

Mapping the trends of Industry 4.0: a bibliometric review

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Abstract: Ten years after the first appearance of the term “Industry 4.0” in the Hannover fair, the advancements of this paradigm are manifold. Among the technologies that constitute Industry 4.0, i.e., Industrial Internet of Things, cloud computing, additive manufacturing, vertical and horizontal integration, big data and analytics, cyber-physical systems, simulation, augmented reality and cyber security, a variety of applications have been developed in relation to products, factories, and cities. From an industrial point of view, the changes at the shop floor and supply chain level will affect the way the supply chain and operations management activities will be conducted. Mapping the path of this growth highlights today’s opportunities and challenges related to Industry 4.0 and helps researchers and practitioners in taking chances and dealing with issues. Hence, the aim of this work is to identify the main trends of evolution of this paradigm by means of a review of literature on the topic. To achieve such a result, this research adopts a dynamic and quantitative bibliometric method including works citations, keywords co-occurrence networks, and keywords burst detection. The aim is to study and analyze the main contributions to this research area and identify prevalent topics and trends over time. The analysis performed on citations traces the backbone of contributions to the topic, highlighted within the main path. Keywords co-occurrence networks depict the prevalent issues addressed, tools implemented, and application areas. The burst detection completes the analysis by identifying the trends and most recent research areas characterizing research on Industry 4.0.

Keywords: Industry 4.0; Trends; Bibliometric Review; Systematic Literature Network Analysis

I. INTRODUCTION

The Industry 4.0 term emerged for the first time in 2011, during the Hannover fair, to describe the next wave of the industrial revolution [1]. Ten years after this first appearance, the advancements of this paradigm are manifold. The body of knowledge relating to Industry 4.0 has been gathering pace over the last decade (2011–2021), and there has been much interest in the area to better understand how manufacturing companies can benefit from technologies such as the Industrial Internet of Things, Cloud Computing, Additive Manufacturing, Vertical and Horizontal integration, Big Data and Analytics, Cyber-physical Systems, Simulation, Augmented Reality and Cyber Security.

Hence, it is timely to map the path of this growth and revisit the body of knowledge so to highlight today’s opportunities and challenges related to Industry 4.0 and help researchers and practitioners in taking chances and dealing with issues. The aim of this research is therefore to present a Systematic Literature Network Analysis (SLNA) of the studies that addressed the Industry 4.0 paradigm over the last decade and answer three main research questions.

RQ1: What relevant contributions relating to Industry 4.0 paradigm emerge in literature over the last decade (2011-2021)?

The first research question addresses the identification of the most relevant contributions relating to the

Industry 4.0 paradigm that added important insights to the literature over the last decade.

RQ2: What themes relating to Industry 4.0 paradigm emerge in literature over the last decade (2011-2021)?

The second research question addresses the understanding of the prevalent topics addressed by the Industry 4.0 literature over the last decade and the categorization of these issues under different themes.

RQ3: What trends relating to Industry 4.0 paradigm emerge in literature over the last decade (2011-2021)?

The third research question addresses the analysis of the trends and most recent research areas characterizing research on Industry 4.0.

II. MATERIALS AND METHODOLOGY

A. Materials

In this research, Scopus has been used as the main database. Indeed, it is considered one of the most reliable and complete when considering the scientific journal coverage [2]. To cope with the broad view of this paper and facilitate the searching for relevant work, the authors used “Industry 4.0” as the main keyword, and added a set of inclusion criteria for the searching, in line with the scope of the research. First, the papers found in the database search were added if they had the keyword selected in the title. This initial query led to a total number of 6,326 documents detected. Moreover, the research has been refined by limiting the subject

area to “Business, Management and Accounting”, resulting in 1,513 documents. Finally, only journals and English-written papers have been taken into account, so to narrow the analysis and ensure the quality of the citations based on the most up-to-date sources of information. This leads to a final number of considered papers of 911, detected with the search query: TITLE ("Industry 4.0") AND (LIMIT-TO (SUBJAREA , "BUSI")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j")). What's more, also 2022 papers have been included in the bibliometric analysis to be as complete as possible. Data extraction has been held in March 2022.

