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Industry 4.0: a tertiary literature review

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ABSTRACT

Industry 4.0 has become one of the most discussed subjects in academic and professional fields. The number of articles published is large and continues to increase, introducing new issues, concepts, methods, and technologies. Many review articles deal with specific issues and not always with the necessary rigor, making a more general understanding of the subject difficult. Motivated by the large volume of literature, this study makes a tertiary review of Industry 4.0 (i4.0), identifying the main concepts, methods, and technologies. The study is guided by three research questions: What are the literature reviews on i4.0? What are the research questions of these reviews? What are the main results of i4.0 reviews? The reviewed articles are systematic review articles indexed in the Scopus and Web of Science databases. This study presents a descriptive analysis of the review articles (46 articles) and a second descriptive analysis of the references cited in them (1542 articles). In content analysis, we grouped the articles into three classes: conceptual articles, articles on enabling technologies, and articles that address operations management in i4.0. The reviewed articles show the multidisciplinary nature of the topic and the still relative scarcity of studies on its application in companies.

1. Introduction

Industry 4.0, or the Fourth Industrial Revolution, represents a new way of organizing industrial resources and processes, making them more responsive to an ever-changing environment (Kamble et al., 2018). Therefore, it quickly became one of the themes of great relevance in academic and professional circles (Liao et al., 2017) and particularly for professionals in engineering and operations management.

The volume of publications on i4.0 continues to increase significantly. Researchers worldwide have produced extensive literature covering a wide range of topics with different approaches and perspectives. A search in the Scopus and Web of Science databases in December 2020, with the keywords "Industry 4.0" and "Smart Factory," resulted in 14,125 and 7762 articles, respectively. Among these, 251 in Scopus and 216 in Web of Science were literature review articles (secondary studies).

Literature reviews provide an overview of a line of research, synthesizing what has already been studied and the gaps for further research (Thomé et al., 2016). However, some reviews fall short of meeting this main objective, either because of a lack of methodological rigor or because they address specific research questions.

This study is motivated by this context of the literature on i4.0, which, despite being relatively new, brings together a huge amount of published works. This research aims to make a systematic review of review articles on i4.0, that is, to perform a tertiary analysis of this literature, seeking to identify advances and gaps in the subject. The following questions will guide the review:

RQ.1 What are the literature reviews on i4.0?
RQ.2 What are the research questions of these reviews?
RQ.3 What are the main results of i4.0 reviews?

To answer the first question, the article presents, through bibliometric techniques, a characterization of the review articles in i4.0 selected from among the articles published in high-impact academic journals. In addition, a second descriptive analysis is performed with the articles cited in the review articles. The second research question, addressed in content analysis, aims to identify the research questions of the selected review articles. Finally, the third question explores the results in these review articles, that is, the questions answered and the gaps still to be explored.

Despite the large volume of primary and secondary research publications on i4.0, we did not find tertiary studies on the subject. Therefore, this study contributes to the literature, providing a comprehensive and structured view of secondary studies in i4.0.

This article is structured as follows. Section 2 describes the research

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method, which involves collecting, selecting, and analysing review articles. In Section 3, a descriptive analysis of the selected review articles is carried out, followed by an analysis of their references. In Section 4, the content analysis of the review articles is performed. Section 5 provides a discussion of the results. Section 6 concludes the article with some final remarks.

2. Methods

The tertiary study is a particular case of literature review. This type of study synthesizes results of literature review articles in a specific research area, providing a more comprehensive understanding of state of the art, being especially important in cases where there is a large volume of publications (Martins and Pato, 2019).

In the present work, we carry out a tertiary review on i4.0, considering only articles that effectively constitute systematic literature reviews and that address relevant topic to i4.0, as will be detailed in the following sections.

2.1. Research protocol

The objectives of this study are: i) to map existing literature reviews on i4.0, ii) to identify the research questions and objectives of these studies, and iii) to discuss the contributions of these studies to the literature.

To achieve these objectives, a research protocol was developed, summarized in Table 1. This protocol includes the steps of collection, selection, and analysis of articles.

2.2. Survey of papers

Once the research questions were defined (step 1 of 7), the next step was to survey articles. The articles were collected using the Scopus and Web of Science (WoS) databases (step 2 of 7) on December 21, 2020. This choice, verified in many of the articles reviewed in this study, provides wide coverage of the literature under review.

The searches were performed with the keywords “Industry 4.0” and “Smart Factory.” Additionally, they were limited to publications from 2010 to 2020, English language, and review-type documents. The Engineering and Computer Science areas were chosen (step 3 of 7). The initial search in the Scopus database returned 251 articles, and in WoS returned 216 articles. Joining the articles from the two databases, excluding duplicates, we reached a sample of 362 articles (stage 4 of 7).

2.3. Selection of papers

After defining the sample, the articles were sorted in descending order of the average number of citations per year and included or excluded based on the criteria defined in Table 1 (step 5 of 7). This selection took place in two stages of reading: i) title, abstract, and keywords and ii) article first reading.

Two researchers performed the analyses, who assigned a score (scale from 1 to 5) to each article, based on two criteria: method and scope. These scores were discussed and used to define the final sample.

An article was considered very suitable if it was effectively a Systematic Literature Review (SLR) and covered topics pertinent to i4.0 in manufacturing. From reading the abstracts, we classified the articles in terms of scope into three classes, as follows:

(i) industry 4.0: articles covering i4.0 concepts and methods in general,
(ii) technologies: articles dealing specifically with i4.0 enabling technologies,
(iii) management innovation: articles that discuss innovations in management functions for i4.0.

2.4. Second reading and annotations

Once the 46 articles were selected, we did a second reading and created a spreadsheet with metadata and notes of the main points of each article.

The records included: (1) authors, (2) institutions, (3) countries, (4) title, (5) year, (6) journal, (7) journal area, (8) authors keywords, (9) number of citations, (10) citations per year, (11) abstract, (12) scope, (13) objective, (14) research questions, and (15) main contributions.

Lastly, descriptive and content analyses were performed, the results of which are presented in Sections 3 and 4.

Table 1
Research protocol.

