

International Journal of Production Research

ISSN: 0020-7543 (Print) 1366-588X (Online) Journal homepage: http://www.tandfonline.com/loi/tprs20

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To cite this article: Yongxin Liao, Fernando Deschamps, Eduardo de Freitas Rocha Loures & Luiz Felipe Pierin Ramos (2017): Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal, International Journal of Production Research, DOI: 10.1080/00207543.2017.1308576

To link to this article: http://dx.doi.org/10.1080/00207543.2017.1308576

Published online: 28 Mar 2017.

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International Journal of Production Research, 2017
http://dx.doi.org/10.1080/00207543.2017.1308576

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Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal

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(*Received 18 October 2016; accepted 6 March 2017*)

Over the last few years, the fourth industrial revolution has attracted more and more attentions all around the world. In the current literature, there is still a lack of efforts to systematically review the state of the art of this new industrial revolution wave. The aim of this study is to address this gap by investigating the academic progresses in Industry 4.0. A systematic literature review was carried out to analyse the academic articles within the Industry 4.0 topic that were published online until the end of June 2016. In this paper, the obtained results from both the general data analysis of included papers (e.g. relevant journals, their subject areas and categories, conferences, keywords) and the specific data analysis corresponding to four research sub-questions are illustrated and discussed. These results not only summarise the current research activities (e.g. main research directions, applied standards, employed software and hardware), but also indicate existing deficiencies and potential research directions through proposing a research agenda. Findings of this review can be used as the basis for future research in Industry 4.0 and related topics.

Keywords: the fourth Industrial revolution; Industry 4.0; systematic literature review; qualitative research; quantitative research; research agenda

1. Introduction

In the realm of manufacturing, the advances of science and technology continuously support the development of industrialisation all around the world (Belvedere, Grando, and Bielli 2013). Though there is still no universal agreement on what constitutes an industrial revolution (Maynard 2015), from a technological evolution perspective, there are four stages commonly identified (Kagermann, Wahlster, and Helbig 2013). The first three industrial revolutions took around two centuries, and are the result of, respectively: (1) the introduction of water and steam-powered mechanical manufacturing facilities; (2) the application of electrically-powered mass production technologies through the division of labour; and (3) the use of electronics and information technology (IT) to support further automation of manufacturing (Drath and Horch 2014). In recent years, along with the increased research attention on the Internet of Things (IoT) (Atzori, Iera, and Morabito 2010) and Cyber-Physical Systems (CPS) (Khaitan and McCalley 2015), governments and industries worldwide have noticed this trend and acted to benefit from what this new industrial revolution wave could provide (Ridgway, Clegg, and Williams 2013; Siemieniuch, Sinclair, and Henshaw 2015): (i) From the government plans perspective,

- Since 2011 the United States (US) government began a series of national-level discussions, actions and recommendations, titled 'Advanced Manufacturing Partnership (AMP)', to ensure the US to be prepared to lead the next generation of manufacturing (Rafael, Jackson Shirley, and Liveris 2014).
- In 2012, the German government passed the 'High-Tech Strategy 2020' action plan, which annually sets billions of euros aside for the development of cutting-edge technologies. As one of the ten future projects in this plan, the 'Industrie 4.0' represents the German ambitions in the manufacturing sector (Kagermann, Wahlster, and Helbig 2013).
- The French government initiated a strategic review in 2013, named the 'La Nouvelle France Industrielle', in which 34 sector-based initiatives are defined as France's industrial policy priorities (Conseil national de l'industrie 2013).

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- In 2013, the United Kingdom (UK) government presented a long-term picture for its manufacturing sector until the year of 2050, called the 'Future of Manufacturing'. It aims to provide a refocused and rebalanced policy for supporting the growth and resilience of UK manufacturing over the coming decades (Foresight 2013).
- The European Commission lunched the new contractual Pubic-Private Partnership (PPP) on 'Factories of the Future (FoF)' in 2014. It is under the Horizon 2020 programme that plans to provide nearly 80 billion euros of available funding over 7 years (from 2014 to 2020) (European Commission 2016).
- In 2014, the South Korea government announced the 'Innovation in Manufacturing 3.0' that emphasised four propulsion strategies and assignments for a new leap of Korean manufacturing (Kang et al. 2016).
- The Chinese government issued the 'Made in China 2025' strategy alongside the 'Internet Plus' plan in 2015. It prioritises ten fields in the manufacturing sector to accelerate the informatization and industrialisation in China (Li 2015).
- In 2015, the Japanese government adopted the 5th Science and Technology Basic Plan, where particular attentions have been paid to the manufacturing sector for realising its world-leading 'Super Smart Society'. (Cabinet Office 2015)
- The Singapore government has committed $19 billion to its RIE 2020 Plan (Research, Innovation and Enterprise) in 2016. Eight key industry vertical have been identified within the advanced manufacturing and engineering domain (National Research Foundation 2016).

(ii) From the industrial plans perspectives, AT&T, Cisco, General Electric, IBM and Intel founded the 'Industrial Internet Consortium (IIC)' in 2014 to catalyse and coordinate the priorities and enabling technologies of the Industrial Internet (Evans and Annunziata 2012). Meanwhile, other big firms like Siemens, Hitachi, Bosch, Panasonic, Honeywell, Mitsubishi Electric, ABB, Schneider Electric and Emerson Electric have also already invested heavily in IoT and CPS related projects.

These driving forces have made the fourth industrial revolution become one of the most frequently discussed topics of many manufacturing conferences, forums and exhibitions in the past few years. Meanwhile, a fast growing number of research centres, universities and companies have also taken part and contributed to this new challenge through laboratory experiments (e.g. Smart Factory OWL[1]) or industrial applications (e.g. Digital Enterprise Software Suit,[2] by Siemens). Looking at all of these contributions from academia and industry and the broad range of different interests that they encompass a question arises: *after years of efforts, what is the current status of the fourth industrial revolution?* This work tries to answer this by systematically reviewing some of these contributions, according to procedures presented by Nightingale (2009) and Pickering and Byrne (2014) and explained in Section 2.

In the course of our systematic literature review, eighteen review and survey papers have been discovered within this context. They provided answers based on their own research interests and through applying different kinds of methods, such as Narrative Literature Review (Baumeister and Leary 1997; Green, Johnson, and Adams 2006), Systematic Literature Review (Nightingale 2009; Pickering and Byrne 2014), Interview Survey and Questionnaire Survey. However, some existing drawbacks can be noted.

Based on their research interests, it can be found that most of them focused on reviewing or surveying a domain specific research topic. For example, cloud technologies (Zhan et al. 2015), industrial wireless networks (Li et al. 2015), standards (Janak and Hadas 2015; Leitao et al. 2015), integration technologies (Bangemann et al. 2016; Schmidt, Luder, et al. 2015), virtual engineering (Shafiq et al. 2015), information systems (Haddara and Elragal 2015), company strategies (Sommer 2015; Wahl 2015), service provision (Rennung, Luminosu, and Draghici 2016), lifecycle models (Thoben et al. 2014), ubiquitous computing technologies (Chen and Tsai 2017) and agent-based technologies (Adeyeri, Mpofu, and Adenuga 2015). These reviews and surveys are not suitable as the answer to our main research question from a compressive perspective. (Schmidt, Möhring, et al. 2015; Hozdić 2015; Kang et al. 2016; Shrouf, Ordieres, and Miragliotta 2014) are the only ones that have intentions of providing a general review or survey related to this new industrial revolution. However, to our knowledge, the review of the current status is still not their main research focuses. In which, they are either paying attentions to analyse the experts' opinions about the possible influence factors (Schmidt, Möhring, et al. 2015), or focusing on the study of the important concepts related to smart factory (Shrouf, Ordieres, and Miragliotta 2014; Hozdić 2015) or smart manufacturing (Kang et al. 2016).

Based on their review or survey methods, it can be found that besides two Interview Surveys (Haddara and Elragal 2015; Rennung, Luminosu, and Draghici 2016) and one Questionnaire Survey (Schmidt, Möhring, et al. 2015), most of them (Shrouf, Ordieres, and Miragliotta 2014; Thoben et al. 2014; Zhan et al. 2015; Li et al. 2015; Janak and Hadas 2015; Leitao et al. 2015; Schmidt, Luder, et al. 2015; Shafiq et al. 2015; Sommer 2015; Wahl 2015; Hozdić 2015; Bangemann et al. 2016; Chen and Tsai 2017; Kang et al. 2016) applied the Narrative Literature Review method. This type of review method is capable of critiquing and summarising a body of literature and drawing conclusions about their

research topics (Cronin, Ryan, and Coughlan 2008). However, it is commonly recognised as more subjective (e.g. based on the experience of the author) (Cipriani and Geddes 2003), difficult in data reproduction (e.g. lack of an explicit methodological approach description) (Rother 2007), and, sometimes, the absence of a quantitative analysis (Pickering and Byrne 2014). Among them, (Adeyeri, Mpofu, and Adenuga 2015) is the only one that applies the systematic literature review method. However, it is specifically focusing on reviewing the agent-based technologies.

Therefore, in order to provide a more appropriate answer to the stated main research question, the objective of our work is to review and analyse the academic progresses of the fourth industrial revolution in a systematic manner. This paper will present this systematic literature review within the Industry 4.0 subject as the first stage result of a larger research effort that will include reviews in other high-level projects and plans related to the fourth industrial revolution around the world (like the Industrial Internet in the US). More specifically, four research sub-questions are listed as follows:

(1) Which are the enabling features of Industry 4.0?
(2) Who is working on Industry 4.0, when and where?
(3) What are the main research directions and the current research efforts?
(4) What are the existing Industry 4.0 application fields?