Some general descriptive analysis has been carried out to provide an overall view of the current situation of the literature. Firstly, throughout the use of a line plot, the trend of the published journal papers has been depicted (Figure 1). From the analysis, it is quite clear that the literature presents a greatly positive trend in publications about Industry 4.0. Indeed, it can be noticed that in the period 2020-2022, 643 papers have been published (considering 71 papers already published in 2022), which represents nearly 71% of the total considered documents.

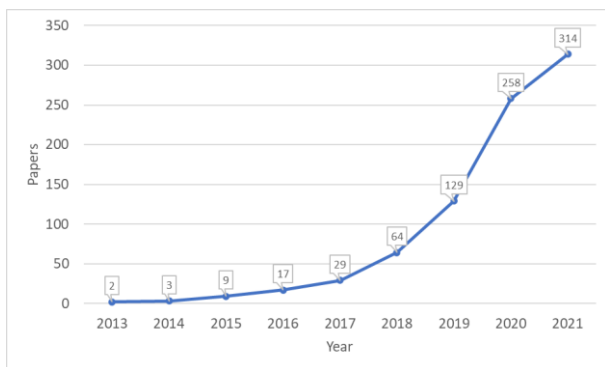


Fig. 1. Published Papers by Year

Secondly, an analysis of the main publishers and journals when considering Industry 4.0 papers has been performed. It is immediately clear that two journals arise when considering Industry 4.0-related publications.

Indeed, it can be noticed that the Technological Forecasting and Social Change and the International Journal of Production Research are the most representative journals in this field, presenting respectively 48 and 49 papers with the characteristics of the ones included in this study.

B. Methodology

To respond to the three RQs, this study performs a SLNA. This method allows the analysis of a large number of contributions in an accurate and reliable way, throughout the development of citation networks as well

as keywords cluster analysis and keywords burst detection/trend detection [3]

Firstly, the analysis of the main path of the research in Industry 4.0 is proposed in order to answer the first RQ. In doing so, a citation network is developed in order to delineate the main development trajectory of the literature. All the papers belonging to the detected main path have been analyzed and categorized. In order to perform such analysis, two software have been exploited, i.e., VOSViewer and Pajek. The first software has been mainly used in order to generate networks files from the bibliometric data. Pajek, instead has been exploited to analyze the generated networks. In particular, for what it regards the development of the main path, firstly an analysis of the weak connected components has been carried out. On the basis of the obtained results, throughout a key-route global search on the largest connected components, the main trajectory has been extracted.

Secondly, in response to the second research question, a co-word network analysis has been developed, aiming at defining the principal topics that addressed the theme of Industry 4.0 in the last ten years. In doing so, VOSViewer has been exploited in order to create a keyword network, as well as to extract a list of keywords clusters with a VOS Clustering algorithm. In order to be considered relevant enough to be included in the list, the minimum amount of occurrences of a keyword has been set to 6. This parameter has been computed to be able to locate sufficiently relevant clusters while keeping into account the specificity of the results. Moreover, a thesaurus has been implemented in VOSViewer with the aim of substituting synonyms and similar concepts with a unique keyword. In this way, duplication of keywords is avoided.

Finally, the third research question has been addressed with an analysis aimed at identifying trends of keywords during the considered timespan has been carried out throughout the exploitation of a Keyword Trend Detection (KTD) methodology [4]. In doing so, a bar plot of the utilization of the keywords that have been discovered as belonging to a cluster in the SLNA has been developed. More in detail, for each keyword three main elements have been taken into consideration, i.e., the year of the first appearance, the year of the last appearance, and the total number of occurrences per year. Then, a bar for each keyword has been drawn, in which the height represents the occurrences of each year. However, in order to enhance visualization and normalize the results, a base-two logarithmic function has been applied to the total number of occurrences. What's more, since the aim of this analysis is to show the most relevant evolution of the trends in the topics related to Industry 4.0, only the segments of the bars that presented a total value of the logarithmic function superior to three have been taken into consideration. Finally, the keywords have been ordered firstly by cluster and then by the total number of occurrences.

III. RESULTS

The results of the SLNA on the presented sample of documents can be summarised in three main categories, i.e., paper citation networks, co-word network analysis, and keyword trend/burst detection.

