Industry 4.0: Mapping the Structure and Evolution of an Emerging Field

Yaşar Tonta and **Güleda Doğan**[1]
Hacettepe University Department of Information Management, 06800 Beytepe, Ankara, Turkey {yasartonta, guledaduzyol}@gmail.com

ABSTRACT
Industry 4.0 is a brand new interdisciplinary field combining cyber-physical systems, the Internet of Things and Services, and smart factories. It is promising to provide a new way of value creation in both physical and networked worlds. This paper attempts to witness the emergence of Industry 4.0 through bibliometric analysis of the characteristics of 89 papers published between 1945 and 2015. Scholarly papers on Industry 4.0 appeared very recently (2012) in the literature. Findings indicate that this is due, in large part, to the involvement of Germany in Industry 4.0-related research and innovation (R&I) within the last couple of years. Most papers were published by German researchers. The number of papers intensified very rapidly especially in 2014 and 2015. If the sharp increase in the numbers of papers and citations in the last two years is any indication, we should expect more Industry 4.0 R&I activities including publishing in the near future.

Keywords
Industry 4.0, cyber-physical systems, industrial Internet of Things and Services, bibliometrics

INTRODUCTION

We are about to enter the era of the Fourth Industrial Revolution. The First Industrial Revolution started at the end of the 18th century with the use of steam power for mechanical manufacturing facilities while, in early 20th century, the Second Industrial Revolution began with the use of electrically-powered mass production facilities based on the division of labor (i.e., Taylorism). The Third Industrial Revolution starting in 1970s involved the use of electronics and information technology (IT) to further automate the production processes. Dubbed as the "Industry 4.0" (or "Industrie 4.0" because of its origins in Germany), the Fourth Industrial Revolution has started in early 2010s and is based on cyber-physical systems (CPS) (Kagermann, Wahlster, & Helbig, 2013, p. 13). "In essence, Industrie 4.0 will involve the technical integration of CPS into manufacturing and logistics and the use of the Internet of Things and Services in industrial processes. This will have implications for value creation, business models, downstream services and work organisation." (Kagermann et al., 2013, p. 14).

Industry 4.0 is part of the Internet of Things and Services (IoTS). IoTS "makes it possible to create networks incorporating the entire manufacturing process that convert factories into a smart environment" involving smart grids, smart products, smart

[1] Corresponding author.

buildings, smart logistics and smart mobility (Kagermann et al., 2013, pp. 14, 19). Smart factories consisting of CPS are the main value creation facilities in Industry 4.0. The future production, energy, transportation and health systems will be shaped by smart factories making use of intelligent technical systems, cloud-based design, big data analytics, cloud computing and predictive manufacturing. Germany is at the forefront of the Fourth Industrial Revolution and its "High-Tech Strategy 2020 for Germany" initiative focuses on Industry 4.0 since 2011 (UNESCO, 2015, p. 264).

Although Industry 4.0 will likely play a paramount role in our day-to-day professional and personal lives in the near future, Industry 4.0 as a concept is somewhat difficult to define. Based on the findings of an extensive literature review, Hermann, Pentek, and Otto (2015, p. 11) defined it as follows:

> Industrie 4.0 is a collective term for technologies and concepts of value chain organization. Within the modular structured Smart Factories of Industrie 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. Over the IoT [Internet of Things], CPS communicate and cooperate with each other and humans in real time. Via the IoS [Internet of Services], both internal and cross-organizational services are offered and utilized by participants of the value chain.

This definition includes the main components of Industry 4.0; namely, CPS, IoT, IoS, and Smart Factory (SF). Authors also introduced six design principles that apply to one or more of Industry 4.0 components: Interoperability (between CPS and humans; applies to all four components), Virtualization (through which CPS monitors production of SF), Decentralization (with CPS making independent decisions in the SF), Real-time capability (to analyze production data at SF), Service orientation (applies to IoS and offers personalized products), and Modularity (adapting to changing requirements; applies to IoS) (Hermann et al., 2015, p. 11; UNESCO, p. 264). Discussing these design principles in detail is beyond the objectives of this paper. It should be noted, however, that the 6C system of big data analytics plays a crucial role in implementing the Industry 4.0 design principles. The 6C system consists of "Connection (sensor and networks), Cloud (computing and data on demand), Cyber (model & memory), Content/context (meaning and correlation), Community (sharing & collaboration), and Customization (personalization and value)".[2]

This paper aims to track the emergence and evolution of interdisciplinary field of Industry 4.0 by means of a bibliometric analysis of the characteristics of published papers. It intends to map the intellectual structure of Industry 4.0 on the basis of its relationship with other more established fields such as Engineering and Computer Science. Findings of this paper will likely facilitate our understanding of the Industry 4.0 field and its interaction with other disciplines.

