Enabling Technologies of Industry 4.0 and Their Global Forerunners: An Empirical Study of the Web of Science Database

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Abstract. Knowledge management in organizations brings many benefits for R&D operations of companies and corporations. This empirical study demonstrates the power of large database analyses for industrial strategies and policy. The study is based on the Web of Science database (Core Collection, ISI) and provides an overview of the core enabling technologies of Industry 4.0, as well as the countries and regions at the forefront of the academic landscape within these technologies. The core technologies and technologies of Industry 4.0 and Manufacturing 4.0 are: (1) Internet of Things and related technologies (2) Radio Frequency Identification (RFID), (3) Wireless Sensor Network (WSN), and (4) ubiquitous computing. It also covers (5) Cloud computing technologies, including (6) Virtualization and (7) Manufacturing as a Service (MaaS), and new (8) Cyber-physical systems, such as (9) Digital Twin-technology and (10) Smart & Connected Communities. Finally, important for the manufacturing integration Industry 4.0 enabling technologies are (11) Service Oriented Architecture (SOA), (12) Business Process Management (BPM), and (13) Information Integration and Interoperability. All these key technologies and technology drivers were analysed in this empirical demonstration of knowledge management.

Keywords: Industry 4.0 · Web of Science · Technology foresight

1 Introduction

In order to remain successful, organizations today must face the challenges and opportunities provided by digitalization, automation, and other rapidly emerging new technologies. In the context of manufacturing firms, this rapid transformation is captured by the term Fourth Industrial Revolution [1], or, in short, Industry 4.0 [2, 3].

The concept of Industry 4.0 has received very broad attention in recent years from all parts of the innovation Triple Helix: Industries, governments, and academia. It is also clear that Industry 4.0 has very important implications for knowledge management. Some scholars have even begun to talk of 'Knowledge Management 4.0' [4–6].

However, it appears still difficult to pin down an exact and commonly accepted definition of the term Industry 4.0 [7]. Similarly, a number of studies have attempted to elaborate various definitions of what 'Industry 4.0' constitutes [8–11].

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Elaborating the constituting elements of Industry 4.0 is not only relevant in order to settle academic debates. It will also be a helpful element in order to prepare real-world organizations for their own changing landscapes. If organizational decision-makers have hard times grasping the meaning of the concept, they will also have hard times using the terminology as guidance for decisions on their organizations' strategy, business model, or production system. In that case, 'Industry 4.0' might remain as little more than an academic and business consulting catchphrase.

For adapting organizational knowledge management to this new emerging business environment, it is therefore paramount not only to understand the general concepts of Manufacturing 4.0 and Industry 4.0, but also to explore their core enabling technologies.

This article draws on several key survey articles in order to establish a list of core technologies of Industry 4.0. This answers our first important research question:

R1: *What are the core enabling technologies of Industry 4.0?*

Thereafter an empirical study is performed in the *Web of Science-database* for peer-reviewed academic articles on these core technologies, identifying more than 100,000 published articles featuring these technologies either in the title or as topic keywords. Based on this large-scale literature search, we then perform analyses answering to two additional important Industry 4.0 research questions breaking down the geographical, technological, and temporal dimensions of the Industry 4.0 technology waves:

R2: *Where in the world are the forerunners of Industry 4.0?*
R3: *Where in the world are the forerunners of the individual core enabling technologies of Industry 4.0?*

This empirical study provides important empirical insights into the driving forces of Industry 4.0, as well as the state of the art of the field. Simultaneously, it also demonstrates the power of large database analyses for industrial strategies and policy. This is a pertinent point for developing R&D knowledge management methods in organizations.