The rest of this paper is organised as follows. Section 2 presents the systematic literature review method and the fundamental review principles. Section 3 illustrates and discusses the obtained results from both the general data analysis of included papers (providing a general overview of the topic) and the specific data analysis corresponding to each research sub-question (providing specific insights related to what is being researched) – the 'past' and the 'present' in this paper's title. Based on the results, Section 4 presents a general research agenda for research in Industry 4.0 and related topics – the 'future' in this paper's title. Section 5 concludes this paper and points out the following stages.

2. Principles and methods

2.1 *Review principles*

To ensure that all papers could be consistently assessed with less subjective opinions, three fundamental review principles were defined:

- *Explicit inclusion and exclusion criteria*. The criteria for including or excluding collected papers should be explicitly outlined. In this paper, as can be seen in Table 1, six main inclusion and exclusion criteria, together with their subsets have been outlined.

Table 1. Inclusion and exclusion criteria and their explanations.

I/E	Criteria	Criteria explanation
Exclusion	Search engine reason (SER)	A paper has only its title, abstract, and keywords in English but not its full-text
	Without full-text (WF)	A paper without full text to be assessed
	Non-related (NR)	NR-1: A paper is not an academic article. For example, editorial materials, conference reviews, contents, or forewords NR-2: The definition about 'the fourth industrial revolution' is not related to IoT and CPS
	Loosely related (LR)	A paper doesn't focus on the review, survey, discussion, or problem solving of industry 4.0. In which, LR-1: Industry 4.0 is *only* used as an example fact LR-2: Industry 4.0 is *only* used as a part of its future research direction, future perspective or future requirement LR-3: Industry 4.0 is *only* used as a cited expression LR-4: Industry 4.0 is *only* used in keywords and/or references
Inclusion	Partially related (PR)	PR-1: A research about the fourth industrial revolution without mentioning Industry 4.0 PR-2: Industry 4.0 is *only* used to support the description of some challenges, issues, or trends that a paper intends to deal with PR-3: Industry 4.0 is *one of several* objects that to be reviewed, surveyed, or discussed
	Closely related (CR)	The research efforts of a paper are explicitly and specifically dedicated to Industry 4.0

- *Objective review strategy*. Each collected paper should be reviewed by at least two examiners (collaborators of the research that have a working knowledge of Industry 4.0 and its meaning) for its inclusion or exclusion. Each cluster that summarised collected data should be reviewed by at least two examiners for its applicability. In both cases, if two examiners cannot reach consensus, a third examiner will make the final decision.
- *Data collection with evidences*. For the collection of particular data that require subjective judgments (e.g. which potential area for action that an included paper put its main focus on?), the original supporting text descriptions of the paper should also be gathered as notes into the database.

2.2 *Systematic literature review method*

In the past few years, different kinds of Industry 4.0 academic contributions were proposed based on their own requirements. In order to provide a neutral data collection and analysis in this outcome unpredictable situation (Bryman 2006) and also to enhance the statistical and graphical data descriptions (Curry, Nembhard, and Bradley 2009), this research is conducted by applying the systematic literature review method through a mixed-methods approach (both the qualitative research method (Curry, Nembhard, and Bradley 2009) and the quantitative research method (Pickering and Byrne 2014)). Furthermore, this paper is structured by following the method outlined in the Preferred Reporting Items for Systematic review and Meta-Analysis (PRISMA) Statement (Moher et al. 2009). The PRISMA flow chart that reports the different phases of this systematic literature review is shown in Figure 1.

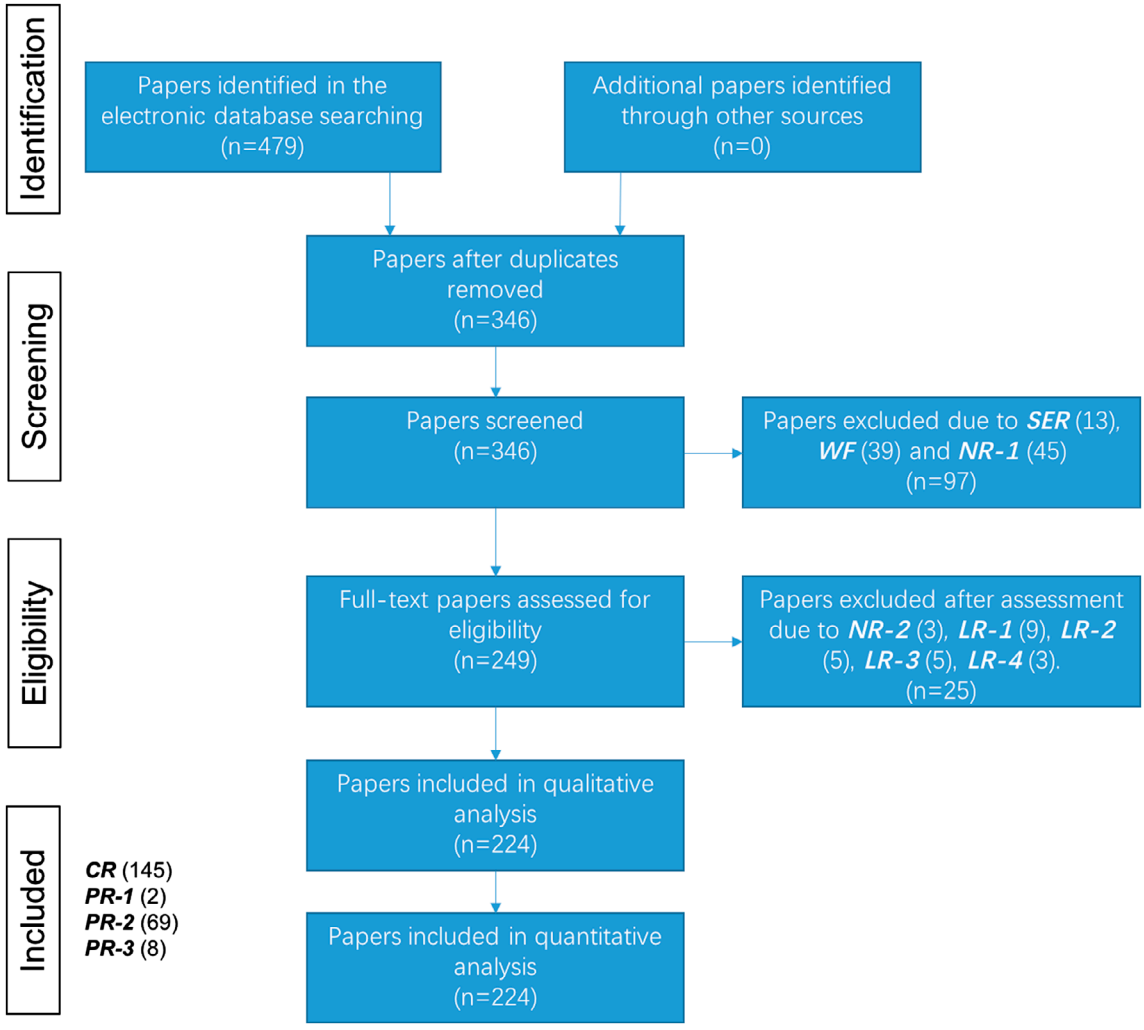


Figure 1. The PRISMA flow chart that reports the different phases of the systematic literature review.

2.2.1 *Paper collection*

To obtain a comprehensive set of papers, the search string was constructed through the combination of the operator 'or' in between each two of the following four terms: 'the fourth industrial revolution', 'the 4th industrial revolution', 'Industry 4.0' and 'Industry 4.0'. The systematic search used three electronic databases, namely *Web of Science*, *SCOPUS*, and *Science Direct*, to collect academic research papers that: (1) were published online before the end of June 2016; (2) contained at least one of the identified terms in either the abstract, title and keywords; (3) were published in journals, conference proceedings or book series; (4) were written in the English language.

After removing duplicates, the first screening process was carried out to exclude for which (1) there was no access to their full texts (*WF*); (2) had only their titles, abstracts, and keywords in English (*SER*); or (3) were not academic articles (*NR-1*). Then, all the papers that passed the initial screening process were briefly reviewed by reading their titles, abstracts or, if more information to conclude about its inclusion or exclusion was needed, full texts. This second screening process was employed to exclude papers that (1) define 'the fourth industrial revolution' out of the scope of this work (*NR-2*); or (2) do not focus on Industry 4.0 research (*LR-1* − *LR-4*). Finally, all eligible papers were studied in detail and classified into diverse sub-categories of the inclusion criteria (*CR* and *PR-1* − *PR-3*).

2.2.2 *Data collection*

For each included paper, two types of information were collected and entered into the database.

The first type is basic data about the papers, which include: (1) *paper titles*, (2) *paper keywords*, (3) *electronic databases* where papers can be found, (4) their *source-based categories* (e.g. from a *journal* or a *conference*) and related information. For a journal paper, *journal titles*, *journal categorizations* based on SCImago[3], and the *journal impact factors* (2015) based on the Thomson Reuters impact factor[4] were collected. For a conference paper, *conference names* and *conference years* were collected. Moreover, each paper was also classified according to the following four *content-based categories*:

- *Review or Survey*, which presents a review or survey related to Industry 4.0 as its main content.
- *Discussion*, which presents a discussion of challenges, issues or trends within Industry 4.0 as its main content without a comprehensive solution.
- *Theoretical Solution*, which identifies Industry 4.0 research problems and proposes some conceptual or theoretical solutions, but without any laboratory experiments or industrial applications.
- *Practical Solution*, besides the conceptual or theoretical solutions, a laboratory experiment or an industrial application is also provided as part of its contribution.