1. Research Questions	1.1 What are the literature reviews on i4.0?		
	1.2 What are the research questions of these reviews?		
	1.3 What are the main results of i4.0 reviews?		
2. Databases	Scopus and Web of Science (WoS)		
3. Search Criteria		*Scopus*	*WoS*
	3.1 Search Terms	“Industry 4.0” OR “Smart Factory”	
	3.2 Year of Publication:	2010 to 2020	
	3.3 Language:	English	
	3.4 Subject area(s):	Engineering; Computer Science	Engineering, Computer Science and Telecommunication
	3.5 Document Type(s):	Review	
	3.6 Date of Search:	21 December 2020	
4. Screening		*Scopus*	*WoS*
	Keywords	14.125	7.762
	AND Year of Publication	14.087	7.755
	AND Language	13.397	7.327
	AND Subject area(s)	11.440	5.309
	AND Document Type(s)	251	216
	Total after elimination of duplicate records	362	
5. Exclusion Criteria	5.1 Article is not a systematic literature review (method)		
	5.2 Article does not address i4.0 issues in manufacturing (scope)		
6. Selection	6.1 After reading the title, abstract and keywords		105
	6.2 After first reading		46
7. Analysis	7.1 Descriptive Analysis		
	7.2 Content Analysis (second reading)		

3. Descriptive analysis

To answer the first research question, two descriptive analyses were carried out. The first considers the 46 selected review articles, and the second includes all the cited references in the selected articles, totalling 1542 articles.

3.1. Descriptive analysis of the review articles

The 46 selected review articles were written by 147 researchers from 63 institutions (59 universities and 4 companies). The articles gathered authors from 23 countries, with a predominance of Italy, a country where 20 % of the authors of review articles work.

These review articles were published in 23 journals. Five journals account for 51 % of all publications, namely: i) International Journal of Production Research (11 %), ii) Computers in Industry (11 %), iii) Computers & Industrial Engineering (11 %), iv) Journal of Manufacturing Technology Management (9 %), v) Journal of Manufacturing Systems (9 %).

Fig. 1 shows the areas of the journals that published the articles analysed, according to the Scimago Journal and Country Rank. As expected, there is a greater concentration in journals in the Computer Science and Engineering areas (54 %).

Another point analysed was the keywords used by the authors. We found a total of 88 keywords with two or more occurrences, where the 5 most frequently used keywords were: Industry 4.0 (22 %), Cyber-Physical Systems (8 %), Internet of Things (6 %), Embedded Systems (5 %), and Smart Manufacturing (4 %).

The 46 review articles analysed were published in the last 4 years (2017–2020), with most of them published in 2020 (61 %). These articles were classified into three classes, as shown in Fig. 2.

First, there are those articles that address i4.0 concepts in general (52.2 %). Then come articles that deal specifically with i4.0 technologies (34.8 %). Finally, some articles discuss innovation of some specific function of industrial management in the context of i4.0 (13 %).

The content analysis of the review articles in each category will be carried out in detail in Section 4. Next, in Section 3.2, we present a bibliometric analysis of the references cited in the selected articles for a broader view of the research in i4.0.

3.2. Descriptive analysis of the references cited

This section presents an analysis of the references cited in the 46 selected review articles, which initially added up to 3959 references. From this total, the following were excluded: duplicate references, references to websites, books, conference articles, and references dealing with other topics, such as articles on research methodology. After this screening, the final sample had 1542 original articles, which are analysed below.

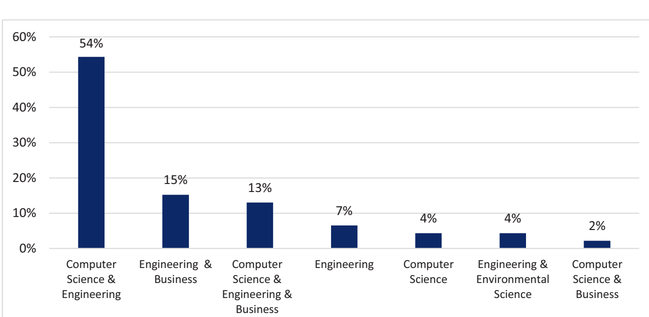

Fig. 1. Classification of journals.

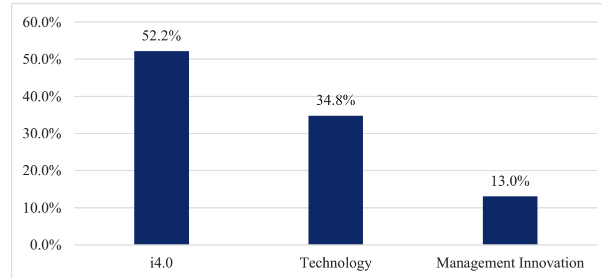

Fig. 2. Classification of selected articles.

3.2.1. Publications per year

Fig. 3 presents the distribution of articles over time, which shows an increasing trend in the number of articles published until 2018. The drop from 2019 is because we are using the references cited in the review articles selected, which, as mentioned in Section 3.1, were published between 2017 and 2020.

3.2.2. Contributions by country

The original articles gathered authors from 69 countries, with a predominance for China, United States, United Kingdom, Italy, and Germany, where 57 % of the authors work. Fig. 4 shows that 80 % of authors are from only 11 countries.

3.2.3. High-contributing institutions

Table 2 presents the first twenty institutions, ordered by the number of associated authors in the articles.

3.2.4. Contributions by journal

The 1542 articles were published in 120 different academic journals. Fig. 5 shows the academic journals with the highest share of articles published in the sample.

3.2.5. High-contributing authors

Fig. 6 shows the main authors based on the number of publications and the co-authorship network. Circle sizes are related to the number of articles published, and colours are related to interconnections between authors. The top 20 authors by the number of publications are listed in Table 3.

3.2.6. Keywords statistics

Fig. 7 shows the 100 most used words and their connections. The size of the circle is related to the number of times these words are cited, and the colours are related to the interconnections between these words. The top ten keywords are: i) manufacture, ii) industry 4.0, iii) internet of things, iv) embedded systems, v) cyber physical systems, vi) supply chains, vii) big data, viii) cloud manufacturing, ix) computer aided manufacturing, x) scheduling.

4. Content analysis

In the previous section, we present a descriptive analysis of the selected review articles (46 articles) and their references (1542 articles) to provide an overview of the research in i4.0. This section presents a content analysis of the articles in three parts: i) industry 4.0, ii) enabling technologies, and iii) operations management.

4.1. Industry 4.0

In the sample of 46 review articles, 24 were classified in this first-class, formed by articles that deal with the topic in a conceptual and general way. From reading the articles, with special attention to research questions and goals, we defined four dimensions of analysis: i)

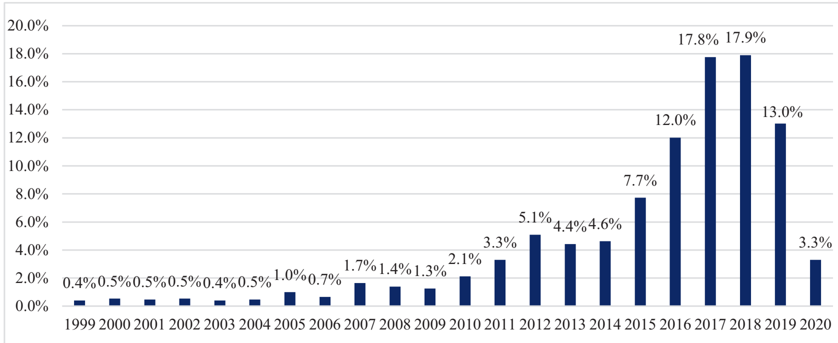

Fig. 3. Year of publication of the cited references.