2 Core Enabling Technologies of Industry 4.0

Despite increasing interest about Industry 4.0, it is still a non-consensual concept [10]. There are differences in the understanding of the definition, the vision, the implications, and also of the important driving technologies behind Industry 4.0. In a survey article from 2017 [8], Lu identifies 20 different research articles on key technologies of Industry 4.0. Since then, the number has likely grown significantly. From a technical point of view, Industry 4.0 has been described as the increasing digitization and automation of the manufacturing environment, as well as the creation of a digital value chain enabling communication between products, their environments and business partners [12]. In practice, numerous technologies related to automation, digitization, and increased connectivity are therefore used to implement elements of Industry 4.0.

Lichtblau et al. [13] and Oztemel and Gursev [14] lists as basic components of Industry 4.0: i. *IoT platforms*, ii. *Location detection technologies*, iii. *Advanced* *human-machine interfaces*, iv. *Authentification & fraud detection*, v. *3D printing*, vi. *Smart sensors*, vii. *Big data analytics and advanced algorithms*, viii. *Multilevel customer interaction and customer profiling*, ix. *Augmented reality/wearables*, and x. *Cloud computing*.

Using more general concept terms, Posada et al. [15] lists the technologies of Industry 4.0 as related to: i. *Semantic technologies*, ii. *Internet of Things, Industrial Internet, cloud technologies*, iii. *Product life-cycle management*, iv. *Visual computing*, v. *Industrial automation*, vi. *Intelligent robotics*, vii. *Cybersecurity*, and viii. *Industrial big data*.

Cheng et al. [16] talks of "*Industry 4.0's nine pillars of technology, including virtual reality, artificial intelligence, industrial internet, industrial big data, 3D printing, cloud computing, knowledge work automation, and industrial network security*".

This article uses the operationalization of Xu et al. [17], as illustrated in Figure 1. This is explicitly not an exhaustive list, but it does function as a guide to "*selected technologies that are particularly significant for Industry 4.0*". The technologies also relate to the four main features of Industry 4.0: Interconnectivity, data, integration, and innovation [16].

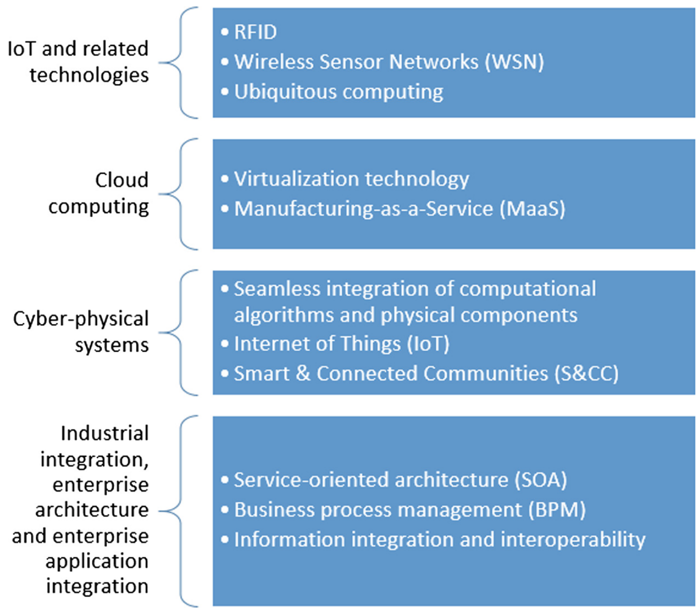

Fig. 1. Enabling technologies of Industry 4.0 (Adapted from [17, 18])

The first category of technologies is related to *'IoT and related technologies'*. The first foundation for Internet-of-Things (IoT) can be considered as a global network infrastructure composed of connected devices relying on sensory, communication, networking and information processing technologies. The aim of IoT is to interconnect all objects across different purposes, types and locations [19]. Several communication technologies has helped paved the way for a new ICT environment allowing for

Industry 4.0. These key enabling technologies are (1) *Internet-of-Things*, (2) *Radio Frequency Identification (RFID)*, (3) *Wireless sensor networks (WSN)*, and (4) *Ubiquitous computing*.