The second type is specific data related to the four research sub-questions, which include:

- For *Q1* 'Which are the enabling features of Industry 4.0?', the data collected from included papers are: (1) *text descriptions* (sentences in the title, abstract, and main body of a paper) that contain either 'Industry 4.0' or 'Industrie 4.0', and (2) *references* of the paper that contain either 'Industry 4.0' or 'Industrie 4.0' in their titles.
- For *Q2* 'Who is working on Industry 4.0, when and where?', the data collected from included papers are: (1) *authors*, (2) *publication years*, (3) *institutions* to which paper authors belong, and (4) *geographical locations* of these institutions.
- For *Q3* 'What are the main research directions and the current research efforts?', the data collected from included papers are: (1) *research objects* (e.g. robots, production data or workers) included in each paper, and (2) *research purposes* (e.g. guaranteeing the security during the human-machine collaboration) focused by each included paper.
- For *Q4* 'What are the existing Industry 4.0 application fields?', the data are specifically collected from those papers classified as *Practical Solutions*: (1) *standards* that were mentioned and (2) *software* and *hardware* that were employed. In the case it is an industrial application, (3) the corresponding *industry information* was also investigated.

2.2.3 *Data analysis*

Finally, collected data were analysed through applying both qualitative and quantitative methods. More specifically, before the quantitative analysis, such as statistical and graphical data descriptions, the following three procedures were carried out to qualitatively pre-process collected data.

2.2.3.1 *Data 'denoising'.* A pre-processing step is performed to unify data expressions due to the fact that: (1) *references* from *Q1* might be presented in different formats; (2) *authors*, *institutions* and *geographical locations* from *Q2* might be presented in different languages or in the form of abbreviations; and (3) *standards*, *software* and *hardware* from *Q4* might be presented through their synonyms, abbreviations or singular/plural forms.

2.2.3.2 *Qualitative data clustering.* This analysis method is accomplished through a close examination of the collected data to: (1) understand its contextual meanings (e.g. *paper keywords* from *basic data collection*); and (2) discover its original objectives and usages (e.g. *standards*, *software* and *hardware* from *Q4*). Then, based on the obtained knowledge, collected data were clustered into groups.

2.2.3.3 *Qualitative data analysis.* The tool named ATLAS.ti[5] was initially employed to extract word frequencies within *text descriptions* from *Q1*. Next, some specific words were excluded from the list, such as prepositions (e.g. in, from, by), definite and indefinite articles (e.g. a, an, the) and pronouns (e.g. that, this, it). Next, besides the word 'industry', 'industrie', and '4.0', the top 25 nouns (each noun counts both in its singular and plural formats) and adjectives in the final frequency list were used to perform automatic sentence coding. Then, for each code, the first three co-occurrence words were used to construct meaningful noun phrases. Finally, the top 10 noun phrases more closely related to Industry 4.0 were summarised based on their frequencies.

3. Characterisation of industry 4.0 current research

According to the six main inclusion and exclusion criteria and their subsets presented in Table 1, the number of papers that are included or excluded are shown in Figure 1 according to the PRISMA flow chart. In the end, 224 papers out of 346 potential ones entered the data collection stage for qualitative and quantitative analysis. This section first presents the basic data analysis to provide an overall picture of included papers (Section 3.1), then gives corresponding answers to each research sub-question (Section 3.2).

3.1 *Basic data analysis: an overview of included papers*

Firstly, based on the *electronic databases* that papers were collected, it was discovered that, among the 224 included papers, 90.2% of them (202 papers) can be found in the *Scopus* reference database. Included papers that can only be found in the *Science Direct* reference database, in the *Web of Science* reference database, or in both amount to 4.5% (10 papers), 4.9% (11 papers), and 0.4% (1 paper) respectively.

Secondly, according to the *content-based categories*, 18 of the included papers (8.0%) are classified as *Review or Survey* papers, which have already been introduced and analysed in Section 1. For the rest, 42 papers (18.8%) fall into *Discussion* category, 61 papers (27.2%) are classified as *Theoretical Solution* and 103 papers (46%) belong in *Practical Solution* category.

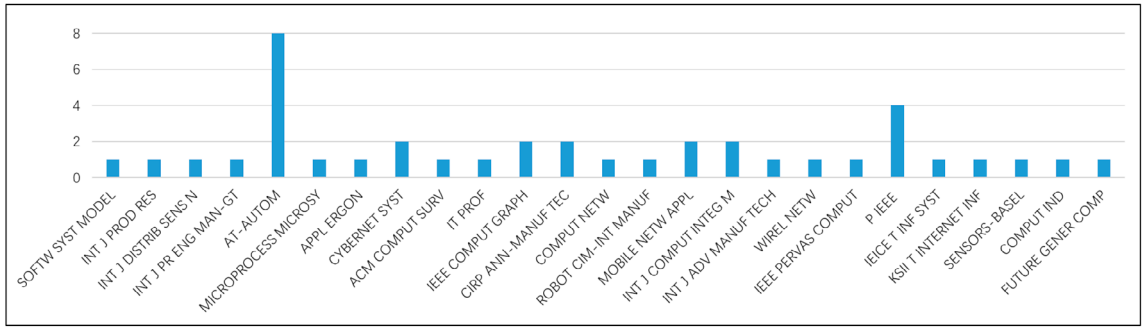
Thirdly, a more detailed investigation was carried out to analyse (1) the included *journal* and *conference* papers (Section 3.1.1), and (2) the *paper keywords* (Section 3.1.2).

3.1.1 *The analysis of journal and conference papers*

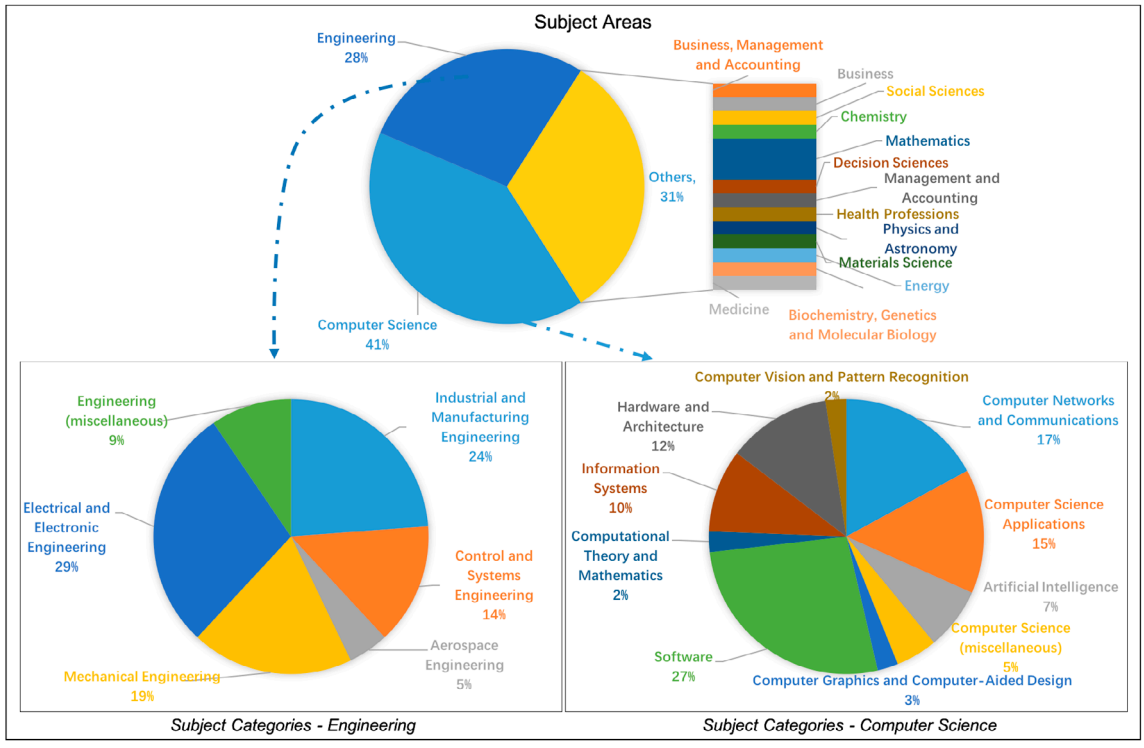
The data of the *source-based categories* were collected with respect to the real and original source of a paper. It means that even though some conference proceedings are classified as journals according to the electronic database search, such as the Procedia CIRP in the *Science Direct*, those papers are still categorised as the conference papers. Therefore, around 29% of the included papers (64 papers) are identified as papers from journals and the other 71% (160 papers) are categorised as conference papers.

According to the *impact factors* and *journal titles*, it was found that, among the 64 included journal papers, only 62.5% of them (40 papers) were published in journals with the 2015 Thomson Reuters Impact Factor (IF). As can be seen in Figure 2(a), the bar chart displays 25 different journals together with the number of included papers published. 'AT-AUTOM' (AT-Automatisierungstechnik, a German journal with IF 0.212) and 'P IEEE' (Proceedings of the IEEE, a United States journal with IF 5.629) are currently two of the most frequent journals for Industry 4.0 research, making up 20% (8 papers) and 10% (4 papers) of the total journal papers with IF respectively.