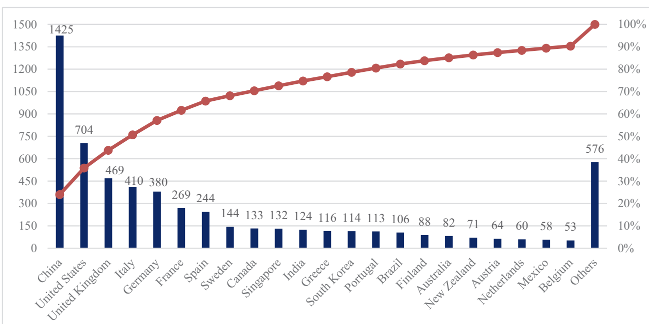

Fig. 4. Contributions by country of the cited references.

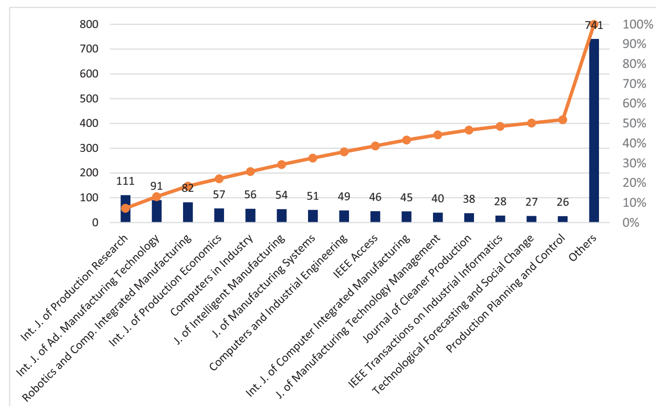

Fig. 5. Contributions by journals of the reference list.

Table 2
Top 20 High-contributing Institutions on the Reference List.

#	Institution	Number of Publications	Country
1	Beihang University	191	China
2	South China University of Technology	104	China
3	Wuhan University of Technology	85	China
4	University of Patras	80	Greece
5	University of Hong Kong	71	Hong Kong
6	Chongqing University	61	China
7	National University of Singapore	61	Singapore
8	Shanghai Jiao Tong University	58	China
9	Tsinghua University	52	China
10	Cranfield University	50	United Kingdom
11	Politecnico di Milano	48	Italy
12	Guangdong University of Technology	46	China
13	North-western Polytechnical University	41	China
14	University of Michigan	39	United States
15	University of Cambridge	39	United Kingdom
16	University of Modena and Reggio Emilia	38	Italy
17	University of Bremen	37	Germany
18	Aalto University	36	Filande
19	University of Auckland	34	New Zeland
20	Loughborough University	33	United Kingdom

concepts; ii) technologies; iii) applications; and iv) competencies.

4.1.1. Concepts

In the reviewed articles, the authors typically present the emergence and evolution of i4.0, which is characterized by the intensive use of automation and digital technologies (Mittal et al., 2018).

The use of these digital technologies in different areas of the company characterizes the digital transformation in manufacturing, where traditional factories are transformed into smart factories. In addition to manufacturing, there are many applications in other segments, such as smart cities and smart services (Osterrieder et al., 2020; Romero et al., 2020).

Digitization is responsible for the emergence of more responsive, flexible, and self-organizing factories, which integrate technologies and resources with systems for data collection, communication, analysis, and decision making (Strozzi et al., 2017; Ding, 2018).

Digital transformation opens a new perspective for the industry, as it allows connecting different types of physical devices, enriched with embedded electronics, to a local network or the internet to interact during the production process (Kamble et al., 2018).

Another fundamental concept for i4.0 is cyber-physical systems (CPS). CPS monitor physical systems from digital copies, allowing for a decentralized and integrated decision-making process (Lu, 2017). To this end, CPS collect, transmit and analyse data and control physical systems (Napoleone et al., 2020), enabling smarter decision-making, both vertically and horizontally, in the value chain (Ding, 2018).

Human-machine integration and interoperability are two others important i4.0 concepts that result from the intensive use of automation and digital technologies (Lu, 2017; Strozzi et al., 2017; Jerman et al., 2018; Galati and Bigliardi, 2019; Wagire et al., 2020). Lu (2017) characterizes i4.0 as an integrated, optimized, service-oriented, and interoperable manufacturing process that demands big data analytics and employs advanced production technologies.

Sony and Naik (2020) characterize i4.0 with five main attributes: (i) digitization, optimization, and customization of production; (ii) automation and adaptation; (iii) human-machine interaction; (iv) value-

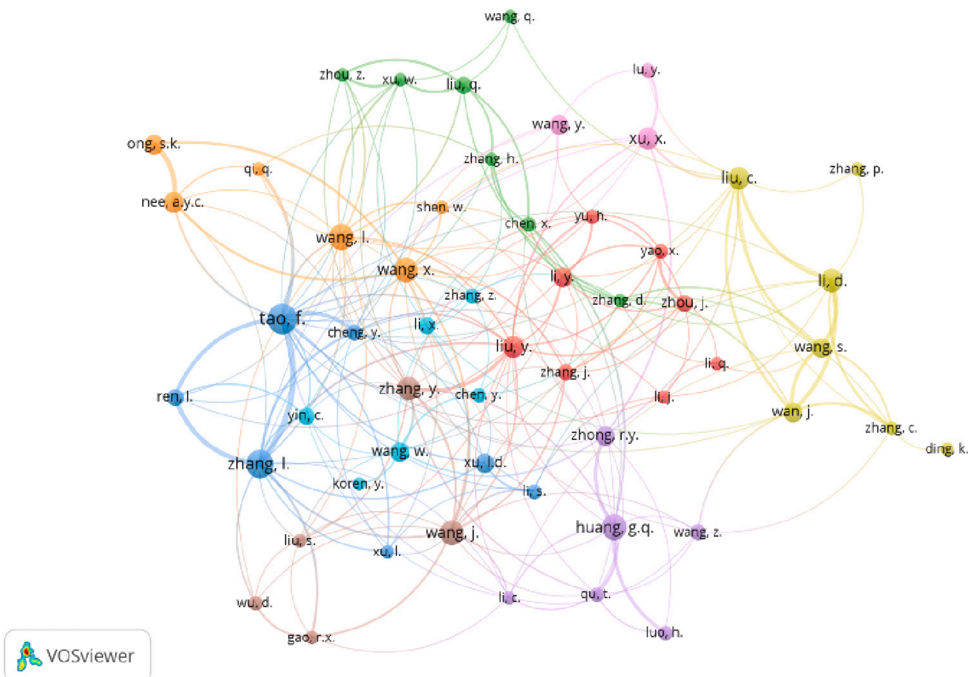

Fig. 6. High-contributing authors.