DATA AND METHODS

We performed an advanced search on December 20, 2015, on Thomson Reuters' Web of Science (WoS) online databases (SCI-Expanded, SSCI, A&HCI, CPCI-SSH, ESCI)

[2] https://en.wikipedia.org/wiki/Industry_4.0

to identify papers published between 1945 and 2015 on Industry 4.0 using the following search query:

> ti=("industry 4.0") or ts=("industry 4.0") or ti=("industrie 4.0") or ts=("industrie 4.0") or ti=("4th industrial revolution") or ts=("4th industrial revolution") or ti=("fourth industrial revolution") or ts=("fourth industrial revolution")

It should be noted that the terms "industry 4.0" or "fourth industrial revolution" (or variants thereof) are not the only ones to describe the relevant papers in the literature. We are aware of the fact that the terms "industrial Internet", "integrated industry", "smart industry" and "smart manufacturing" are sometimes used interchangeably with (or instead of) "industry 4.0" in the literature (Hermann et al., 2015, p. 6). However, this requires a more extensive analysis of the retrieved papers (rather than bibliographic records) to find out if they pertain to "industry 4.0" or if they are simply "false drops". We plan to expand our study to include these synonymous terms in the near future and analyze the data accordingly.

We identified a total of 89 papers and downloaded their full bibliographic records including authors, titles, abstracts and reference lists. We used CiteSpace to analyze and visualize certain characteristics of bibliographic data to better understand the structure of the new field Industry 4.0. As a visualization tool, CiteSpace helps identify the emerging knowledge domains by supporting visualization of collaborative networks of co-authors, institutions and countries, documents co-citation networks, concept networks of noun phrases and keywords, and hybrid networks that consists of multiple types of nodes and links (Chen, 2004; Chen, Zhang, & Vogeley, 2009).

FINDINGS AND DISCUSSION

As mentioned earlier, the total number of papers on Industry 4.0 published between 1945 and 2015 is 89. The distribution of these papers by document type is as follows: conference papers: 52 (or 58%); journal articles: 21 (or 24%); editorials: 15 (or 17%); and a news item (1%). They were written mostly in English (79 papers or 89%), followed by German (9 or 10%) and Spanish (1 or 1%).

The term "4th industrial revolution" was used for the first time by L. Steipe in the title of a journal article on microelectronics published in *Nachrichtentechnische Zeitschrift* in 1978 ("Micro electronics today – 3rd or 4th industrial-revolution"). This was followed by a general article on 4th industrial revolution by D. Hague that appeared in the *New Scientist* in 1984, a conference paper by W.W. Rostow in 1986, and another journal article by D.A. Smith published in *Instrumentation & Control Systems* in 1999. For more than 10 years no papers appeared in the literature on Fourth Industrial Revolution. Then, in 2012, we see the term "industry 4.0" used by Hofmann et al. in the context of smartphones in a conference paper. From then on, the number of papers on Industry 4.0 has increased tremendously. In fact, the overwhelming majority (84%) of 89 papers were published in 2015 (42 papers or 47%) and 2014 (33 papers or 37%). Eight papers (or 9%) were published in 2013 and two papers in 2012. Less than 5% of all papers (4 papers) were published before 2000.

The great majority of the papers on Industry 4.0 were (co-)authored by researchers based in Germany (59), followed by those in: China (8); Spain and USA (5 each); Austria (3); and Australia, England, Italy, Hungary, Malta, Poland, and Portugal (2 each). Altogether, authors from more than 20 countries contributed to the Industry 4.0 papers (including one each from Denmark, Romania, Serbia, Singapore, Switzerland, and Ukraine).