The second category of Industry 4.0-technologies is related to (5) *Cloud Computing* which allows high performance computing cost-effectively. Enabling technologies within this framework are (6) *Virtualization* technologies, and new technological and business model opportunities provided by (7) *Manufacturing-as-a-Service*. Service-orientation is an effective mean of enabling large-scale manufacturing collaboration, smart manufacturing [20].

The third category is the development of (8) *Cyber-Physical Systems*. This is perhaps the most central element of the Industry 4.0-concept [21]. Part of Cyber-Physical Systems is the seamless integration between the virtual and the physical world, and an important enabler for this is (9) *Smart and Connected Communities (S&CC).* Another important enabling technology for this is (10) *Digital Twin*-technology [20, 21].

The final important category relates to the dimension of industrial integration and covers manufacturing and enterprise architecture. In some of the originating work on Industry 4.0 [10, 22], the whole concept rested primarily on three dimensions of integration: (1) Horizontal integration in value networks, (2) Vertical integration within manufacturing systems, and (3) End-to-end digital integration of engineering across the full value chain. Among important supportive building blocks for these integration mechanisms are (11) *Service-oriented architecture (SOA)*, and (12) *business process management* (BPM). The research area of industrial integration is covered by the technology term (13) *Information integration and interoperability* (III).

3 Methodology

3.1 Web of Science Database

The Web of Science-database was inaugurated in 2004 by Thomson Scientific, a part of the Thomson Corporation, and it quickly came to dominate the field of academic reference [23]. Since 2016, the database has been part of the then-established company Clarivate Analytics.

Web of Science has a quick basic search (by entering a topic), a cited reference search, an advanced search, an author search, and a structure search. Results can be restricted by languages (51 different languages are available at the time of writing), by timespan (from 1900 onwards), by document types, or by various Web of Science Core Collection: Citation Indexes. For advanced searches, a range of Field Tags are available, e.g. topic, title, research area, and DOI. It also is possible to use Boolean operators (AND, OR, NOT, SAME, NEAR).

Advanced searches allow for numerous opportunities of refining the results as well as several visualization tools. This makes the database very useful for researchers and knowledge managers who want to perform targeted literature searches in which scientific areas (broad or narrow) are swiftly broken down into analytical or operational elements.

3.2 Literature Search

The literature search is performed as advanced search in the Web of Science-database with the use of Field Tags, Boolean operators and truncated search strings. Field tags ensures that all results including the truncated search strings in either the publication topic (TS) or title (TI) are identified. For certain technologies both the name of the technology and commonly accepted abbreviations thereof are used. In other cases, testing shows too many false positives related to e.g. other scientific fields, wherefore only names of the technology are used.

All searches were performed in December 2018 and results limited to a period ending in 2017.

Table 1. Web of Science Industry 4.0 literature search

Technology	Search strings	Results
Internet-of-Things	TS="Internet-of-Things" OR TI="Internet-of-Things"	23,053
Radio Frequency Identification (RFID)	TS="Radio Frequency Identification" OR TI="Radio Frequency Identification" OR TS=RFID OR TI=RFID	22,427
Wireless Sensor Network (WSN)	TS="Wireless Sensor Network" OR TI="Wireless Sensor Network"	24,417
Ubiquitous computing	TS="Ubiquitous comp*" OR TI="Ubiquitous comp*"	7,337
Cloud computing	TS="Cloud comput*" OR TI="Cloud comput*"	34,766
Virtualization technologies	TS=Virtualization OR TI=Virtualization OR TS=Virtuliasation OR TI=Virtualisation	12,461
Manufacturing as a Service (MaaS)	TS="Manufacturing-as-a-service" OR TI="Manufacturing-as-a-service"	14
Cyber-physical systems (CPS)	TS="Cyber-physical syst*" OR TI="Cyber-physical syst*"	594
Digital Twin (DT)	TS="Digital Twin*" OR TI="Digital twin*"	182
Smart and Connected Communities (S&CC)	TS="Smart and Connected Communities" OR TI="Smart and Connected Communities" OR TS=S&CC OR TI=S&CC	349
Service Oriented Architecture (SOA)	TS="Service Oriented Architecture" OR TI="Service Oriented Architecture"	6,684
Business Process Management (BPM)	TS="Business Process Management" OR TI="Business Process Management"	2,995
Information Integration and Interoperability (III)	TS="Information integration and interoperability" OR TI="Information Integration and Interoperability"	13