Table 3
Top 20 Authors.

#	Authors	Publications References	Institution Country
1	Tao F	34	China
2	Zhang L	29	China
3	Huang G Q	24	China
4	Wang L	23	Sweden
5	Wang J	21	China
6	Wang X	21	Singapore
7	Zhang Y	19	China
8	Li D	19	China
9	Xu X	18	New Zealand
10	Liu Y	18	China
11	Liu C	17	New Zealand
12	Nee A Y C	16	Singapore
13	Wan J	14	China
14	Wang S	14	China
15	Wang Y	14	United Kingdom
16	Xu L D	14	China
17	Li Y	14	China
18	Zhong R Y	13	Hong Kong
19	Wang W	13	United States
20	Ong S K	13	Singapore

added services and businesses; and (v) automatic data exchange and communication.

In a broader perspective, the new i4.0 technologies allow creating a digital value chain in which products, equipment, and people are integrated into its production environment and with its business partners (Galati and Bigliardi, 2019). These technologies provide new business models driven by customer needs and mass customization (Nosalska et al., 2019).

Kamble et al. (2018) highlight that, since the first steps of i4.0, enabling technologies is one of its main characteristics. Therefore, many research efforts have focused on this topic, which is addressed in the following section.

Finally, many authors address digital security issues, which become more relevant with the increasing use of information technology (Kamble et al., 2018; Lezzi et al., 2018). Studies in this area seek to characterize the vulnerabilities of systems and protection measures against cyberattacks (Lezzi et al., 2018).

4.1.2. *Technologies*

Industry 4.0 is marked by automated and digitized processes, making intensive use of information and automation technologies (Lu, 2017). The technology most directly associated with i4.0 is the Internet of Things (IoT), which allows the connection of agents that make up cyber-physical systems (CPS) in intelligent factories (Kamble et al., 2018).

Lu (2017) includes in his review, besides IoT, mobile computing, cloud computing, and big data technologies. Liao et al. (2017) show that in addition to these technologies, data modelling, augmented and virtual reality, machine learning, and 3D printing are also enabling technologies for industry 4.0.

Kamble et al. (2018) included rapid prototyping, simulation, and advanced robotic systems in this group. In addition, artificial intelligence (AI) concepts and methods, sensors and actuators, radio-frequency identification (RFID), and real-time location systems (RTLS) are also cited as enabling technologies (Mittal et al., 2018).

Digital security technologies, which aim to protect digital systems and processes, are also highlighted in the i4.0 research agenda (Kamble et al., 2018). Furthermore, many other authors also address the topic of i4.0 enabling technologies. Table 4 highlights the main technologies, classified into six groups as proposed by Nosalska et al. (2019).

Adopting these technologies in an integrated way helps increase the quality and productivity of processes, resulting in greater competitiveness in supply chains (Calabrese et al., 2020). Therefore, many review papers, which will be analysed in Section 4.2, are specifically dedicated to the topic of enabling technologies for i4.0.

4.1.3. *Applications*

As i4.0 is a relatively new movement, applied research is still rare. Liao et al. (2017) highlight two reasons for the low adoption of these technologies by companies: (i) uncertainty regarding the return on investments and (ii) low maturity of some technologies.

Galati and Bigliardi (2019) carry out research using text mining to understand the main research areas in i4.0. The authors classified the results into four clusters: (i) business, (ii) operations, (iii) technologies, and (iv) training. The areas of operations and technologies, together,

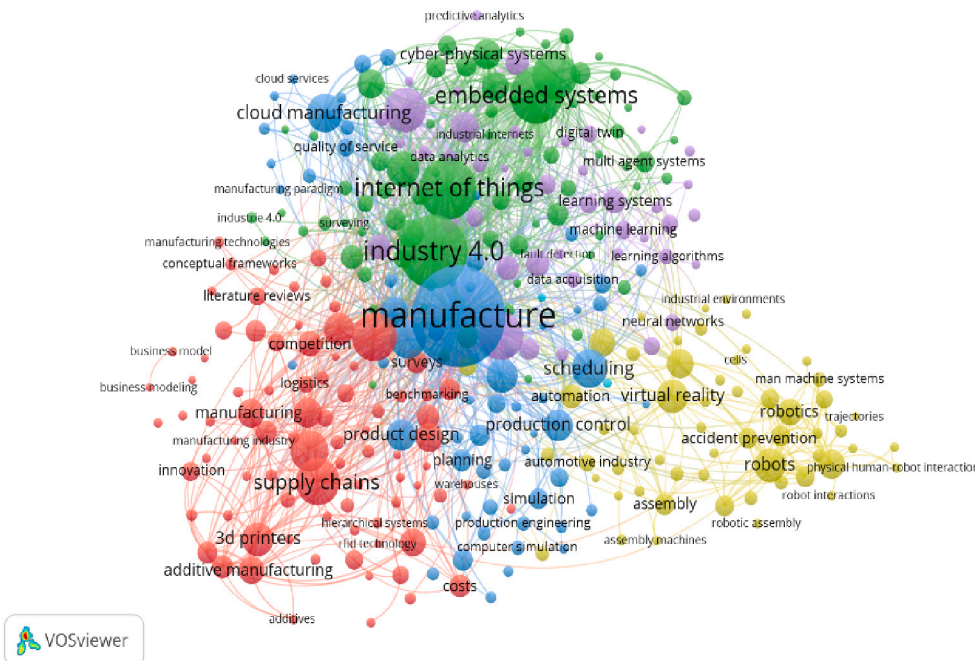

Fig. 7. Authors keywords statistics.

Table 4
Enabling technologies.

