O4.0 technologies, only the application of VR and AR technologies for facilitating competencies and skills training was addressed equally by all key industrial stakeholders. The O5.0 approach and its dimensions were not sufficiently addressed from a holistic perspective. Policymakers should be more active as they were aware of the possible benefits, to fulfill what the industry expects from their contribution. Not to mention new regulations should be introduced for circulating core O4.0 technologies on the market, but academic research should be supported for developing more customized and adept solutions. Mass introduction and mindset education should be done on a societal level, to shorten the research-to-market period, ensure efficient usage, and avoid any unforeseen negative social effects.

In short, this paper contributed to relevant stakeholders as follows:

- The later researchers can use this review as a guide for developing O5.0 enabling technologies.
- Technical developers should consider the context of this study, to understand what they need to do, to make their technology applicable in a specific manufacturing context, and improve the time-to-market of their solutions.
- Industrial managers can sketch their future manufacturing system based on the current benefits while preparing themselves for the change and development. The current drivers can help to shape favorable conditions, and the restrainers should be mitigated before adopting any human-centric technology.
- Policymakers should facilitate the knowledge of the I5.0 and O5.0, to guide more research and practice activities.

The result of this paper generalizes the current O4.0 development and establishes a better understanding of the O5.0 transition. We call for more attention to the social dimension of human-centric technology adoption in the threshold of I5.0. Though social aspects are not in the current mainstream, they will soon gain more importance. Such a conclusion is supported by the fact that human-centrism, sustainability, and resilience were raised as the main issues correlated with the I4.0 implementations, as learned lessons from many previous technological innovation introductions. One drawback of this study was the importance of grey literature was not fully assessed. However, considering I5.0 is still in an exploratory phase, the influence of prominent players can be recognized later.

Further literature studies should consider a wider range of grey literature: including not only national and international policies but also white papers, reports from consulting companies, and reports from authorities (on different levels such as the EU, national, local, etc.). The proposed agenda includes strengthening the transition from an academic perspective to an industry perspective through thorough surveys conducted with companies being current or potential stakeholders of the O4.0/O5.0 paradigm. Aligned with the conclusion from this current paper, our future experimental studies will diagnose more in-depth the suitable context for each O5.0 type, and establish pilot use

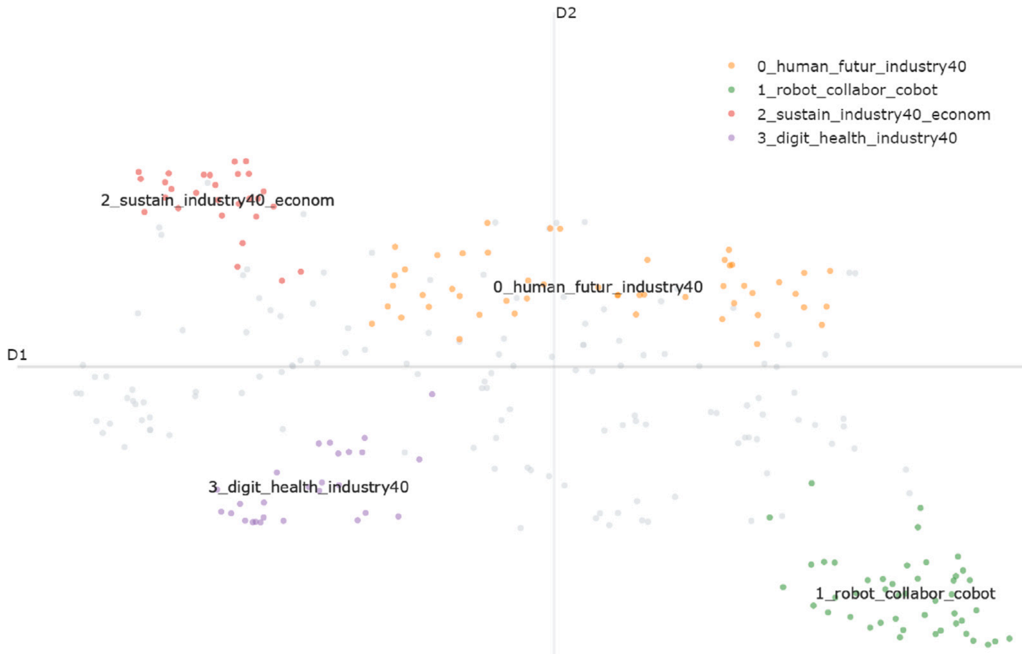

Fig. E.17. The inter-topic distance of topic clusters from BERTopic. The topics are well-recognized, with many studies blended in between.