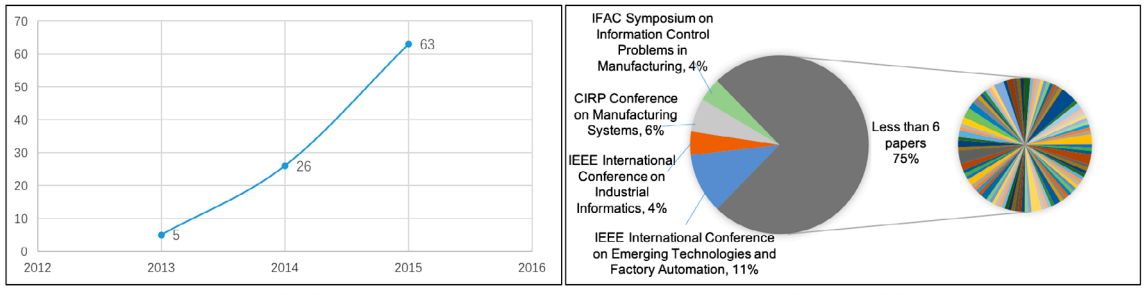
Based on the *journal categorizations*, the pie charts in Figure 2(b) illustrate the coverage of Subject Areas (on the top) and two detailed Subject Categories (on the bottom) for the 25 journals from Figure 2(a). It can be seen that Computer Science (41%) and Engineering (28%) are the two most prominent subject areas for Industry 4.0 research.



(a) Number of Included Papers in Each Different Journal with an IF



(b) Journal Categorizations (SCImago) based on Each Different Journal with an IF



(c) Number of Conferences by Year (d) Number of Papers in Different Conferences

Figure 2. Basic data analysis of included journal papers and conference papers.

To be more specific, on one hand, the categories of Software (27%), Computer Networks and Communications (17%) and Computer Science Applications (15%) are ranked as the top three in the Computer Science area. On the other hand, the categories of Electrical and Electronic Engineering (29%), Industrial and Manufacturing Engineering (24%), and Mechanical Engineering (19%) accounted for the highest three in the Engineering area.

According to the *conference names* and *conference years*, as can be seen in Figure 2(c), there is a gradual increase in the number of conferences related to Industry 4.0 from 2013 (5 conferences) to 2015 (63 conferences). More specifically, Figure 2(d) illustrates four conferences with more Industry 4.0 publications. The IEEE International Conference on Emerging Technologies and Factory Automation (ETFA) is the one with most included papers published (5 papers in 2014 and 13 papers in 2015). The CIRP Conference on Manufacturing Systems (CIRP- CMS) is ranked the second, with 3 papers in 2014 and 7 papers in 2015. After them, the IEEE International Conference on Industrial Informatics (INDIN) and the IFAC Symposium on Information Control Problems in Manufacturing (INCOM) are tied for the third place, the former with 2 papers in 2013, 2 papers in 2014 and 3 papers in 2015, and the latter with 7 papers in 2015. Based on the main themes of these four conferences, several related research topics can be identified: (1) intelligent manufacturing and automation technologies, (2) enabling technologies for the factories of the future, (3) industrial informatics and their applications, and (4) advanced information and manufacturing systems for a sustainable economy.

3.1.2 *The analysis of paper keywords*

A keyword represents a significant concept that is addressed in the content of a paper. The analysis of *keywords* that are explicitly mentioned in included papers was carried out to provide a preliminary glance of research focuses, research areas, enabling technologies, employed standards and Industry 4.0 related features. The 967 collected keywords were firstly examined and grouped into corresponding clusters. For example, the keywords 'Cyber-Physical System(s)', 'CPS (s)', 'Industrial Cyber-Physical System(s)', 'Cyber-Physical Production System(s)', 'CPPS', 'Cyber-Physical Sensor System(s)', 'Cyber-Physical Human System(s)', 'Cyber Physical Assembly System(s)' and 'Cyber-Physical System Platform(s)' were grouped into the cluster of Cyber Physical System.

Clusters were identified by grouping keywords with closely related meaning. Out of the 56 main clusters, the top 5 clusters are Industry 4.0 (127 keywords), Cyber Physical System (61 keywords), Manufacturing (44 keywords), Smart Factory (30 keywords) and Internet of Things (25 keywords), which cover 29.7% of the total keywords. More specifically, the generated clusters are studied and quantitatively measured, and grouped in the following five categories.

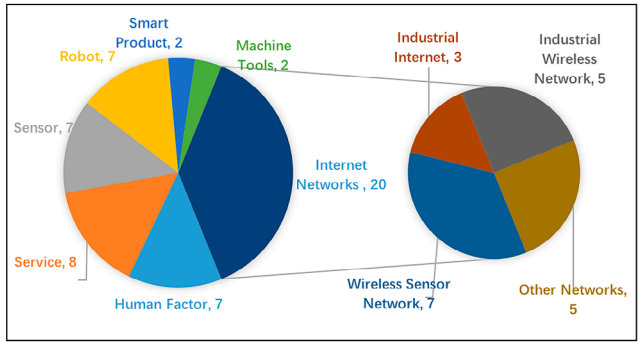
3.1.2.1 *Main components of a smart factory category.* Main components of a smart factory category as can be seen in Figure 3(a), Internet Networks play a key role in smart factories, in which Wireless Sensor Networks and Industrial Wireless Networks are two main research focuses. Despite this, more balanced efforts can be found in the Service, Human Factor, Sensor and Robot components, which have a closer frequency of occurrence. By contrast, less attention was drawn to the Smart Product and Machine Tool components, which occur less.

3.1.2.2 *Product life cycle category.* Figure 3(b) illustrates the keyword clusters that are related to different phases along the Product life cycle (PLC). On one hand, as it is expected (Kagermann, Wahlster, and Helbig 2013), Manufacturing is the main keyword cluster. In which, Assembly, Manufacturing System, Smart Manufacturing, Manufacturing (used directly as a keyword) and Production were the five most frequent sub-clusters. On the other hand, one can infer that less efforts have been directed towards research related to the clusters of Maintenance, Logistics, User Experiences and Supply Chain.

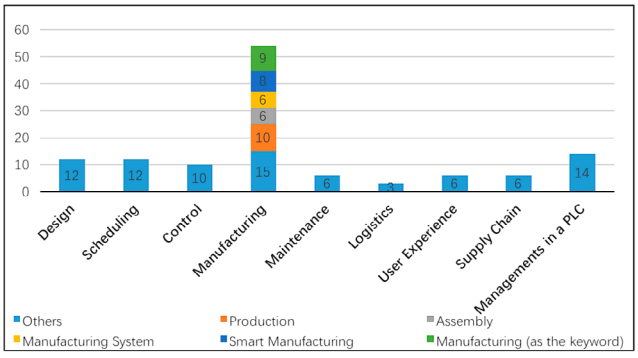
3.1.2.3 *Standards category.* Figure 3(c) illustrates the keyword clusters about the standards that are used in Industry 4.0 research. It was discovered that, most of the standards are related to interoperability or network communication. The Open Platform Communications (OPC), OPC Unified Architecture (OPC-UA), IEEE 1588 (Precision Time Protocol), and IEC 62,439 (Industrial Communication Networks - High Availability Automation Networks) are the four most frequently employed ones.

3.1.2.4 *Enabling technologies category.* Enabling technologies category as can be seen in Figure 3(d), several different technologies have been applied to support the realisation of Industry 4.0. The Modelling Technology and the Virtualization and Visualisation Technology are the two most frequent keyword clusters. In the first cluster, keywords related to the data modelling represent 41.7% of the total (10 keywords). In the second cluster, augmented reality (5 keywords) and virtual reality (3 keywords) are the two most frequently mentioned technologies. In comparison, technologies related to Machine Learning, 3D Printing, and Natural Language Processing appeared to be less frequent.

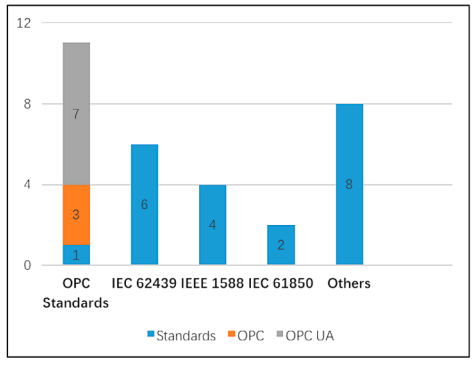
3.1.2.5 *Features Category.* Figure 3(e) provides information on the related features of Industry 4.0. It was discovered that current research efforts were mainly directed to support: (1) from the process/action perspective, Automation (e.g. Industrial Automation), Integration (e.g. System Integration), Collaboration (e.g. Human-Machine Interaction); and



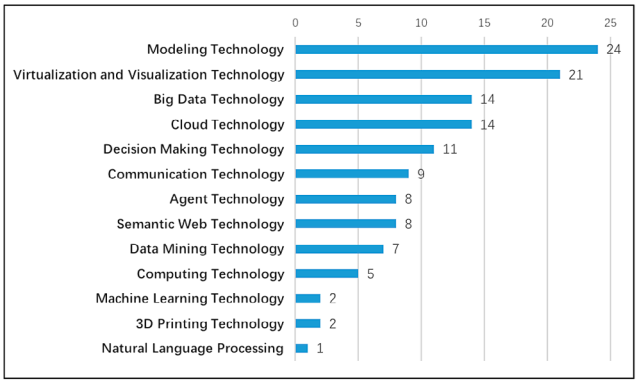
(a) Keywords Related to Different Components of a Smart Factory



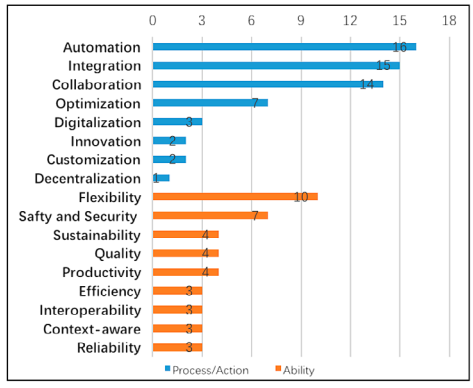
(b) Keywords Related to Different PLC Phases



(c) Keywords Related to Standards



(d) Keywords Related to Enabling Technologies



(e) Keywords Related to Industry 4.0 Features

Figure 3. Analysis of keywords clusters according to their categories.