C. Paper citation networks

In order to build a reliable main path, an accurate paper citation network needs to be developed. In doing so, the general co-occurrence network has been extracted from VOSViewer and elaborated in Pajek. Exploiting the functionalities of the latter, the weak connected components have been considered and a partition of the initial network has been derived. In this step, 664 papers on 911 have been included by the algorithm in the largest connected component. Therefore, only one connected component has been considered in the further analysis, involving the 71.94% of the papers. Then, in this group, the key-route global search algorithm has been exploited to determine the main trajectory. From the analysis, a main path composed of 15 papers has been detected (Figure 2). These works can be located in the time period between 2015 and 2022.

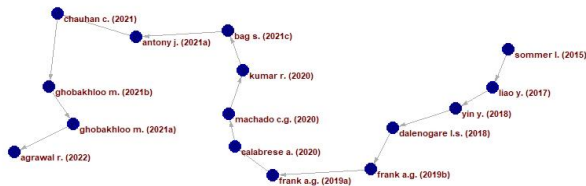


Fig. 2. Pajek Main Path Network

The main path presents a linear structure, that starts with a review by [5], in which the author in the first years of the Industry 4.0 paradigm analyses the relationship between the I.40 readiness and company size, with particular attention to German (Small Medium Enterprises) SMEs. The presence of literature reviews is heavy on the main path. Indeed, every year represented in the main trajectory presents at least one review, while 2020 has two review papers in the main path [5]–[12]. This constant need for literature reviews can represent an index of the vivacity of the scientific community around the theme of Industry 4.0 in the last years. When considering the time flow of the main path, it is also clear the importance of questionnaires or survey-based papers. As a matter of fact, it is possible to appreciate a growing presence of papers based on these methodologies since 2018 [13]–[17]. However, overall, the papers constituting the main path discuss different concepts. Indeed, the second paper on the trajectory, i.e., the one by [6], reports an analysis of the literature about the current state of the art of the Industry 4.0 paradigm and a comprehensive view. Accordingly, this contribution, as confirmed by its position in the main path, has been of great impact in the determination of future research agenda. Then, the paper by [7], pointed

the attention on a more specific topic. As a matter of fact, the authors performed a review of the literature aimed at describing the evolution of production systems from the second industrial revolution to Industry 4.0. In the paper by [13], it can be noticed the appearance of a new research thematic. Indeed, in this survey, the authors focus on the perception that companies had on the potential contribution of Industry 4.0 technologies on industrial performances, with a glance at Brazilian companies. In the work by [14], the attention switched to an implementation point of view. In this research, the authors proposed a survey aimed at providing an analysis of adoption patterns of Industry 4.0 technologies in companies. Then, the paper by [8], pointed out the difference between two concepts, i.e., servitization and Industry 4.0. In doing so, the authors proposed a framework that aims at connecting these two concepts through a business model innovation perspective. In the work by [9], for the first time when considering the papers in the main path, an analysis of the barriers and enablers of Industry 4.0 is proposed. Indeed, in this work, the authors conduct a review identifying the main issues that arise when implementing the Industry 4.0 paradigm in companies, as well as showing enabling technologies and goals. In doing so, the research proposed a framework that links these three elements. The paper by [10] is instead the first in the main path that brings to the light the theme of sustainability. Thanks to an intensive literature review, the authors identified the contribution of sustainable manufacturing to the Industry 4.0 paradigm. Then, in the work by [15] the theme of sustainability is again faced. The proposed survey, indeed, is centered on the analysis of how Industry 4.0 technologies could help SMEs in achieving sustainable as well as ethical operations. The paper by [18], through the use of a multi-criteria decision-making methodology, highlights again the attention to the barriers to digital manufacturing. However, the authors point attention to the challenges that are related to the world of sustainability, and in particular to the concept of circular economy. Then, the research by [16] proposed a conceptualization of Industry 4.0 readiness models with the use of a survey. In this work, the authors developed a validation of the readiness models in a general context, in order to cope with differences of companies for what it regards size, sectors or organizations. The work by [17] deals with the concept of Industry 4.0 and digitalisation. In particular, the authors, with the use of an analysis of moment structure methodology, analyse the presence and the effect of intrinsic and extrinsic barriers to digitalization with respect to Industry 4.0 performances. In the paper by [19], the authors proposed a content-centric qualitative review aimed at the identification of the main Industry 4.0 energy sustainability functions. In doing so, an interpretative structured modelling is adopted as a methodology. The theme of sustainability is central also in the work by [11], in which the authors perform a review about the connected concepts of innovation, sustainability and