cases on the symbiosis integration of relevant I4.0 technologies and human physiological parameters, that can be practically implemented in a manufacturing environment.

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.

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Appendix A. The search query

The keyword matrix is illustrated in Fig. A.14, consisting of four sets. The first set including "industry 4.0", "industry 5.0", "operator 4.0" and "operator 5.0" sets the interested context. The words "manufactur*" and "product*" defined the research fields in the manufacturing and production environment. The third set with "ergonomic*", "sustain*", "resilien*", "human-centri*"/"human centri", and "well-being"/"wellbeing" determined the scope of human worker and social aspect. The last set including "worker", "operator" and "employee" defined the human role in relevant research. These four sets of keywords are joined with the logical operator AND, with each keyword within the set equally inputted with the logical operator OR. The wildcard search is used with the asterisk sign to maximize the result of derivative words (e.g., resilient, resilience).

Noticeably, two sets of keywords: "human-centri*"/"human centri" and "well-being"/"wellbeing" are interchangeably deployed in the literature, thus they yielded different results. The authors decided to keep both in the search query. The words "well being" standing separately can lead to another meaning, thus they were excluded. The final Scopus query is the following:

(TITLE-ABS-KEY ("industry 4.0" OR "industry 5.0" OR "operator 4.0" OR "operator 5.0")

AND TITLE-ABS-KEY ("manufactur*" OR "product*")

AND TITLE-ABS-KEY ("ergonomic*" OR "sustain*" OR "resilien*" OR "human-centri*" OR "human centri*" OR "well-being" OR "wellbeing")

AND TITLE-ABS-KEY ("worker" OR "operator" OR "employee"))

AND PUBYEAR < 2023

AND (EXCLUDE (DOCTYPE,"cr") OR EXCLUDE (DOCTYPE,"ed"))

AND (LIMIT-TO (LANGUAGE,"English"))

Appendix B. Adjustment for KNIME flow

The adjustment for LDA with KNIME flow is listed below:

- The well-recognized terms consist of more than two words (e.g., "industry 4.0", "operator 4.0", "human-machine interaction", "augmented reality", "circular economy", "big data", "machine learning", "human factor") were defined as a single word to avoid being broken down. These keywords are defined based on the author and index keywords;
- The popular terms that have the same meaning (e.g., "human-centered", "human-centred", and "human-centric") were coined together into one term (i.e., "human-centered").
- The phrases that have the same meaning are replaced by one single term (e.g., "social sustainability", "socially sustainable" are replaced by "sustainability", while "collaborative robotics", "collaborative robot", and "CoBot" are replaced by one term "cobot").

After the POS tagging step, only the informative adjectives and nouns were kept. Non-contextual keywords and irrelevant terms (e.g., authors, papers, research, survey, result, etc.), and terms with less than three characters are excluded. After the Snowball stemmer step, the survived root-form terms that are non-contextual (e.g., industri, compani, factori) are also excluded. The input to the Topic Extractor

Table E.13
Human-centric technology developments: other aspects in the included experimental studies.