(2) from the ability perspective, Flexibility (e.g. Plug-and-Work) and Safety and Security (e.g. privacy). By contrast, several other features of Industry 4.0, such as Innovation, Customisation, and Decentralisation, didn't receive sufficient attention.

3.2 *Data analysis with specific purposes: four research sub-questions*

3.2.1 *Which are the enabling features of Industry 4.0?*

The data analysis of this research sub-question is divided into two parts: (1) the classification and quantitative measurement of *references*, and (2) the qualitative data analysis of *text descriptions*.

3.2.1.1 *The analysis of references.* The analysis of *references* containing either 'Industry 4.0' or 'Industrie 4.0' in their titles inside included papers can provide an overall summarisation about the common agreed Industry 4.0 citations.

There are 436 collected references in total, which were firstly reformatted into a unified expression. Through this data denoising process, 176 different references were discovered, which were studied and quantitatively analysed according to the following two perspectives.

From the academic perspective: based on their sources, Figure 4(a) shows the proportion of the six main generated publication clusters. On one hand, the Journal and Conference Papers, Book Chapters, and Books clusters are seen as more academic, covering roughly less than half of the total references. On the other hand, the clusters of Magazine Papers and Contents from Websites are considered to be less academic, but still occupied around one third of the total references.

From the frequency perspective: as can be seen in Figure 4(b), the English version (64 times) and German version (27 times) of the Industry 4.0 working group final report (Kagermann, Wahlster, and Helbig 2013) is the most cited reference. More than 40% of the included papers used it to support their Industry 4.0 descriptions. After it, seven references: 2 papers from journals (Brettel et al. 2014; Drath and Horch 2014), 1 white paper (Hermann, Pentek, and Otto 2015), 2 reports (Spath et al. 2013; Roland-Berger 2015), 1 conference paper (Lee, Kao, and Yang 2014), and 1 book (Bauernhansl, ten Hompel, and Vogel-Heuser 2014). They were cited from 8 to 17 times. The remaining references, were cited less frequently, with an average of 1.6 times.

3.2.1.2 *The analysis of text descriptions.* As it is pointed out in psychology research (Bullinaria and Levy 2007), statistics of same sentence word co-occurrence, which typically express some specific relations, can be used as a basis for semantic representations. The analysis of *text descriptions* (the sentences), which contain either 'Industry 4.0' or 'Industrie 4.0', can provide a summarisation of the terms that are closely related to Industry 4.0. There are 2,169 collected sentences. From an average point of view, each included paper contains around 10 sentences that directly describe Industry 4.0. However, in reality, two extremes exist. 6.7% of the included papers (15 papers) contain more than 30 sentences, whereas 40.6% of the included papers (91 papers) contain 3 or less sentences.

As can be seen in Table 2, the three columns on the left show the 25 most frequent words, their frequency, and their share considering the total number of words from the collected sentences. The three columns on the right show the top 3 words co-occurring with the word in the first column form the collected sentences. Based on their combinations, the top 10 meaningful noun phrases (with their counts) were summarised. First of all, commonly recognised terms that are always associated with Industry 4.0 appear, such as *Cyber Physical Systems* (147), *Smart Factories* (132), *Industrial Revolutions* (108) and *Internet of Things* (101). Next, terms like *Production Systems* (76), *Manufacturing Systems* (43), *Smart Manufacturing* (37), *Production Processes* (26) and *Cyber Physical Production Systems* (25) prove that the manufacturing sectors are really the main research areas of Industry 4.0. Finally, the *Industrial Internet* (60), which is commonly associated with the United States' effort, was the most frequently used term that to be enumerated or compared with Industry 4.0. Additionally, a further investigation was carried out to discover other possible related noun phrases based on those frequent words that are missing in the above-mentioned terms. It turns out that, several interesting noun phrases emerged: Some are more general terms, such as *Industry 4.0 Contexts* (87), *Industry 4.0 Concepts* (46) and *Industry 4.0 Technologies* (31). Others are more specific terms, such as *Big Data* (69) and *Horizontal Integration* (25). Though they have not appeared in the top 10 noun phrases, they still appear 25 times or more.



(a) Proportions of the Six Reference Clusters

(b) Frequency of References (More Than 5 Times)

Figure 4. Analysis of references from the academic and frequency perspectives.

Table 2. Top 25 most frequent words related to Industry 4.0 and words they co-occur with.

Word	Count	% (relative frequency)	Co-occurrence words		
			1st	2nd	3rd
System(s)	506	0.933	Physical	Cyber	Production(s)
Production(s)	380	0.700	System(s)	Process(es)	Industrial
Manufacturing	344	0.634	System(s)	Industrial	German
Industrial	340	0.627	Revolution	Internet	System(s)
Technology(ies)	295	0.544	System(s)	Industrial	Manufacturing
Smart	264	0.487	Factory(ies)	System(s)	Manufacturing
Physical	243	0.448	Cyber	System(s)	Industrial
Factory(ies)	243	0.448	Smart	System(s)	Production(s)
Data	229	0.422	System(s)	Technology(ies)	Manufacturing
Concept(s)	219	0.404	System(s)	Technology(ies)	New
Internet	215	0.396	Thing(s)	Industrial	System(s)
Process(es)	211	0.389	Production(s)	System(s)	Manufacturing
Cyber	203	0.374	Physical	System(s)	CPS(s)
New	200	0.369	System(s)	Industrial	Technology(ies)
Integration(s)	173	0.319	System(s)	Manufacturing	Production(s)
CPS(s)	135	0.249	System(s)	Physical	Cyber
Context(s)	130	0.240	System(s)	Production(s)	New
Research(es)	129	0.238	German	Industrial	System(s)
Revolution(s)	128	0.236	Industrial	Manufacturing	System(s)
Information	125	0.230	Technology(ies)	System(s)	Production(s)
Business(es)	125	0.230	New	Process(es)	Values
Value(s)	123	0.227	System(s)	Business(es)	Integration(s)
German	122	0.225	Manufacturing	Industrial	System(s)
Paper(s)	119	0.219	System(s)	Concept(s)	Production(s)
Thing(s)	115	0.212	Internet	System(s)	Industrial

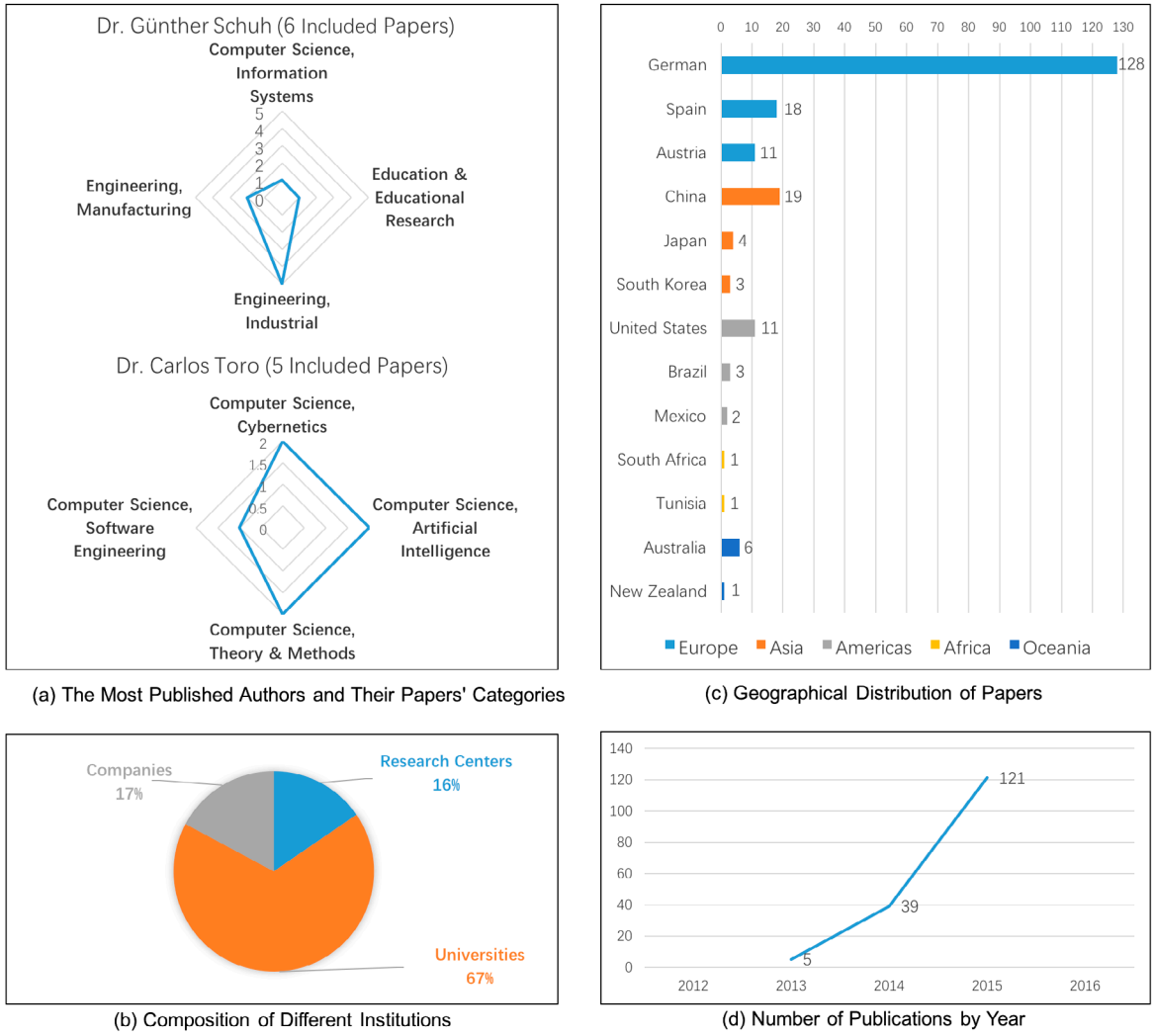
3.2.2 *Who is working on Industry 4.0, when and where?*

The data analysis for this research sub-question can provide a summary of the authors, institutions and their geographical locations that are involved in Industry 4.0 research in recent years. Based on this investigation, it was discovered that, Germany is not the only country that promotes Industry 4.0. Its influence has already been spread firstly in European countries, and then all around the world. More specifically, the answer to this question is divided into the following four perspectives.