Germany being in the prominent position is consistent with the decision to make Industry 4.0 an integral part of the country's high-tech strategy as mentioned earlier. Following this decision, Germany set up the Industry 4.0 Working Group and the Platform Industry 4.0 to describe the Group's vision and came up with recommendations in 2013 to implement this vision (Kagermann et al., 2013). It is estimated that the Industry 4.0 initiative will contribute close to 80 billion euro to German GDP by 2025 (Hermann et al., 2015, p. 3).

The most prolific authors were Schuh G (contributed to 6 papers), Toro C (4 papers), and Jasperneite J, Potente T, and Thoben KD (3 papers each). All researchers but one (C Toro, Spain) are affiliated with German institutions. The great majority of authors contributed to either one (76 authors including two anonymous ones) or two papers (22 authors).

Papers on Industry 4.0 generated a total of 29 citations (including 14 self-citations). Most citations (24 out of 29 citations or 83% of the total) were from papers published in 2014. As the bulk of the papers (84%) were published in 2014 and 2015, they did not have enough time (2 to 5 years) to generate citations. The titles of the most frequently cited papers were as follows: "Scalability of OPC-UA down to the chip level enables 'Internet of Things'" (cited 5 times); "Industrie 4.0: Hit or hype", "Service innovation and smart analytics for Industry 4.0 and big data environment", and "Cyber-physical production systems: Roots, expectations and R&D challenges" (cited 4 times each).

Schuh G, Jasperneite J and Imtiaz J were the most frequently cited authors (5 times each). Drath R, Horch A, Lee J, Kao H-A, Yang S, Potente T and Monostori L were cited 4 times each, followed by Wesch-Potente C, Hofmann D, Margull R and Paul-Gerald (cited 2 times each).[3]

Using CiteSpace, we created an author co-citation network for Industry 4.0 with 157 cited authors and 349 co-citation links (Fig. 1). The co-citation network seems to have been formed in 2014 and 2015, as the linkages are only green and yellow. The most frequently co-cited authors in the Industry 4.0 field are Kagermann H, Wiendahl HP and Schuh G(unther). Note that the WoS data set we used included Industry 4.0 papers authored by Schuh G(unther), Drath R, Lee J, Vogel-Heuser B and Zuhlke D, but not by Kagermann H and Wiendahl HP. However, Professor Henning Kagermann, the president of acatech – German Academy of Science and Engineering, chaired the German Industry 4.0 Working Group and was the first author of its final report with recommendations mentioned earlier (Kagermann et al. 2013). He is "one of the main representatives of the concept Industry 4.0, which applies increased digitalization and

[3] Note that the total number of citations exceeds 29 due to co-authored papers.

the Internet of Things and Services to industrial production".[4] Similarly, Professor Hans-Peter Wiendahl is an expert on industrial manufacturing, automatic production control systems, factory planning for changeable manufacturing, and co-founded the Hanover Institute of Integrated Production.[5]

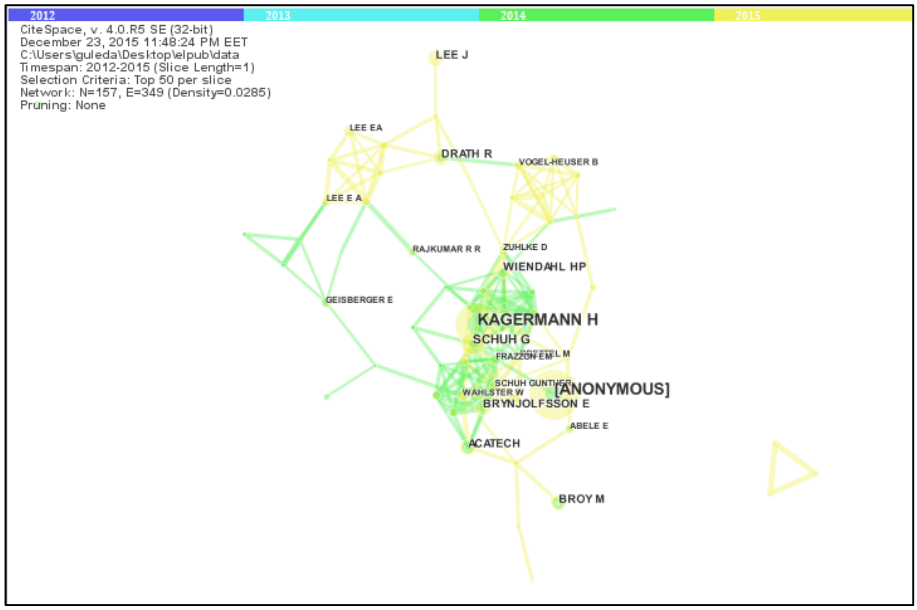

Figure 1. An author co-citation network (2012-2015) including 157 cited authors and 349 co-citation links