Aspect	Consideration and pillars	Considered context [Study] with readiness level		
		Concepts & Proposals	Enabling technologies	Adoption Initiatives & Framework
System-integration	Individual optimization.	Individual cognitive load according to demands and characteristics of workers [134]; tune the adaptive behavior of system according to human status [135]	–	Individual optimization with ergonomics score [78]
	Natural and ergonomic interaction.	Natural communication dialog system [145]; Use interconnected visual-based sensors to recognize human natural gestures [138]	Recognize hand gesture by the natural working movement [128], monitor postural stability by smart soles [146]	–
	Human physical and psychological reaction.	Effect of robot appearance on human performance virtual environment [129,130]	Adjustable smoothness of robot trajectory according to human cognitive stress [139,140]; Measure human performance with eye tracker [131]; Subjective and physiological response during human–robot collaboration [133]; Human attention tracking for online cognitive load assessment [134]	–
System-modification	Retrofitting	–	–	Human-centric retrofitting with low cost technical improvements [147]
	System design with human consideration.	–	–	Multi-disciplinary design framework for labor-intensive manufacturing [81]; Workstation design to improve physical ergonomics and production efficiency of operators [61]; Axiomatic design for a workstation with cobot [143,148]
	Service orientation.	Service-oriented function for safety engineering [149]	Service-oriented digital twin [144]	–
	Enhanced system with situational awareness	Bi-directional information flows between operators and robots by sensors and interactive HMI [137,141]; Modify robot trajectory according to human movement tracking and action prediction [150]	Low-cost scalable people tracking system [150]	–
	Interactive visualization.	–	Human–Machine interface with 3D digital twin [151]	–

Table E.14
The similarities of topics extracted from BERTopic and LDA result. Each topic can be matched with another between two methods.

BERTopic	No. of study	Ten most frequent terms	Lowest - Highest probability	Equivalent LDA topic	No. of matched studies
BERTopic 0	69	human; futur; industry40; worker; technolog, well-being; cognit; design; mainten; framework	0.9177 – 1	LDA 1	34
BERTopic 1	51	robot; collabor; cobot; human; safety; human–robot; assembl; design; task; industry40	0.4209 – 1	LDA 3	35
BERTopic 2	47	sustain; industry40; econom; develop; environment; energi; process; lean; social; circular	0.6823 – 1	LDA 2	27
BERTopic 3	27	digit; health; industry40; safeti; occup; inform; process; technolog; transform; remot	0.6877 – 1	LDA 0	18

step with Parallel LDA will be a list of documents containing frequently occurring terms. Before deploying the Parallel LDA, the Elbow method with PCA and k-Means algorithms will be applied to this input set to discover the number of topics that best describe its diversity.

Appendix C. Author and keyword clusters

See Tables C.10 and C.11.

Appendix D. Term association in knowledge graph

The details of interesting groups of terms can be discovered in the extracted KG as illustrated in Fig. D.15. The sub-figure (1) shows the wide connection of the I4.0 with all aspects. The sub-figure (2) illustrated that the I5.0 is strongly connected with sustainability but shows no association with resilience- and social-related terms, even with the I4.0. The O4.0 concept lacks supporting aspects and is not connected to I5.0 as seen in the sub-figure (3). Though the intention for sustainability appeared, a lack of supporting technology is recognized

Table F.15
Drivers and Restrainers for solution adoption in the included experimental studies.