Group	Technologies	References
Systems and automation	Cyber-Physical Systems Modelling Technologies Simulations and Prototype Augmented Reality Virtual Reality	Lu (2017), Liao et al. (2017), Kamble et al. (2018), Strozzi et al. (2017), Galati and Bigliardi (2019), Ding (2018), Rojas and Rauch, 2019, Jerman et al. (2018), Nosalska et al. (2019), Vianna et al. (2020), Calabrese et al. (2020), Mittal et al. (2018)
Networking and connectivity	Internet of Things RFID Technologies RTLS Technologies Sensors and Actuators	Lu (2017), Kamble et al. (2018), Strozzi et al. (2017), Galati and Bigliardi (2019), Ding (2018), Rojas and Rauch, 2019, Jerman et al. (2018), Nosalska et al. (2019), Vianna et al. (2020), Calabrese et al. (2020), Mittal et al. (2018), Nosalska et al. (2019)
Data science	Big Data Analytics Artificial Intelligence Machine Learning	Lu (2017), Liao et al. (2017), Kamble et al. (2018), Mittal et al. (2018), Galati and Bigliardi (2019), Ding (2018), Rojas and Rauch, 2019, Nosalska et al. (2019), Vianna et al. (2020), Calabrese et al. (2020)
Manufacturing technologies	Additive Manufacturing (3D printing)	Liao et al. (2017), Kamble et al. (2018), Mittal et al. (2018), Ding (2018), Nosalska et al. (2019), Vianna et al. (2020), Calabrese et al. (2020)
Robots	Advanced Robotic System	Kamble et al. (2018), Mittal et al. (2018), Nosalska et al. (2019), Calabrese et al. (2020)
Information technologies	Cyber Security Cloud Technologies Mobile Technologies	Lu (2017), Liao et al. (2017), Kamble et al. (2018), Mittal et al. (2018), Rojas and Rauch, 2019, Nosalska et al. (2019), Calabrese et al. (2020), Vianna et al. (2020)

Table 5
Applications of Industry 4.0 Technologies.

Applications	References
Smart factory	Lu (2017), Wagire et al., 2020, Galati and Bigliardi (2019)
Smart product	Lu (2017), Wagire et al., 2020, Sony and Naik (2020)
Smart city	Lu (2017), Wagire et al., 2020
Services	Liao et al. (2017)
Semicondutor industry	Liao et al. (2017)
Energy	Da Silva et al. (2020)
White goods industry	Liao et al. (2017)
Automobile industry	Liao et al. (2017)
Pharmaceutical Industry	Ding (2018)
Automotive tier-1 supplier	Liao et al. (2017)

account for more than 70 % of the publications raised by the authors.

Another application presented by Da Silva et al. (2020) refers to energy consumption at i4.0 facilities. Energy management includes methods to monitor, predict and control energy consumption (Ding, 2018).

The authors highlight that IoT, BDA, and CPS are the main technologies applicable for energy management. They also point to the need for research on prediction using machine learning, pattern recognition to understand peak consumption, and the combination of fog and cloud computing for energy-efficient data processing.

Regarding the practical application of i4.0 methods and technologies in companies, Sony (2020) discusses its advantages and disadvantages. As advantages, the author identified gains in competitiveness, efficiency, effectiveness, agility, process innovation, safety and quality, environmental and social benefits.

The disadvantages are related to the risks of data sharing in a competitive environment, the need for full i4.0 deployment, handling employees and trade unions apprehensions, the need for highly skilled labour, socio-technical implications, cybersecurity, and high initial cost.

Table 5 lists the main application areas cited in the articles.

4.1.4. Core competences

Certainly, the implementation of i4.0 methods and technologies in companies requires new professional skills. In the review, we found five works that address this issue, more specifically, two that deal with individual competencies (Jerman et al., 2018; Motyl and Filippi, 2020) and three that address maturity models to assess organizational competencies (Mittal et al., 2018; De Jesus and Lima, 2020; Hizam-Hanafiah et al., 2020).

Table 6
Individual skills.

Competence	Characteristics
Technical	IT security Coding capabilities Understanding of processes Technical capabilities Understanding the analogies of the operation of new technologies
Methodological	Ability to solve complex challenges Creativity Problem solving Conflict resolution Analytical skills Research skills Seeing the big picture
Social	Ability to lead Ability to communicate effectively Network Ability to work in a team Language skills Ability to transfer knowledge to others
Personal	Commitment to lifelong learning Personal flexibility Motivation for learning Adaptability Ability to work in stressful situations

Table 7
Research questions of Industry 4.0 conceptual articles.

Research Question	References
1. What is the status of the research in i4.0?	Lu (2017), Liao et al. (2017), Kamble et al. (2018), Galati and Bigliardi (2019), Wagire et al., 2020, Strozzi et al. (2017)
2. What is the status of the research in CPS e CPPS?	Rojas and Rauch, 2019, Napoleone et al. (2020)
3. What are the challenges and benefits of i4.0 for the pharmaceutical supply chain?	Ding (2018)
4. What are the critical success factors for i4.0?	Sony and Naik (2020)
5. How to assess the maturity of i4.0 in SMEs?	Mittal et al. (2018)
6. What is the status of research in i4.0 readiness models?	Hizam-Hanafiah et al. (2020)
7. What are the main differences among maturity models described in the literature?	De Jesus and Lima (2020)
8. What are i4.0's enabling technologies, strengths, weaknesses, opportunities, and threats (ESWOT) for adopters?	Calabrese et al. (2020)
9. What are the core competencies for i4.0?	Jerman et al. (2018)
10. What is Industry 4.0?	Nosalska et al. (2019)
11. What are the pros and cons of Industry 4.0?	Sony (2020)
12. What is the role of crowdsourcing in Industry 4.0?	Vianna et al. (2020)
13. What is the impact of energy consumption on the scope of i4.0?	Da Silva et al. (2020)
14. What is the status of Cybersecurity?	Lezzi et al. (2018)
15. What are the educational strategies adopted for teaching Additive Manufacturing?	Motyl and Filippi (2020)
16. What are the applications of i4.0 enabling technologies in the manufacturing companies?	Zheng et al. (2020)
17. What is the status of the research in smart factory?	Osterrieder et al., 2020
18. What is the status of the research in smart systems?	Romero et al. (2020)

Motyl and Filippi (2020) highlight that i4.0 radically transforms work, demanding an engineering professional with new skills, and that educational institutions are already incorporating subjects related to i4.0 into their programs. For this, investments in professors, technicians, and laboratory equipment are necessary.

Table 6 presents the competencies of this new engineering professional, grouped as proposed by Jerman et al. (2018).

Concerning maturity models, Hizam-Hanafiah et al. (2020) review thirty maturity models for i4.0. From the analysis of these models, the authors point out six main dimensions of evaluation: i) technology, ii) people, iii) strategy, iv) leadership, v) process, and vi) innovation, the first being the most important of them.

Mittal et al. (2018) searched fifteen different maturity models related to industry 4.0. The objective of their research was to identify models suitable for small and medium-sized enterprises (SMEs), which do not have a lot of resources. The authors find that the available models are not suitable for SMEs.