We then created the network of 89 Industry 4.0 papers on the basis of subject categories (SC) assigned to them by WoS (Fig. 2). Currently, no WoS SC exists for Industry 4.0. Therefore, more general WoS SCs were assigned to relevant papers (e.g., Engineering: 48 papers; Computer Science: 29 papers; Automation Control Systems: 15 papers; Telecommunications: 8 papers; Education Educational Research, and Materials Science: 7 papers each).[6] Management, Business & Economics, and Social Sciences as WoS SCs were assigned to Industry 4.0 papers less frequently.

Starting from 2012, most Industry 4.0 papers were classified under Engineering. Industry 4.0 papers were linked directly from Engineering to Business and Economics, Management, Materials Science, Nanoscience and Nanotechnology in 2012 and to Computer Science in 2013. Industry 4.0 papers were linked to Telecommunications via Computer Science in the same year (2013), indicating that the Industry 4.0 papers classified under Computer Science provide the connection between Engineering and Telecommunications. It appears that Industry 4.0 became a new research topic via Engineering in 2014 in the areas of Automation and Control Systems, Construction and Building Technology, Instruments and Instrumentation, and Robotics. Most links in Fig. 2 are yellow, indicating that research on Industry 4.0 was linked to Education and

[4] https://en.wikipedia.org/wiki/Henning_Kagermann.
[5] https://en.wikipedia.org/wiki/Institut_für_Integrierte_Produktion_Hannover
[6] Note that more than one WoS SCs may be assigned to any given paper.

Educational Research, Social Sciences, Economics, Government and Law, and Political Science for the first time in 2015.

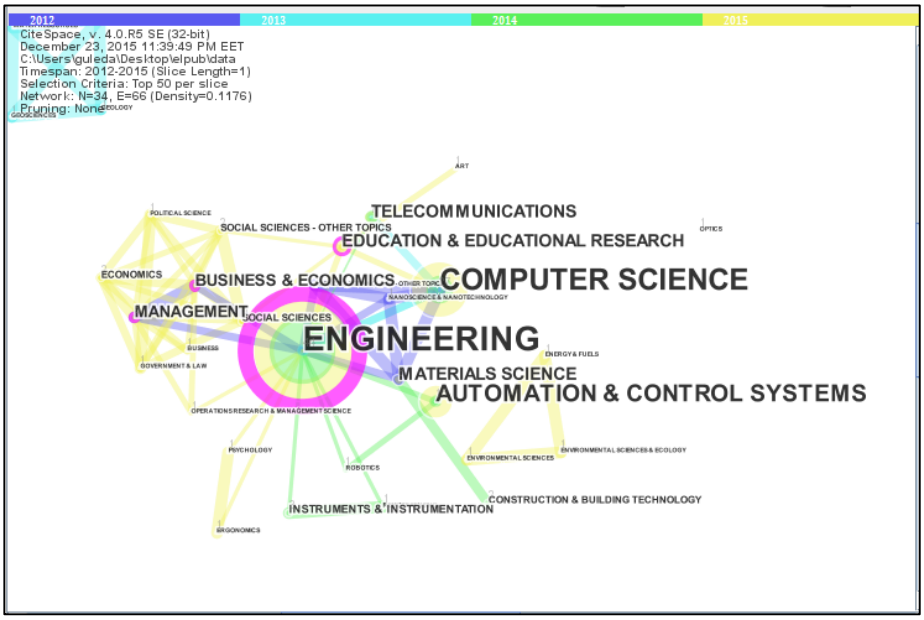

Figure 2. The subject category network of the 89 papers (2012-2015)

We also checked to see the most frequently occurring terms in the titles of Industry 4.0 papers. Needless to say, "industry 4.0" and "industrie 4.0" were the most frequently occurring terms (35 times out of 89), followed by "cyber physical production systems" (6 times), "fourth industrial revolution" (4 times), and "the Internet of Things" (2 times). In some cases, "industry 4.0" co-occurred with other terms such as "smart factory", "big data" and "the Internet of Things" (once each). The terms "digital factory" and the "factory of the future" occurred once in the titles of papers.