(*continued*)

Table 1. (*continued*)

Technology	Search strings	Results
All Industry 4.0 enabling technologies	TS="Internet-of-Things" OR TI="Internet-of-Things" OR TS="Radio Frequency Identification" OR TI="Radio Frequency Identification" OR TS=RFID OR TI=RFID OR TS="Wireless Sensor Network" OR TI="Wireless Sensor Network" OR TS="Ubiquitous comp*" OR TI="Ubiquitous comp*" OR TS="Cloud manufactur*" OR TI="Cloud manufactur*" OR TS=Virtualization OR TI=Virtualization OR TS=Virtualisation OR TI=Virtualisation OR TS="Manufacturing-as-a-service" OR TI="Manufacturing-as-a-service" OR TS="Cyber-physical syst*" OR TI="Cyber-physical syst*" OR TS="Digital Twin*" OR TI="Digital twin*" OR TS="Smart and Connected Communities" OR TI="Smart and Connected Communities" OR TS=S&CC OR TI=S&CC OR TS="Service Oriented Architecture" OR TI="Service Oriented Architecture" OR TS="Business Process Management" OR TI="Business Process Managament" OR TS="Information integration and interoperability" OR TI="Information Integration and Interoperability"	119,634

Table 1 shows the total literature search for Industry 4.0-technologies with almost 120,000 published articles by the end of 2017, even when search terms are limited to titles and topics. This amount of articles is clearly too large for any comprehensive human-based literature review, but it provides a great framework for further analysis through systematic use of data analytics. With modern methods of text mining and machine learning, knowledge managers have new options of combing through this large accumulation of knowledge in order to obtain targeted information. The example in [12] of frequency analysis within Industry 4.0 may serve as a rather simple inspiration.

Table 1 also shows the developed 'global' search string, which can underpin more targeted searches in specific organizational contexts. To use examples from the largest manufacturing operations of the region of Southwest Finland [24], shipbuilding and the automotive industry, knowledge managers can assess the state of the art of Industry 4.0-technologies by combining the global search string with AND (TS=shipbuild* OR TI=shipbuild*) or (TS=automotive OR TI=automotive). Again limiting to the end of 2017, these searches provide 16 results within the shipbuilding industry compared to 529 results in the automotive industry, showing also the close connections between the development of concepts of Industry 4.0 and the manufacturing of cars.

4 Global Forerunner Regions of Industry 4.0

Using tools directly available in Web of Science, we now analyze the geographical distribution of the almost 120,000 articles by sorting them by countries of origin. For this Web of Science distributes by locations of the organizations submitted by article authors (in the case of international collaboration, articles are attributed to several countries).

Table 2. Regional shares of total articles on Industry 4.0 enabling technologies

Region share of total	**-2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Total no. of articles	4,059	2,657	4,061	4,882	6,202	5,454	6,594
Europe	32,6 %	27,0 %	30,8 %	30,9 %	36,5 %	38,6 %	36,0 %
USA	32,3 %	24,7 %	23,1 %	19,0 %	17,7 %	20,4 %	17,9 %
Japan, South Korea, Taiwan	17,8 %	24,9 %	23,1 %	19,2 %	15,9 %	15,8 %	14,6 %
China	6,4 %	13,5 %	14,8 %	21,1 %	21,2 %	19,1 %	24,4 %
India	1,2 %	2,2 %	1,8 %	2,3 %	2,7 %	2,8 %	4,3 %
CELAC	1,3 %	1,5 %	1,2 %	2,3 %	1,6 %	2,4 %	2,3 %
ASEAN	1,1 %	2,1 %	2,1 %	2,8 %	2,9 %	2,5 %	2,7 %
Africa	0,4 %	0,3 %	0,5 %	0,5 %	1,0 %	1,2 %	1,1 %