De Jesus and Lima (2020) also discuss maturity models, considering both generic models (companies of any size or sector) and specific models (size, sector, country, etc.). The authors point out the need for studies to guide companies in choosing the most appropriate maturity model for their needs.

4.1.5. Summary

In this first section, we discuss review articles that cover i4.0 in general. Table 7 summarizes the research questions presented in these articles.

4.2. Enabling technologies

Among the 46 systematic review articles researched, sixteen deal specifically with i4.0 enabling technologies. These articles address eleven enabling technologies: i) the internet of things (Liao et al., 2018; Ben-Daya et al., 2019), ii) cyber-physical production systems (Wu et al., 2020), iii) mobile technologies (Barata et al., 2018), iv) blockchain (Martins et al., 2019), v) cloud manufacturing (Wan et al., 2020), vi) big data analytics (Cui et al., 2020), vii) machine learning (Cadavid et al., 2020), viii) augmented reality and virtual reality (Egger and Masood, 2020; Guo et al., 2020), ix) reconfigurable manufacturing system (Bortolini et al., 2018), x) additive manufacturing (Franco et al., 2020; Florén et al., 2020), and xi) human-robot collaboration (Gualtieri et al., 2021; De Pace et al., 2020; Dobra and Dhir, 2020).

4.2.1. Internet of things

Ben-Daya et al. (2019) review the Internet of Things (IoT) application in supply chain management, covering its main processes: purchasing, production, sales, and distribution. The authors show that IoT has a stronger positive impact on production and distribution processes. However, security and interoperability are still two strong barriers to IoT spread.

Liao et al. (2018) present a research on the Industrial Internet of Things (IIoT). The IIoT function is to connect shop floor agents to planning and control systems so that the data collected can be analysed and used in decision-making. The authors point to the growth of IIoT research in China and the USA and its applications in the food, electronics, and vehicle industries.

4.2.2. Cyber physical production systems

As mentioned before, CPS monitor physical systems from digital copies, allowing for a decentralized and integrated decision-making process (Lu, 2017). The application of CPS in manufacturing gives rise to Cyber-Physical Production Systems - CPPS (Wu et al., 2020).

Wu et al. (2020) present a literature review in which they analyse the articles according to the following three stages of the CPPS's life cycle: i) concept development, ii) engineering development, and iii) post-development.

Based on the review, the authors propose a conceptual map of topics for future research on CPPS, emphasizing maturity models and analysis of the engineering development stage.

4.2.3. Mobile technologies

Barata et al. (2018) carried out a review focused on the application of mobile technologies (smartphones, tablets, etc.) in Supply Chain Management, which they called mobile Supply Chain Management (mSCM).

The authors classified the articles into three categories: i) technical, ii) managerial, and iii) applications. Technical articles address issues mainly related to connectivity to management systems. The second group addresses the impact of dissemination of these devices on management. Finally, the third one brings application examples, with prominence on the hospital service and pharmaceutical industry.

The main research opportunities identified by the authors are: i) updating of research in SCM, considering the use of mobile technologies, ii) case studies on mSCM, iii) regulation, iv) maturity models, and v) social and work aspects.

4.2.4. Blockchain

Blockchain (BC) is an information technology that uses distributed and interconnected databases, where records of operations are stored and shared reliably (Martins et al., 2019). According to the authors' review, research focuses on four application areas: i) manufacturing, ii) logistics, iii) autonomous transport, and iv) energy.

Most of these research papers are directed to the technical aspects of privacy and security, which still entail high costs and computational times. As most works deal with technical aspects, there is a need for more research on managerial aspects of the use of technology (Martins et al., 2019).

4.2.5. Cloud manufacturing

Wan et al. (2020) review cloud manufacturing (CMfg) in China, where the government policies 'Internet +' and 'Made in China 2025' served as the basis for the development of CMfg, which is still advancing slowly due mainly to the lack of knowledge of most potential industrial customers.

Cloud Manufacturing integrates the company's existing information systems with new technologies such as IoT and Big Data. The main barrier to use is related to the issue of data security for companies. Another point that deserves attention is the difficulty of real-time connection between agents on the factory floor and cloud management systems (Wan et al., 2020).

4.2.6. Big data analytics

Big Data Analytics (BDA) extracts information from a company's large databases relevant to decision-making in different management areas (marketing, logistics, production, purchasing, etc.).

Cui et al. (2020) point out that the construction of a BDA Platform includes nine components: i) data ingestion, ii) storage, iii) computation, iv) analytics, v) visualization, vi) workflow and dataflow, vii) data management, viii) infrastructure and deployment model and ix) cybersecurity.

Regarding future research, there are five promising directions: i) modelling and simulation, ii) connectivity and interoperability, iii) standardized big data platform design, iv) real-time big data analytics, and v) cybersecurity (Cui et al., 2020).

4.2.7. Machine learning

Machine Learning (ML) is an Artificial Intelligence (AI) problem-solving method based on algorithms (machine) that use new data for continuous improvement of the solving process (learning). Thus, ML can be used in various management activities, where the ability to learn with data updated in real-time allows reacting to deviations or unplanned events (Cadavid et al., 2020).

Cadavid et al. (2020) perform a systematic review on the use of ML with a focus on Production Planning and Control (PPC) and present an implementation roadmap with eleven steps. The authors showed that the most used ML-PPC techniques are Nearest Neighbours Search, Q-Learning, and Decision Trees. They highlight that research in this area is focused on self-management, self-regulation, and self-learning of production processes.

Other areas with application potential, such as sustainability, human-machine interaction, and product development, are still incipient. In addition, most research uses fictitious data due to the difficulty of accessing real data from companies (Cadavid et al., 2020).

4.2.8. Augmented reality / virtual reality

Augmented Reality (AR) is a technology that allows interaction between the human being and the machine and between the human being and smart manufacturing systems through the superposition of virtual elements to the vision of reality (Egger and Masood, 2020).

On the other hand, Virtual Reality (VR) is a technology that gives users various intuitive sensations by simulating mechanisms of the physical or imaginary world (Guo et al., 2020). AR and VR have different goals. While AR includes projections of content and complementary information from the real world, VR takes the user to a new environment created by the computer.

Egger and Masood (2020) present a review of research on AR, which is more advanced in the field of logistics and concentrated in Europe and Asia. The expectation is that there will be a rapid diffusion of AR due to the growing number of research in partnerships with companies. However, there are still challenges and limitations related to hardware (processing capacity) and software (usability).

Regarding VR, Guo et al. (2020) analyse its application in maintenance. The authors show that VR is a useful tool for optimizing maintenance processes, improving process efficiency and safety, and reducing operating costs. However, as an emerging technology, VR still has challenges, such as creating a more user-friendly and robust design.