Next, we extracted the noun phrases from the titles and abstracts of papers (Fig. 3). Note that noun phrases were not standardized (e.g., "cyber physical system" occurs twice in the network in both singular and plural forms). "Industry 4.0" and "fourth industrial revolution" were used for the first time in 2012. Other noun phrases such as "cyber physical systems", "digital factory", "cyber-physical production system" first appeared in the map in 2014.

Lastly, we analyzed the sources (conference proceedings books or journals) in which papers on Industry 4.0 were published. The following source titles published the highest number of relevant papers: *Procedia CIRP*: 15 papers; *AT Automatisierungstechnik*: 9 papers; and *2014 IEEE International Conference on Emerging Technology and Factory Automation ETFA*; *IFIP Advances in Information and Communication Technology*; *5th Conference on Learning Factories* (5 papers each). Co-cited source titles can also be seen in Fig. 3. The intensity of green and yellow colors in Fig. 4 indicates that the majority of Industry 4.0 papers were published in 2014 and 2015 and they were

scattered in both proceedings books and journals. As yet, no specialized Industry 4.0 journal exists.

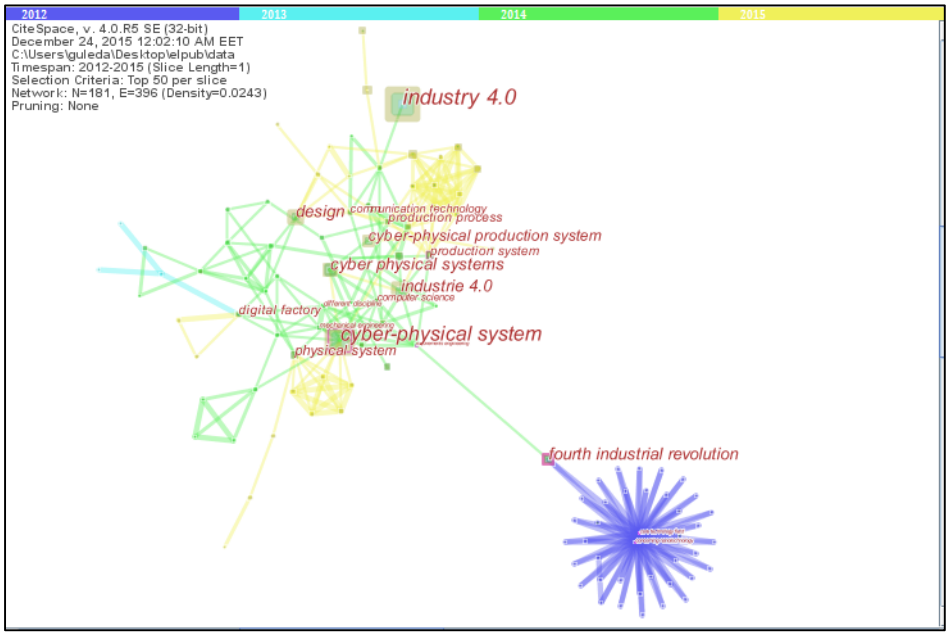

Figure 3. The network of noun phrases for industry 4.0 (2012-2015)