Type	Details	Explanation	Study
Drivers	In-depth process analysis and management	The process or work procedure was analyzed in detail before considering technical solutions. Close control of the process is applied after implementation.	[61,77,78,80,84,134,136,138,141–143,145–149]
	Well-designed human–machine interaction	The workflow and task allocation between humans and machines were carefully diagnosed and designed. The interaction was considered based on the characteristics of both sides.	[61,77,80,128,129,131,133,138,139,142,145,148,150]
	Suitable approach and method	The technological development and adoption followed a certain approach, such as multi-disciplinary, trans-disciplinary, worker-centric, structured, combined, synchronized, value-oriented, etc.	[81,90,126,127,134,135,141–144,147,149]
	Technical readiness	The availability of technical infrastructure, or enabling technologies, developed algorithms played an important role. The technology should be ready for the application.	[76,78,82,84,91,127–129,131,138,139]
	Involvement of end-users and stakeholders	The workers, engineers as end-users, and management as stakeholders should be involved in making a technology adoption decision.	[81,132,143,147,151]
Restrainers	Lack of multi-disciplinary knowledge	The approach required multi-disciplinary knowledge, such as life science (correlation of physiological parameters, scientific validation, uncertainty from survey and questionnaire), social science (workforce characteristics, ethical principles), psychological science (cognitive models, psychosocial factors)	[61,98,126,129,131–135,139,145,146]
	Lack of standards, guidelines, and policies	The technical development needed standards or guidelines for a successful implementation. The policies or change management of the company played an essential role.	[78,81,98,126,141,144,151]
	Technological accuracy, reliability, and trustworthiness	The accuracy of adopted technology obstructed the intended usage or raised concerns about the effectiveness.	[77,84,91,126–128,138,150]
	Technical development complexity	Difficulties during the technical development progress, such as multiple vendors, different APIs, dependencies, or the negative characteristics of the technology, such as long time to market, inappropriate hardware ergonomics, inflexible customization, and low readiness level.	[77,78,84,127,145,147,149–151]
	Data strategy: handling, management, and security	The data-related concerns, such as lack of digital strategy, difficulties in handling big data, redundant data, safe data storage, and sensitive and personal data protection.	[76,132,141,147]

Table G.16
Different groups of benefits for solution adoption in the included experimental studies.

Type	Details	Explanation	Study
Sustainable operation	Higher resource utilization	Efficient use of machines, materials, and energies. Better use of legacy equipment and facilities.	[76,147]
	Enhanced operational effectiveness	Improved manufacturing process, productivity, quality, and cost performance. Enhanced transparency of the company.	[61,76,81,90,91,127,131,133,136,141–144,149]
	Enhanced supply chain effectiveness	Enhanced outbound logistics, efficient process and operation with partners and suppliers.	[78,144]
Human–system collaboration	Natural interaction with industrial assets	The interaction with machines and equipment was designed with human user experience and natural human-like language, gesture, and communication.	[128,138,145,146,148]
	Better system autonomy and human synchronization	Enhanced systematic automation of machines, robots, and equipment while considering the work harmony with human workers.	[98,129,135,138,139,141,145]
	Advanced intervention, smart adaptation	Enabled timely intervention for human workers, including physical and cognitive aspects.	[131,134]
Human-centric consideration	Fast decision-making process	Support the human workers with the necessary information to make fast decisions during manufacturing scenarios.	[77,81,84,126,136]
	Individual customization	The work content, such as workload, work pace, sequence, etc., can be modified based on the individual preference, and physical or mental status of workers.	[78,134,135,141,146]
	Safer and healthier working environment	Transform the workplace into a safer environment for workers, reduce the associated occupational risks and hazards.	[61,76,78,81,82,84,90,126,127,133,142,143,148,150]
Social resilience	Improved work experiences	Increased trust and acceptance, and decreased stress and frustration during the interaction with robot/system.	[77,82,98,129,132,139,144,151]
	Improved workforce sustainability	Enabled knowledge sharing and skill transition to create a robust workforce. Utilizing work experience of operators and management. Including elderly or personnel with a temporal or permanent disability.	[132,147]
	Boosted communication, work morale, and CSR	Enhanced communication within the workforce, and consequently the awareness of work morale and corporate social responsibilities.	[76,132,136]

in the sub-figure (4), while the need for understanding emerged in the sub-figure (5).

Appendix E. LDA and BERTopic results

The input set for LDA contains 240 terms, with the most frequent ones depicted in Fig. E.16. Details of LDA results were displayed in Table E.12.

These clusters from BERTopic are well-separated as shown in Fig. E.17. 109 papers remained unassigned, as they stood in the blending regions between topics.

The topics from BERTopic were matched with the ones from LDA as described in Table E.14.

Appendix F. Drivers and restrainers

The five most frequently mentioned drivers and restrainers of technological solution adoption of included experimental studies were categorized in Table F.15.

Appendix G. Possible benefits for solution adoption

Details of proposed benefits and their occurrence in included experimental studies were described in Table G.16.

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