Region share of total	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Total no. of articles	8,665	11,013	13,073	15,876	18,189	18,833
Europe	32,6 %	32,9 %	35,2 %	35,7 %	36,3 %	36,1 %
USA	16,6 %	15,7 %	15,6 %	14,7 %	15,2 %	15,7 %
Japan, South Korea, Taiwan	13,3 %	11,9 %	11,3 %	10,3 %	10,1 %	10,2 %
China	25,7 %	25,7 %	24,4 %	22,7 %	23,1 %	22,1 %
India	5,6 %	6,7 %	9,5 %	11,7 %	12,4 %	12,5 %
CELAC	2,5 %	2,9 %	3,3 %	3,9 %	3,4 %	2,8 %
ASEAN	3,3 %	4,0 %	4,5 %	3,6 %	4,2 %	4,6 %
Africa	1,9 %	2,3 %	3,0 %	3,4 %	3,9 %	4,5 %

Our hypothesis here is that those countries supplying the largest share of these publications at any given time can be considered among the (academic, at least) forerunners of Industry 4.0 at this given time.

Table 2 provides an overview of this analysis. For the purpose of clarity, countries are grouped together in regions, and not all countries or regions are represented. All categories (regions) were created after data analysis on country level.

Europe here refers to countries part of the European Research Area which is broader than the European Union, while ASEAN and CELAC refers to countries which are members of these two international organizations.

Several conclusions can immediately be drawn from reading Table 2. First, Europe consistently remains the world's leading region for Industry 4.0-technologies (although in relative terms the region's totals is likely boosted by double counting of intra-European international collaborations). Secondly, the East Asian countries of Japan, South Korea, and Taiwan appear to have lost ground over the past decade. Thirdly, the rapid rise of China from a minor player prior to 2006 to overtaking the United States of America as the world's largest national contributor of Industry 4.0 enabling technology publications in 2009. China's share has remained relatively stable within the latest decade, while, fourthly, India is now becoming a major player. Since 2015 the contribution of India has exceeded the combined contributions of Japan, South Korea, and Taiwan. 15–20 years ago this would have been probably have been almost unthinkable. Finally, the contributions from other regions of the world such as Southeast Asia, Caribbean and Latin America, and Africa are growing in absolute and relative terms. Africa, in particularly, has witnessed a major growth in publications over the past four years.

5 Variations of Forerunners Across Technologies

Unsurprisingly, there are major variations between different major players in terms of shares of published articles of given technologies. Table 3 illustrates these differences by ranking the six largest country contributors in the dataset, China, USA, India, South Korea, Germany, and Italy.

Again, several conclusions are easily drawn from these data. First, the rise of India concerns particularly the *interconnectivity* dimension of Industry 4.0. For communication technologies India is among the world leaders. When it comes to other innovation and integration elements of Industry 4.0, the Indian share of global publications is much less. One might summarize the data in such a way that India is a world leader in the ICT technologies underpinning the fourth industrial revolution, but still lacking behind in technologies more closely connected with industrial manufacturing. For Germany, the situation is almost exactly the opposite. The German share of global publications on ICT is relatively small, but for manufacturing integration tools and cyber-physical systems, the country is a titan. For the emerging Digital Twin-technology, Germany is the clear global forerunner.

Another remarkable feature is the South Korean stronghold in ubiquitous computing in which the country is second only to the USA globally. For ubiquitous computing South Korea significantly distances both European and other Asian competitors.