4.2.9. Reconfigurable manufacturing system (RMS)

Reconfigurable manufacturing systems constitute a new manufacturing concept. Its main characteristic is self-organizing to quickly adjust to new manufacturing situations (Bortolini et al., 2018).

The authors show that there are five main streams of research related to RMS: i) conceptual research, ii) maturity, iii) performance analysis, iv) applications, and v) i4.0 interface.

The main studies are related to performance analysis and applications in the following areas: i) movement and storage systems, ii) physical space planning, iii) reconfigurable cell manufacturing, and iv) planning and control systems. On the other hand, assessing the degree of reconfigurability in line with the i4.0 goals still needs further research (Bortolini et al., 2018).

4.2.10. Additive manufacturing

Additive Manufacturing (AM) or 3D printing is a technology for the construction of a three-dimensional object from a digital model, which is obtained through additive processes, where the object is created by deposition of successive layers of material (Franco et al., 2020; Florén et al., 2020).

Franco et al. (2020) show that the reduction in the complexity of production processes and the greater diversity of products are proven effects of the adoption of AM, while the reduction in inventories and greater responsiveness are aspects that have not yet been proven.

Florén et al. (2020) review how AM affects business models in terms of production, distribution, innovation, and costs and discuss how companies are reacting to this new technology.

The authors identify that the adoption of AM is becoming increasingly viable, including the possibility of its use in larger-scale production. However, there is still a lack of research that proves the gains in inventory management and its applicability in different industrial environments.

4.2.11. Human robot collaboration

Three articles deal with the Human-Robot Collaboration (HRC). In HRC projects, the robot interacts with a human operator to carry out work activities on the workstation (Gualtieri et al., 2021; De Pace et al., 2020).

Gualtieri et al., 2021 review the safety and ergonomics issues that effectively allow the transposition of the HRC from the laboratories to the factory floor. The results show that the published studies are more related to safety aspects, especially in prevention than ergonomics (physical, cognitive and organizational aspects).

Dobra and Dhir (2020) classify research on HRC in manufacturing in the following dimensions: i) collaboration, ii) human factors, iii) complexity handling, iv) robot system safety and v) instructing the robot system. Finally, they suggest that future research seeks to improve communication between humans and robots and explore the relationship between people and robots. They also suggest more case studies on the application of the HRC in companies.

Finally, De Pace et al. (2020) make a more specific review, where they address augmented reality to improve interaction and collaboration between the worker and the robot. The authors indicate that the main advantages of using AR for HRC are greater speed and usability than traditional systems and reducing the physical workload. However, the tracking accuracy and field of view of wearable devices need to be improved. Studies are also needed to assess the effectiveness of this technology from user tests to better understand the usability and acceptability aspects of AR interfaces.

4.2.12. Summary

In this section, we reviewed articles that cover i4.0 enabling technologies. Table 8 summarizes the research questions asked in these articles. Some technologies covered in original works, such as cybersecurity and digital twin, have not yet been systematically reviewed and thus do not appear in this section.

Table 8
Research questions on enabling technologies.

Research Question	References
1. What is the impact of IoT on Supply Chain Management?	Ben-Daya et al. (2019)
2. What is the status of Industrial IoT?	Liao et al. (2018)
3. What is the impact of CPPSs on engineering life cycle of a production system?	Wu et al. (2020)
4. What is the status of Mobile Supply Chain Management?	Barata et al. (2018)
5. What is the status of Blockchain in manufacturing?	Martins et al. (2019)
6. What is the status of Cloud Manufacturing in China?	Wan et al. (2020)
7. What is the status of Big Data Analytics?	Cui et al. (2020)
8. What is the status of Machine Learning in Production Planning and Control?	Cadavid et al. (2020)
9. What is the status of the Augmented Reality?	Egger and Masood (2020)
10. What is the impact of Virtual Reality in Industrial Maintenance?	Guo et al. (2020)
11. What is the status of the Reconfigurable Manufacturing Systems?	Bortolini et al. (2018)
12. What is the status of the Additive Manufacturing?	Franco et al. (2020), Florén et al. (2020)
13. What is the status of Human-Robot Collaboration regarding Human Factors?	Gualtieri et al., 2021
14. What is the status of Human-Robot Cooperation in an Industrial Environment?	Dobra and Dhir (2020)
15. What is the impact of Augmented Reality on Human-Robot Collaboration?	De Pace et al. (2020)

4.3. Management innovation

In this section, we cover articles dealing with changes in industrial management functions for the i4.0 environment. We found only six review articles: four on production planning and control (Martins et al., 2020; Parente et al., 2020; Bueno et al., 2020; Jaskó et al., 2020), one on supply chain management (Chauhan and Singh, 2019) and, finally, one on predictive maintenance (Dalzochio et al., 2020).

4.3.1. Production planning and control

Industry 4.0 requires more agile, decentralized, and autonomous Production Planning and Control systems (Wang et al., 2017). Martins et al. (2020) present 14 Autonomous Production Control (APC) models. These models have been used mainly for scheduling tasks, aiming to minimize the time that orders remain on the shop floor.

Parente et al. (2020) highlight some technologies that are transforming production control in the smart factory. The authors point out as research opportunities: i) to understand how and to what extent decision-making can be decentralized; ii) how to overcome the challenges of human-machine interaction and self-scheduling; iii) explore new production scheduling methodologies.

More generally, Bueno et al. (2020) show the relationship between PPC and i4.0. First, they identify the i4.0 core technologies and the typical PPC activities. Then, based on a systematic literature review, they elaborate an influence matrix in which CPS, IoT, BDA, AI, CMfg, and AM stand out as key technologies for PPC activities.

As a result, Bueno et al. (2020) present eighteen smart capabilities and thirteen performance indicators to integrate PPC activities and i4.0 technologies. Furthermore, they emphasize that the nature of products, demand and processes are critical factors for this integration. Finally, the authors present a research agenda with ten topics related to PPC in the context of i4.0.

Regarding Production Control, Jaskó et al. (2020) present the i4.0 requirements for the new generation of Manufacturing Execution Systems (MES). MES is a class of advanced software that allows you to monitor, control and optimize manufacturing processes.

Based on the review of maturity models for i4.0, the authors highlight that computerization, connectivity, visibility, transparency, predictive capacity, and adaptability are the main requirements for the development of the MES. Thus, Jaskó et al. (2020) propose an ontology that includes concepts of production control and manufacturing digitalization (i4.0).

4.3.2. Supply chain management

Chauhan and Singh (2019) show that most research in i4.0 is directed to manufacturing and logistics and that the digitization of Supply Chain Management (SCM) is a topic of growing interest.