3.2.2.1 *From the contributor perspective.* Inside the 224 included papers, there are 641 different authors. However, most of them (86.0%) have just authored one paper. There are only a few of them (3.6%) that were involved in four or more papers. In which, Dr Günther Schuh from the RWTH Aachen University and Dr Carlos Toro from the Vicomtech-IK4 research centre published the most papers. Based on paper categorisation from the *Web of Science*, as can be seen in Figure 5(a), the former authored one journal paper and five conference papers whose main focus is on Industrial Engineering. The latter authored three journal papers and two conference papers are in the research area of Computer Science.

3.2.2.2 *From the institutional perspective.* There are 233 different collected institutions in total. As can be seen in Figure 5(b), current Industry 4.0 academic research is lead by universities (around two-thirds), with the collaboration from companies and research centres. Based on the number of publications, it was discovered that the RWTH Aachen University (19 papers), the Fraunhofer IOSB (Institute of Optronics, System Technologies and Image Exploitation) (10 papers), and the Siemens AG (3 papers) are the three most prominent university, research centre, and company, respectively.

3.2.2.3 *From the geographical location perspective.* Firstly, more than 83.0% of the included papers (186 papers) involved institutions from Europe. Secondly, Asian institutions participated in 13.8% of the included papers (31 papers). Then, they are followed by contributions of institutions from the Americas, Africa and Oceania, which account for



(a) The Most Published Authors and Their Papers' Categories

(c) Geographical Distribution of Papers

(b) Composition of Different Institutions

(d) Number of Publications by Year

Figure 5. Analysis of researches, institutions, geographical locations and publication years.

around 8.9% (20 papers), 0.9% (2 papers), and 3.1% (7 papers), respectively. In particular, as can be seen in Figure 5(c), the top two or three countries ranked by the number of publications from each continent are illustrated. As the initiator of Industry 4.0, it is expected that most of the included papers involve institutions from Germany (57.1%). Spain and Austria come next, as two of the European countries that were affected the most by this new industrial revolution wave. Despite this, it was discovered that, as one of the world manufacturing centres, China has also shown a great interest in Industry 4.0 research. By contrast, the countries from the Americas, Africa and Oceania, exception made to the United States and Australia, are just currently starting to draw attention to Industry 4.0.

3.2.2.4 *From the year of publication perspective.* Even though the announcement of the Industry 4.0 concept traces back to the April of 2011, it began to attract attentions only after it became one of the ten official projects within the 'High-Tech Strategy 2020' action plan in March of 2012. Afterwards, as can be seen in Figure 5(d), there is a dramatic increase in the number of Industry 4.0 publications from 2013 (5 papers) to 2015 (121 papers). To our knowledge, because of these governmental driving forces, more and more academic research efforts are expected to continually appear, at least, in the next five years.

3.2.3 *What are the main research directions and the current research efforts?*

According to the analysis presented in Section 3.2.1, the final report of the Industry 4.0 working group (Kagermann, Wahlster, and Helbig 2013) is currently the most cited and recognised Industry 4.0 reference. Although there is a need

for a more detailed roadmap regarding the realisation of Industry 4.0, it clearly points out three necessary *integration features* and eight *priority areas for action*. Based on it, the collected data (*Research Objects* and *Research Purposes*) from included papers are used to analyse and classify the current research efforts into corresponding research directions.

To be more specific, the brief summary of each integration feature and each priority area for action is provided (Kagermann, Wahlster, and Helbig 2013). Regarding the three Necessary Integration Features:

- *Horizontal Integration*: integration of the various IT systems used in the different stages of the manufacturing and business planning processes within a company (e.g. inbound logistics, production, outbound logistics, marketing) and between several different companies (value networks).
- *Vertical Integration*: integration of the various IT systems at the different hierarchical levels (e.g. actuator and sensor level, manufacturing and execution level, production management level, and corporate planning levels) to deliver an end-to-end solution.
- *End-to-End Digital Integration*: integration throughout the engineering process so that the digital and real worlds are integrated across a product's entire value chain and across different companies, whilst also incorporating customer requirements.

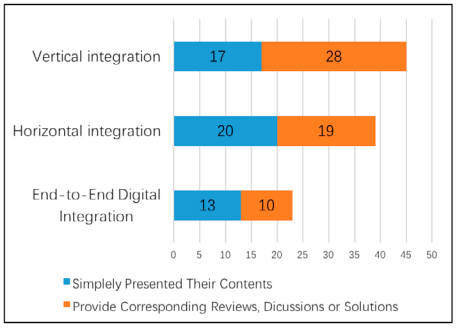
Eight Priority Areas for Action:

- *Standardisation and Reference Architecture*: development of a single set of common standards to support collaboration and of a reference architecture to provide a technical description of these standards.
- *Managing Complex Systems*: development of appropriate planning (for systems to be built) and explanatory models (for existing systems) to provide a basis for managing complex products and manufacturing systems.
- *Delivering a Comprehensive Broadband Infrastructure*: development of a reliable, comprehensive and high-quality communication network to expand the broadband Internet infrastructure in a massive scale.
- *Safety and Security*: to ensure that production facilities and products themselves do not pose a danger either to people or to the environment. Meanwhile, protect the data that they contain against misuse and unauthorised access.
- *Work Organisation and Design*: implementation of a socio-technical approach for work organisation and design to offer workers the opportunity to enjoy greater responsibility and enhance their personal development.
- *Training and Continuing Professional Development* (CPD): realisation of appropriate training strategies and organisation of work in a way that fosters learning, enabling lifelong learning and workplace-based CPD.
- *Regulatory Framework*: mutual adaptation of new innovations with existing legislation. The protection of corporate data, liability issues, handling of personal data and trade restrictions.
- *Resource Productivity and Efficiency*: to deliver gains in resource productivity and efficiency. The calculation of the trade-offs between the additional resources that will be needed in smart factories and the potential generated savings.

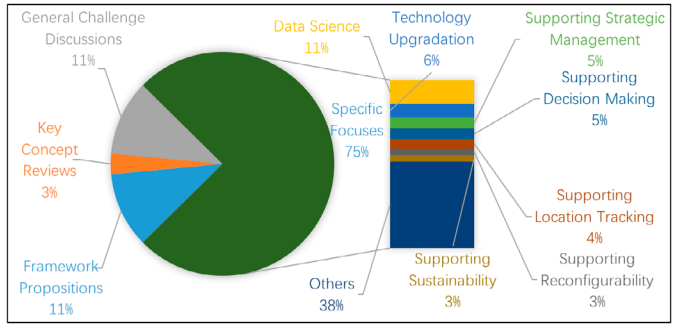
From the Integration Features perspective, 20.5% of the included papers (46 papers) have mentioned at least one of these three Integration Features. In particular, as can be seen in Figure 6(a), more attention has been paid to the concept of *Vertical Integration* (45 papers) and *Horizontal Integration* (39 papers), while less effort has been invested in presenting or discussing issues related to *End-to-End Digital Integration* (23 papers). Moreover, about half of the above-mentioned papers, just simply present the contents of these three Industry 4.0 integration features without providing a corresponding review, discussion or solution based on them.

From the Priority Areas for Action perspective, 54.5% of the included papers (122 papers) explicitly present their contributions in one of the eight priority areas for action. To be more specific, Figure 6(b) illustrates the distribution of current research efforts. It can be seen that *Standardisation and Reference Architecture, Resource Productivity and Efficiency* are two areas that attract most of the research efforts. After them, the areas of *Work Organisation and Design*, *Managing Complex Systems*, *Delivering a Comprehensive Broadband Infrastructure* and *Safety and Security* show a more balanced distribution of research efforts within one another. Additionally, the research efforts related to *Training and Continuing Professional Development* have recently begun to appear. In comparison to all the other above-mentioned priority areas of action, *Regulatory Framework* ends up to be the most neglected one.

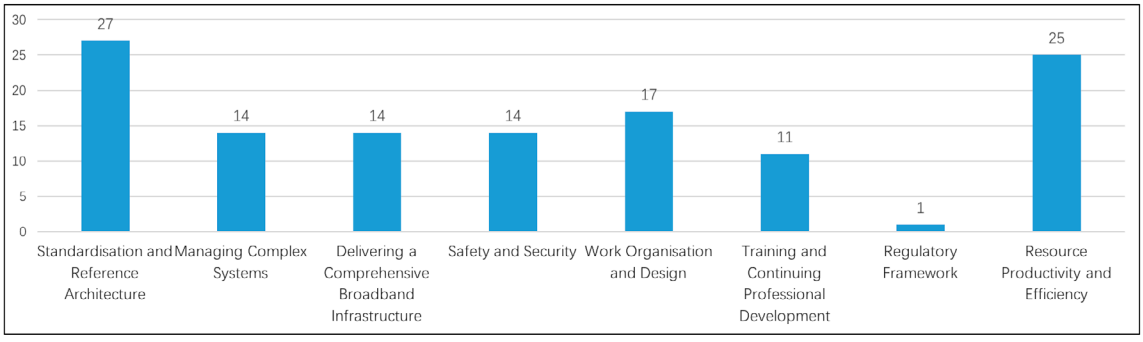
Additionally, for the other 45.5% of the included papers (102 papers), an extended investigation was carried out to classify them. As can be seen in Figure 6(c), a quarter of them presented a general contribution, such as the proposition of frameworks for the realisation of Industry 4.0 (11 papers), the review of key concepts related to Industry 4.0 (3 papers) and the discussion of possible Industry 4.0 challenges (11 papers). The other three quarters dedicated their contributions to specific Industry 4.0 issues.