Table 3. Share of total publications within various technology fields

China		USA		India	
Technology	*Share*	*Technology*	*Share*	*Technology*	*Share*
Wireless Sensor Network (WSN)	28,6 %	CPS	34,0 %	S&CC	15,3 %
Cloud Computing (CC)	25,3 %	DT	27,5 %	WSN	13,8 %
Information, Integration and Interoperability (III)	25,0 %	III	25,0 %	CC	12,0 %
Internet-of-Things (IOT)	22,5 %	VT	21,1 %	IoT	8,3 %
Radio Frequency Identification (RFID)	21,5 %	S&CC	18,6 %	VT	6,2 %
Virtualization Technology (VT)	19,8 %	UC	18,4 %	SOA	4,8 %
Cyber-Physical Systems (CPS)	18,7 %	MaaS	18,2 %	RFID	3,9 %
Manufacturing-as-a-Service (MaaS)	18,2 %	SOA	16,8 %	UC	2,9 %
Service Oriented Architecture (SOA)	17,8 %	CC	16,7 %	CPS	2,8 %
Business Process Management (BPM)	9,8 %	RFID	16,3 %	BPM	1,1 %
Smart and Connected Communities (S&CC)	7,8 %	IoT	14,3 %	DT	1,1 %
Ubiquitous computing (UC)	6,9 %	WSN	14,3 %	MaaS	0
Digital Twin (DT)	5,5 %	BPM	9,0 %	III	0

South Korea		Germany		Italy	
Technology	*Share*	*Technology*	*Share*	*Technology*	*Share*
UC	14,7 %	DT	33,0 %	S&CC	7,2 %
RFID	7,8 %	BPM	19,3 %	IoT	6,3 %
IoT	6,1 %	CPS	12,7 %	DT	5,5 %
VT	4,6 %	SOA	9,2 %	VT	5,2 %
CC	3,5 %	MaaS	9,1 %	CPS	5,1 %
BPM	3,4 %	III	8,3 %	RFID	4,7 %
CPS	3,4 %	VT	7,8 %	SOA	4,3 %
DT	3,3 %	S&CC	7,5 %	BPM	3,8 %
SOA	2,4 %	UC	7,5 %	CC	3,8 %
WSN	1,9 %	IoT	5,1 %	UC	3,6 %
S&CC	1,2 %	RFID	4,8 %	WSN	3,3 %
MaaS	0	CC	3,9 %	MaaS	0
III	0	WSN	1,9 %	III	0

For organizations interested in the prospects of various elements of Industry 4.0, Table 3 provides guidance to where in the world the expertise most promisingly exists. This might be beneficial for strategic decisions on locations, markets and possible partnerships. The conclusion has the forefront of R&D within ICT-sectors has shifted to Asia – primarily China and India – might not come as a surprise, but the analysis highlights the prime role of these countries for emerging manufacturing technology fields.

6 Conclusions

This article has examined the main technologies driving the development of Industry 4.0. A total of thirteen main technologies were analyzed in the database Web of Science, revealing almost 120,000 academic publications by the end of 2017. This impressive amount of scholarly work would be even greater, had the literature search not been limited to publication titles and keywords. Web of Science is therefore an effective method of detecting massive amounts of information - and for targeting context-relevant information within this population.

The large-scale literature search identified shifting global Industry 4.0 frontrunner regions. While Europe (when seen as a whole) remain a global leader of Industry 4.0 technologies, China has risen provide the largest national share of publications. Indeed, the data shows a very rapid academic rise of China in this research arena during the period 2006–2009. Over the past five years (2013–2017), also India has experienced a very rapid rise; in some Industry 4.0-technological fields even to the world's forefront. On the other hand the combined shares of East Asian tigers Japan, South Korea and Taiwan has decreased from almost 25% of global publications in 2006 to a consistent level of around 10% of global publications in 2015–2017. Finally, there are signs of emerging academic powers of African and ASEAN-countries related to Industry 4.0.

Thus the empirical study allows us both to provide robust conclusions about the development and distribution of Industry 4.0, and it can serve as a demonstration of the value large database analyses can have as a R&D knowledge management method for organizations in support of decisions on industrial strategies and policy.

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