The authors present topics covered in the articles in this subject: i) conceptualization of i4.0 for SCM, ii) principles for implementing i4.0 in SCM, iii) digitalization outcomes, iv) performance of digitized supply chains, v) managing digitized supply chains, vi) drivers and barriers of i4.0 in SCM, vii) digitized supply chain practices and viii) collaborative engineering and customization.

Table 9
Research questions on management innovation.

Research Question	References
1. How can production scheduling evolve to i4.0?	Parente et al. (2020), Martins et al. (2020), Bueno et al. (2020)
2. How can supply chain management evolve to i4.0?	Chauhan and Singh (2019)
3. What are the challenges and questions regarding machine learning and reasoning for predictive maintenance in i4.0?	Dalzochio et al. (2020)
4. How can manufacturing execution systems evolve to i4.0?	Jaskó et al. (2020)

Regarding topics for future research, they point out: i) performance measurement, ii) planning and sourcing, iii) models to assess economic viability, iv) trade-off between cost-effectiveness and sustainable performance, v) quality management in digitized supply chains, and vi) industry-specific empirical studies.

4.3.3. Predictive maintenance

Dalzochio et al. (2020) discuss the main issues related to Machine Learning and Reasoning (ML) algorithms for Predictive Maintenance (PM) in the context of i4.0. The authors identify that these algorithms are already applied in various stages of PM, such as diagnosis, prognosis, and useful life estimation.

The authors show that BDA and ML are appropriate solutions to deal with reducing costs and increasing production efficiency from Predictive Maintenance. However, although there are many models proposed and applied in this area, none of them proved capable of dealing with the different scenarios existing in the industry.

4.3.4. Summary

Table 9 brings the research questions of the articles dealing with management innovation for i4.0. Like PPC, SCM, and Maintenance, other functions will be influenced and transformed in this industry digitization process. However, we did not identify systematic review articles dealing with these other functions or even industrial management more broadly.

5. Discussion

This section discusses the three research questions formulated in the introduction to this article, based on the descriptive and content analysis presented in Sections 3 and 4.

RQ.1. What are the literature reviews on i4.0?

The literature on i4.0 is relatively recent and has a considerable volume of publications in high-impact journals. This large production also resulted in a large number of published review articles. In the present study, we selected 46 review articles based on the following criteria: i) they must be a systematic literature review, and ii) they must address the i4.0 in the context of manufacturing.

The review shows a concentration of this production in journals in engineering and computer science, which is expected since these areas are responsible for developing the main enabling technologies for i4.0. There is also a preponderance of work from China, United States, United Kingdom, Italy, and Germany, countries whose governments were pioneers in developing policies for i4.0.

As a relatively new topic, the i4.0 literature is still dominated by publications of a conceptual nature, followed by articles on its enabling technologies, and finally, articles on management innovation. Many researchers develop new technologies with experiments carried out in laboratories, using prototypes and computer simulations, but practical applications studies in companies are still rare.

RQ.2. What are the research questions of these reviews?

The main research questions of the reviewed articles, presented in the previous section, focused first on mapping the state of research on i4.0, the critical factors, and the benefits of its implementation. Then, as it is the basis of i4.0, most articles deal with enabling technologies, analysing their maturity and applications.

Furthermore, although it is still an underexplored theme, we found six works dealing with management innovation, with a greater concentration on Production Planning and Control.

RQ.3. What are the main results of i4.0 reviews?

According to the analysis carried out in Section 4, the main result is related to the i4.0 research agenda. As already highlighted, as it is a recent theme, the vast majority of research is still conceptual in nature. Therefore, there is a need for practical research that validates many of the postulates in the literature.

We identified that i4.0 is marked by a high degree of digitalization, with factories made up of agents that interact intelligently and with decentralized processes control. The coordination of smart factories is provided by the IoT and by cyber-physical systems that, properly connected, have the capacity to generate and share data that can be used for good decision-making.

Regarding i4.0 enabling technologies, we observe that they are subdivided into six main groups: i) systems and automation, ii) networking and connectivity, iii) data science, iv) manufacturing technologies, v) robots, and vi) information technologies.

Some points, however, still need to be deepened, such as the hardware processing capacity, which still generates high costs, user interface improvements, and, above all, cybersecurity, to ensure privacy and data security for companies and customers of the platforms.

In management innovation, i4.0 produces new business models and consequently the need to understand how companies will reorganize themselves in the face of these new environments, also including SMEs, which do not have as much capital to invest in many of these technologies. This subject is still little explored, and further studies are needed to understand how these concepts should be adapted to different contexts (countries, cultures, and sectors).

In addition, i4.0 requires employees to acquire new skills to meet new demands in the labour market. Among the main characteristics of this professional are the ability to deal with new technologies, the ability to work in a team and to communicate well. However, these studies are still theoretical, where a practical study is important to validate the research by Jerman et al. (2018).

6. Conclusion

This article presents a tertiary literature review that analyses systematic review articles on i4.0 published in the Scopus and Web of Science databases.

We analysed 46 review articles, and then their 1542 cited references, presenting bibliometrics on authors, institutions, countries, journals, year of publication, keywords, and research focus. We then analysed the content of the review articles, which were divided into three categories: (i) articles on industry 4.0, (ii) articles on enabling technologies, and (iii) articles on operations management for i4.0.

The results confirm that i4.0 is an extensive and multidisciplinary subject, with works addressing conceptual, methodological, technological, and business issues. Overall, the review articles highlight the need for more applied research in organizations of different sizes and sectors.

This research has some limitations that are inherent to the research method. First, for selecting articles, only two article bases were considered (Scopus and Web of Science), and the selection was based on the evaluation of two researchers, which always entails some subjectivity. Despite this, we consider that the selected articles are well representative of the literature on i4.0.

A second limitation concerns the scope of the research. Initially, we had planned to address i4.0 applications in areas other than just manufacturing (e.g., logistics, healthcare, construction, cities, vehicles, etc.), which we classified as i4.0 extensions. As the volume of articles in this group is also substantial and there is a limitation on the size of this article, we decided to withdraw this content, which should be addressed in a second review article.

The last limitation refers to the identified research agenda. As this is a dynamic agenda, with articles published from 2017 onwards, some of the research opportunities may be surpassed. However, as these are recent articles, we believe that the results obtained are relevant. Future replication of this research may lead to partially different results due to the constant evolution of the i4.0 research.

Despite the limitations, we believe that this review represents the current state of research on i4.0 well and points out suggestions for future research based on the identified gaps. These gaps refer both to new systematic reviews on topics not covered and, mainly, empirical research in companies of different sizes and sectors. Analysis of the reviewed articles allows us to infer that the digital transformation in manufacturing and other important economic sectors is just beginning. There are still many issues and opportunities to be explored.

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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