(a) Composition of The Three Integration Features



(c) Distribution of Research Efforts from Other Perspectives



(b) Distribution of Research Efforts from The Eight Priority Areas for Action Perspective

Figure 6. Analysis of research directions and current research efforts.

3.2.4 *What are the existing Industry 4.0 application fields?*

The data analysis for this research sub-question is mostly based on the 103 included papers that are classified as *Practical Solutions*. It is divided into two parts: (1) the investigation and classification of the mentioned standards, software, and hardware; and (2) the analysis of laboratory experiments and industrial applications.

3.2.4.1 *Standards, software, hardware investigation and classification.* To make the analysis of standards more complete, the discovered standards from the keyword analysis and the two literature reviews (Janak and Hadas 2015; Leitao et al. 2015) about standards within the Industry 4.0 domain are also taken into account. In total, 138 different standards were identified. From a standard diversity perspective, as can be seen in Figure 7(a), 31.8% of the standards are related to Connection and Networking, 23.9% of them are concerned with Data Formatting, and 15.2% of them are focusing on Security and Privacy. From an occurrence frequency perspective, Figure 7(b) illustrates the standards that appeared in more than 10 papers. *Ethernet*, *Internet Protocol* (*IP*) and *Radio Frequency Identification* (*RFID*) are the three most frequently occurring standards related to Connection and Networking. Similar to the results in the keyword analysis, *OPC* and *OPC-UA* appear to be commonly accepted as the 'de facto' Machine-to-Machine (M2 M) Communication standards. Among Data Formatting standards, *eXtensible Markup Language* (*XML*), *Unified Modelling Language* (*UML*), and *AutomationML* are the three most frequently mentioned ones. Furthermore, IEC 61131, for programmable controllers, is the most mentioned domain and application specific standard.

The analysis of software and hardware took only into account explicit mentions to specific brands or models (e.g. Google Glass, Linux, ARM9), disregarding mentions to general concepts describing these objects in a general sense (e.g. smart glasses, operating systems, processors). Among the 177 found results, over 92.0% of them were mentioned only once (76.8%) or twice (15.2%). Figure 7(c) shows results of hardware and software that appear in 3 or more papers. *Linux* and *Microsoft Windows* are the top two computer Operating Systems (OS) employed. *Android* is the most employed mobile OS. *MATLAB* is the most frequently chosen software for the digital modelling and simulation. Furthermore, for Industry 4.0 prototype implementations, as single-board computers, *Raspberry Pi* is the most popular selection.

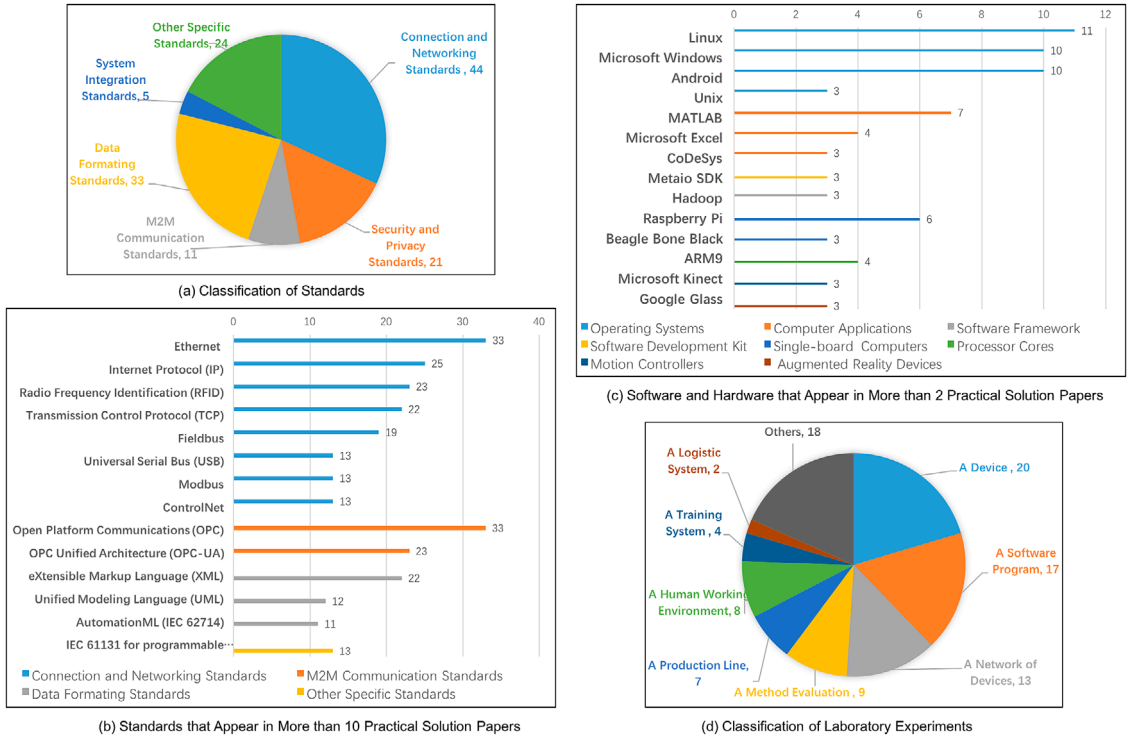


Figure 7. Analysis of existing Industry 4.0 application fields.

Table 3. List of industrial application examples.

References	Year	Company (Country)	Type	Proposed solution
Gath, Herzog, and Edelkamp (2014)	2014	Tiramizoo GmbH (Germany)	Courier and express services	An autonomous multi-agent system to optimise the planning and scheduling of industrial processes using the example of courier and express services
Luhn et al. (2015)	2015	X-FAB AG (Germany)	Semiconductor foundries	An information system to support real-time Fab analysis, fast new product ramp and inherent knowledge discovery
Alexopoulos et al. (2016)	2016	Unspecified (Unknown)	White goods manufacturer	A context-aware manufacturing information system to support information distribution and decision-making at shop-floor
Tuominen (2016)	2016	BMW (Germany)	Automobile manufacturers	A flexible measurement-aided welding cell for body and chassis components in the automotive industry
Flatscher and Riel (2016)	2016	ZF Friedrichshafen AG (Germany)	Automotive tier-1 supplier	A strategic production planning process to integrate design of technology roadmaps for long-term technology planning in industrial organisations

3.2.4.2 *The analysis of laboratory experiments and industrial applications.* Among the papers that were classified as *Practical Solutions*, more than 95.1% of them (98 papers) presented a kind of laboratory experiment as part of their contributions. To be more specific, as can be seen in Figure 7(d), the top three categories of these experiments are: (1) prototyping a device (20.4%), such as a flexible conveyor, a plug-and-work machine, a self-adaptable mobile robot, or a sensing system for machine tools; (2) prototyping a software or its architecture (17.3%), such as a worker assistance solution based on ergonomic feedbacks, a role-based security protection solution, a decentralised data acquisition architecture, or a runtime automation software upgradate approach; (3) prototyping or analysing a network of devices (13.2%), such as a delay-aware Wireless Sensor Network (WSN), a link scheduling scheme for WSN, an efficient spectrum sharing for WSN, or a ultra-low power WSN.

Furthermore, as can be seen in Table 3, the papers that offered industrial application examples barely make 4.9% of the papers (5 papers). It was discovered that: (1) the number of industrial application is constantly growing from 2014 to 2016; (2) besides one paper not specifying the name of the company in which the application was developed (Alexopoulos et al. 2016), the other four companies are all from Germany; (3) while one of the companies provides logistics services (Gath, Herzog, and Edelkamp 2014), the other four are from manufacturing industries; (4) two of the papers (Gath, Herzog, and Edelkamp 2014; Flatscher and Riel 2016) proposed solutions to optimise the planning process at the managerial level, two papers (Luhn et al. 2015; Alexopoulos et al. 2016) focused on developing information systems for data analysis and management, and one paper (Tuominen 2016) provided answers to improve the technological operations in a manufacturing cell.

4. Implications—a research agenda

Considering the period from 2013 to 2015, the growth of the number of conferences and academic publications related to Industry 4.0 appears to be exponential. Without doubt, the fourth industrial revolution has become one of the important topics in the realm of manufacturing. It is going to attract more and more research efforts, at least, in the following five years. Combining the results of the qualitative and quantitative analysis in Section 3, this section offers a research agenda for the identification of knowledge gaps and the proposition of future research focuses from a context perspective, collaboration perspective, research effort perspective, application perspective.

4.1 *A context perspective*

Among all the papers found in this systematic literature review, the earliest presentation of 'The fourth industrial revolution' traces back to 1988, a paper (Rostow 1988) that presents the participation of scientists in a production team that transformed an invention into an innovation. After that, in the decades before the year of 2012, this concept has also been used to indicate the development and application of nanotechnology (Parthasarathi and Thilagavathi 2011; Hung, Wang, and Chang 2012). These years, along with the rapidly increased number of high-level plans and projects, as some of them were introduced in Section 1, which governments and industries worldwide carried out, this concept was then more commonly recognised as the technical integration of CPS into manufacturing and logistics and the use of IoT in industrial processes (Kagermann, Wahlster, and Helbig 2013). Consequently, the first key item in a research of the fourth industrial revolution, more specifically for an Industry 4.0 academic research, must therefore be the accurate identification and understanding of 'Which are the enabling features of Industry 4.0?'