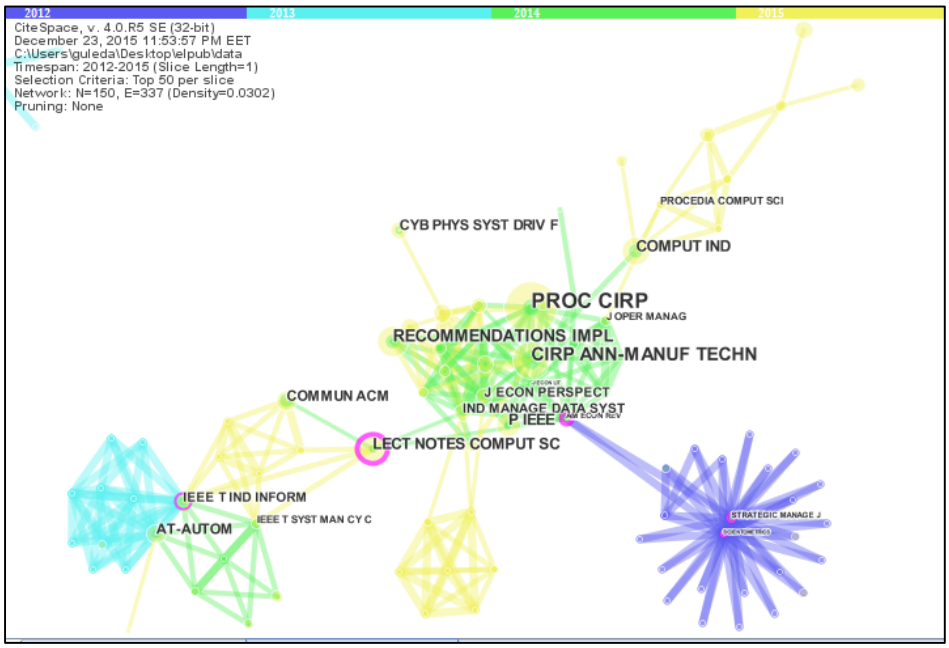

Figure 4. Journal/proceedings book co-citation map for Industry 4.0 (2012-2015)

CONCLUSION

Our bibliometric analysis of the characteristics of Industry 4.0 papers clearly shows that, starting from 2012, we are witnessing the emergence of a truly interdisciplinary field, namely Industry 4.0. As such, the new field tends to get nourished by the research outputs of more established fields such as Engineering, Computer Science, and Telecommunications. More specifically, cyber-physical production systems, the Internet of Things and Services and smart factories seem to be the main components of Industry 4.0. Various terms used in the titles and abstracts of papers reflect the interdisciplinarity of the emerging field of Industry 4.0.

Germany is leading the way in this field: it has not only made Industry 4.0 an integral part of its high-tech strategy but also produced the highest number of scholarly papers in this emerging field. Needless to say, most prolific authors are also based in Germany. As the papers were published quite recently (e.g., in 2014 and 2015) and they appeared in both proceedings books and journals, they have yet to elicit enough citations. Findings indicate that both the numbers of papers and citations are expected to increase considerably in the coming years.

REFERENCES

Chen. C. (2004). Searching for intellectual turning points: Progressive knowledge domain visualization, *Proceedings of the National Academy of Sciences of the USA (PNAS),* **101** (Suppl. (1)), 5303-5310. Retrieved, April 17, 2016, from http://www.ncbi.nlm.nih.gov/pubmed/14724295.

Chen, C., Zhang, J. & Vogeley, M.S. (2009). Visual analysis of scientific discoveries and knowledge diffusion. *Proceedings of the 12th International Conference on Scientometrics and Informetrics (ISSI 2009). July 14-17, 2009. Rio de Janeiro, Brazil*. Retrieved, April 17, 2016, from http://cluster.cis.drexel.edu/~cchen/papers/2009/issi2009/issi2009.pdf.

Hermann, M., Pentek, T. & Otto, B. (2015). *Design principles for Industrie 4.0 scenarios: Literature review*. (Working paper no. 01/2015). Technische Universitaet Dortmund. Retrieved, April 17, 2016, from http://www.snom.mb.tu-dortmund.de/cms/de/forschung/Arbeitsberichte/Design-Principles-for-Industrie-4_0-Scenarios.pdf.

Kagermann, H., Wahlster, W. & Helbig, J. (2013). *Securing the future of German manufacturing industry: Recommendations for implementing the strategic initiative Industrie 4.0: Final report of the Industrie 4.0 Working Group*. April 2013. Retrieved, April 17, 2016, from http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Material_fuer_Sonderseiten/Industrie_4.0/Final_report__Industrie_4.0_accessible.pdf (January 2015).

UNESCO Science Report: Towards 2030. (2015). Paris: UNESCO. Retrieved, April 17, 2016, from http://en.unesco.org/USR-contents.