Critical success factors	Production
Integration	Value chain
Quality 4.0	Intelligent manufacturing
<u>Lean Manufacturing</u>	<u>Circular Economy</u>
Digitalization	Circular economy
Lean manufacturing	Barriers
Emerging economies	Dematel
Operational performance	Multi-criteria decision making
Lean management	Challenges
Survey	Ahp

Furthermore, the co-occurrence keyword network analysis allowed the clusterization of the considered keywords. A total number of eight clusters have been identified, covering specific themes related to Industry 4.0, such as “Human Resources”, “Digital Transformation”, “Technologies”, “Sustainability”, “Performance”, “Supply chain”, “Lean Manufacturing” and “Circular Economy”.

The “Human Resources” cluster highlights the great interest of the literature in the impact that Industry 4.0 and consequent automation are bringing to the competencies needed by employees (e.g., [20]), in particular to the context of assembly systems (e.g.[21]). Moreover, the literature has discussed the role of the digital twin as a means to improve human and technological collaboration [22].

As the digital transformation under Industry 4.0 is complex and resource-intensive, research on the “Digital Transformation” topic was mainly devoted to the development of strategic guidelines for transformation success (e.g.,[23]). Particular attention was devoted to small and medium-sized enterprises (e.g.[24]).

Given the numerous opportunities and impacts provided by Industry 4.0 technologies to practitioners, the literature constituting the “Technologies” cluster mainly clarifies the opportunities for the adoption. Researchers have described and reported practical examples of positive impacts of digital technologies, such as business model innovations and competitive advantage (e.g., [8], [25]).

The research on the relationship between Industry 4.0 and “Sustainability” represents another main topic of research. These studies have focused on the application of technologies in the context of applying sustainability and with the aim to sustain sustainability objectives (e.g., [11]).

Discussion on “Performance” as a measure of expected contribution of Industry 4.0 applied to the industrial context was extensively discussed, investigating the

company level (e.g., [14]) and the supply chain level (e.g., [26]).

“Supply chain”, indeed, is another topic investigated by the Industry 4.0 research. In this field, the challenges and the requirements to adopt technologies as well as the opportunities have been discussed (e.g., [27]–[29])

The mutual support relationship between “Lean Manufacturing” and Industry 4.0 has been proposed and discussed since the first appearance of Industry 4.0 [30]. Research on this topic has focused on three main aspects: the general link between the two paradigms (e.g., [31]); the link between specific technologies and lean practices (e.g., [32]); the complementary impact of lean manufacturing and Industry 4.0 on operational performance (e.g., [33]).

Another increasingly popular topic is the “Circular Economy” and researchers are starting to investigate how digital technologies can support the circularity of resources within supply chains, challenges, and effects (e.g. [34]).

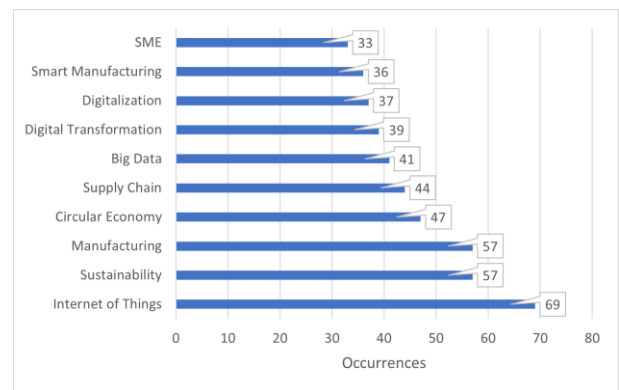


Fig. 4. Top ten Keywords by occurrence

E. Keyword Trend Detection

The analysis of the evolution of the interest of the literature in themes linked to the concept of Industry 4.0 in the last 10 years has been carried out via the exploitation of the KTD method [4]. In Figure 5, the graphical result of the KTD is reported.