To achieve that, the results presented in Section 3.2.1 can provide the following two suggestions: (1) as the most cited reference, the final report of Industry 4.0 working group (Kagermann, Wahlster, and Helbig 2013) can confidently be used as the citation and guidance for identifying the definition of Industry 4.0, and (2) the further investigation of the discovered noun phases that are closely related Industry 4.0 can accurately improve the appropriate understanding of their specific relations. Furthermore, even though the most accepted citation was found, the gap of frequency between it and the other references is still huge. There is still a lack of the commonly recognised academic papers from Journals, Conferences, or Books.

4.2 *A collaboration perspective*

In this new industrial revolution era, the 'Industrie 4.0' from the Germany and the 'Industrial Internet' from the US, the 'Factories of the Future' from the European Commission are three of more frequently mentioned or compared proposals. As an example, among included papers about Industry 4.0, the 'Industrial Internet' appeared in 31 papers (13.8%), and the 'Factories of the Future' appeared in 12 papers (5.4%). In comparison, the other high-level plans and projects, such as the 'Future of Manufacturing' from the UK, the 'La Nouvelle France Industrielle' from the France, the 'Advanced Manufacturing Partnership' from the US, and the 'Made in China 2025' from the China, were rarely shown. They were only appeared in 0.9% (2 papers), 1.4% (3 papers), 1.4% (3 papers), and 1.8% (4 papers) of the included papers respectively. Therefore, to avoid misperception, the backgrounds and circumstances of those plans or projects should be well explored before carrying out an investigation. For an Industry 4.0 academic research, one solution to acquire its background knowledge from the collaboration perspective is through studying 'Who is working on Industry 4.0, when and where?'

The results presented in Section 3.2.2 illustrate a list of contributors (authors), institutions (universities, research centres, or companies) and countries that have relatively more academic publications in the recent years. These data can be used as a basis for advanced investigations, two possibilities are: (1) The further analysis of their research expertise

to identify the most related ones for a new Industry 4.0 academic research, and construct scientific collaboration partnership proposals; (2) The further analysis of their co-authorship network (Newman 2004) from the contributor level, institution level, and country level. Its findings can be used to answer a broad variety of collaboration pattern questions (e.g. what is the typical distance among those contributors in the network, and how patterns of collaboration vary between subjects and over time?).

4.3 *A research effort perspective*

The term 'Industrie 4.0' has attracted more and more attention since it was first announced at the Hannover Fair in 2011 (Drath and Horch 2014). However, even though the Industry 4.0 working group has published their final report in 2013 (Kagermann, Wahlster, and Helbig 2013), which provides *the vision*, *the integration features*, *the priority areas for action* and *the example applications* for the fourth industrial revolution, the detailed roadmap for the realisation of Industry 4.0 is still missing. Due to this fact, in the academic literature, different kinds of research contributions were proposed according to their own requirements. This situation might be resolved through some recent research efforts published at the beginning of 2016, for example: (1) the systematic literature review (Hermann, Pentek, and Otto 2016), in which, four design principles for implementing Industry 4.0 solution were identified; and (2) the Industry 4.0 status report (VDI/VDE 2016), in which, the basic concepts for modelling technical assets, their life cycle and their administration in the information world were presented. Therefore, one of the solutions for discovering the inadequate research efforts in existing Industry 4.0 research is to analyse 'What are the main research directions and the current research efforts?'

The results presented in Section 3.2.3 allow us to uncover this state of the art: on one hand, (1) the research directions that have already attracted more research efforts, such as, *Standardisation and Reference Architecture, Resource Productivity and Efficiency, Vertical Integration* and *Horizontal Integration*, and on the other hand (2) the research directions that are still lack of, or insufficient, research efforts, such as the *Regulatory Framework* and *End-to-End Digital Integration*. Moreover, another key thing to remember is that even though some research directions that are not officially listed as priority areas for action in the Industry 4.0 final report (Kagermann, Wahlster, and Helbig 2013), certain research efforts can also be found. For example, research was undertaken related to Data Science (11 papers), such as Real Time Data Analysis, Data Integration, and Big Data Analytics. The upgrade of existing technologies (6 papers), such as Programmable Logic Controllers, Production Machinery, and Industrial Robots, to meet the needs of Industry 4.0. Moreover, research efforts have also been dedicated to support the management of production systems related to Industry 4.0 area, such as strategic management, decision-making, location tracking, reconfigurability and sustainability.

4.4 *An application perspective*

Academic research is commonly considered as a fundamental role to the continuing vitality of the overall nation effort (Vosper 1965). Industry 4.0 academic research is also an indispensable part during the improvement and strengthening of the fourth industrial revolution. However, a fact needs to be noted is that research contributions are sometimes difficult to be implemented in practice because of a series of factors. From the participation perspective, industrial engineers from companies are rarely engaging with academic research publications (based on Section 3.2.2, only 17.1% of found institution are companies). From the implementation perspective, industries are still holding doubts in implementing these new technologies, because of unclear possible benefits, lack of clear implementation details, and the seemingly large investments required (Theorin et al. 2016). From the standardisation perspective, there is still a lack of common accepted standards, software, and hardware. For example, the three recommended standards in the Reference Architecture Model for Industry 4.0 (RAMI 4.0) (ZVEI 2015), namely IEC 62,890 for Life Cycle and Value Steam, IEC 61512, and IEC 62264 for Hierarchy Levels are still not widely regarded as the Industry 4.0 standards. They have only appeared in 1 paper, 2 papers and 4 papers, respectively. Therefore, to more effectively transform an Industry 4.0 research proposal into an Industry 4.0 implementation, one of the solutions is to make a summarisation from 'What are the existing Industry 4.0 application fields?'

To achieve that, the results presented in Section 3.2.4 can provide systematic and scientific evidences for: (1) the selection of more commonly recognised standards, such as *RFID* for product tagging, *OPC-UA* for M2 M communication, and *AutomationML* for data formatting, and (2) the recommendation of more frequently employed software and hardware, for example, *Raspberry Pi* to support the development of low-cost experiments, the adoption of OPC-UA, the simulation of industrial multi-agent systems, the creation of wireless sensor network, and the realisation of Industrial Internet of Things (IIoT). Moreover, this analysis also confirmed and emphasise the huge gap between Industry 4.0 laboratory experiments (95.1%) and industrial applications (4.9%).

5. Conclusion

The main objective of this research is to review and analyse the academic progresses in topics related to the fourth industrial revolution in a systematic manner, to provide insights into the past, present and future of this topic. As the first stage result, this paper presented the systematic literature review within the Industry 4.0 subject, based on both the general data analysis of included papers and the specific data analysis corresponding to each research sub-question. An overview of Industry 4.0 is firstly captured by (1) enumerating the list of prominent journals and popular conferences for publishing Industry 4.0 related contents, (2) identifying, according to the Scimago categorisation, the two most relevant subject areas of Industry 4.0, together with its sub-categories, and (3) illustrating the Industry 4.0 significance based on keyword classification. Then, special attention has also been given to the following four aspects: (1) the discovery of the most common recognised Industry 4.0 citation through the references, and the list of its closely related concepts through word co-occurrence statistics; (2) the summary of the authors, institutions and their geographical locations that are involved in Industry 4.0 research in recent years; (3) the identification of existing research efforts and also the areas that are being neglected recently in the current literature; (4) the list of standards, software and hardware that more frequently appeared in Industry 4.0 implementations. Finally, following the systematic review of the literature, a research agenda was proposed to summarise the implications of this review to future works related to Industry 4.0 initiatives.

When considering the results of the present study, several limitations should be noted. First, papers were collected from the largest abstract and citation database of peer-reviewed literature (*Scopus*), together with only two other multidisciplinary databases (*Science Direct* and *Web of Science*) as its supplements. Second, because of the search criteria restricted the language of collected paper to English, existing Industry 4.0 research that was published in other languages were excluded. From a completeness point of view, this review could be more comprehensive if more databases and more languages were also taken into account. However, as a systematic literature review, appropriate restrictions should be specified for the review to be feasible. The systematic search of the three electronic databases collected 349 papers, in which 224 of them were included, a number that is within the quantitative literature review recommendations (Pickering and Byrne 2014). It is also worth noting that the most of the Industry 4.0 academic publications were written in English, for example, more than 89% of academic papers from journals, conferences, or book series in *Scopus* were written in English.

In conclusion, despite some limitations, as discussed in this section, this systematic literature review has reported the current status of the fourth industrial revolution through the analysis of academic progresses in Industry 4.0 – its past and present. It has also highlighted suggestions for some potential directions based on gaps in the literature in Section 4 – its future. The research work in the next stage will focus on the review of the academic progresses in other propositions (e.g. Industrial Internet, Factory of the Future, Made in China 2015) and their comparisons.

Acknowledgement

The authors would like to thank the financial support provided the Coordination of Improvement of Higher Education Personal (CAPES) in Brazil, and the Pontifícia Universidade Católica do Paraná (PUCPR) in Brazil.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Coordination of Improvement of Higher Education Personal (CAPES) in Brazil, and the Pontifícia Universidade Católica do Paraná (PUCPR) in Brazil.

Notes

1. Smart Factory OWL: http://www.smartfactory-owl.de/index.php/en/.
2. Siemens Software Suit: https://www.industry.siemens.com/topics/global/en/digital-enterprise-suite/pages/default.aspx.
3. SCImago Journal & Country Rank: http://www.scimagojr.com/.
4. Thomson Reuters Impact Factor: http://wokinfo.com/essays/impact-factor/.
5. ATLAS.ti Quantitative Data Analsysis: http://www.atlasti.com/.

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