The first consideration that is possible to observe when looking at the KTD is related to the main keyword of this research, i.e., Industry 4.0. Indeed, even if the term appeared in the considered literature in 2015, it began gaining remarkable importance only in 2017. All in all, it can be noticed that the most important trends are detectable mainly since 2019. This is probably related to the growth in maturity of Industry 4.0 so that several branches of related contributions can be identified once the main topic has stabilized. Particular attention should be given to the “sustainability” and “circular economy” keywords since it can be noticed from the KTD that they represent the most evident emerging trend of research when considered in Industry 4.0 domain.

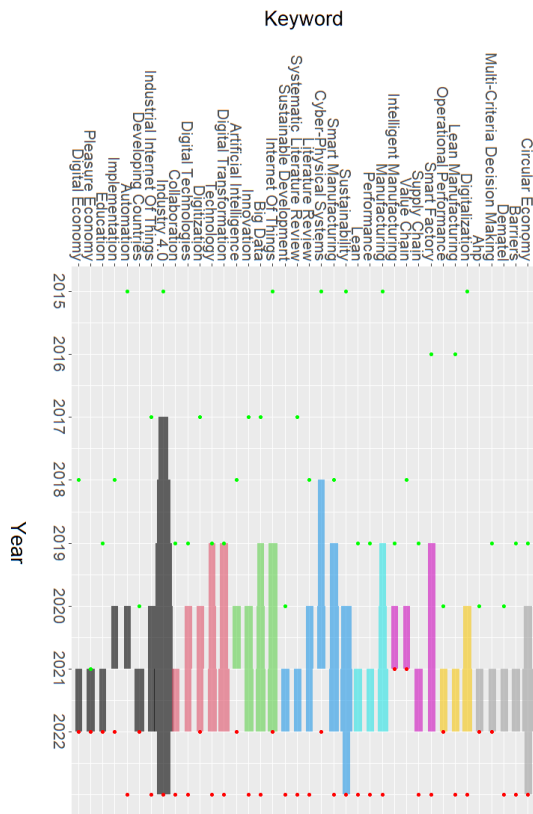


Fig. 5. Keyword Trend Detection

IV. DISCUSSION AND CONCLUSIONS

RQ1: What relevant contributions relating to Industry 4.0 paradigm emerge in literature over the last decade (2011-2021)?

This paper proposes an analysis of the main contributions in the literature related to Industry 4.0 paradigm over the last decade. In doing so, the research identified 15 main contributions that have been described in a main path network in a chronological order.

RQ2: What themes relating to Industry 4.0 paradigm emerge in literature over the last decade (2011-2021)?

The research adopted a co-occurrence methodology on authors keywords to discover the main themes in Industry 4.0 over the last decade. In doing so, in this paper 74 main themes have been detected. Moreover, a categorisation of the themes in eight clusters has been developed.

RQ3: What trends relating to Industry 4.0 paradigm emerge in literature over the last decade (2011-2021)?

In this paper, thanks to the exploitation of the KTD methodology it has been possible to detect trends in Industry 4.0 literature over the last decade. In particular, 38 trends have been detected. Moreover, from this analysis it has been possible to notice that the main trends started to develop after 2019, eight years after the birth of the Industry 4.0 paradigm.

Ten years after the first appearance of Industry 4.0 as an industrial paradigm, research has evolved covering several aspects, not limited to the technology itself. This paper has adopted bibliometric tools to provide an analysis of the evolution of this field of research and identification of works that have studied it, main topics and most recent research trends. Regarding a direction for future research work, this research points the “digital twin” as an underrepresented topic. In fact, keywords associated to this field have not been found within the top keywords neither in the trend detection, while its recent importance is assessed by the literature [35]–[37]. However, there are a few drawbacks to this study. To begin with, only journal papers were considered. Second, the study exclusively exploited data from Scopus, ignoring contributions that may have been published in other bibliometric databases. Third, in the research only papers that belong to the subject area “Business, Management and Accounting” have been considered. Fourth, the study's time frame was chosen solely based on the advent of the Industry 4.0 paradigm. Finally, when performing co-word analysis and trend identification analysis, only the authors' keywords were taken into account.

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