Redefining Industry 4.0 and Its Enabling Technologies

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Abstract. Industry 4.0 currently became a buzzword that mentioned almost in every subject. Admitted as the new industrial revolution, research related to Industry 4.0 has gained excessive attention from academia, government, and industries. However, a formal academic definition of Industry 4.0 that reflected the current advancement is difficult to be found in the literature. The technologies that drive this new revolution also bias. Furthermore, the subject area that significantly contributed to the vision of Industry 4.0, even unknown. This research investigated publications in diverse literature databases to find the answers to those gaps. Based on that, we proposed a comprehensive definition of Industry 4.0 and determined 12 enabling technologies that driven Industry 4.0. In addition, we found manufacturing and computer science as the most contributed research subject.

1. Introduction

The term “Industry 4.0” or “Industrie 4.0” is firstly coined at the annual Hannover Messe trade fair, Germany, in 2011 [1]. This is a strategic initiative to create smart factories to secure the future of German manufacturing industries [2]. Industry 4.0 commonly defined as the forth-industrial revolution. When the forth was coming, then the precedence industry revolutions need to be defined. The federal government of Germany, as the initiator, together with industrial representatives and scientist, agreed on technologies as the main driver of the revolution. They defined mechanization (water and steam powers), electricity, computers and electronics, and cyber-physical systems as the main driver of Industry 1.0, Industry 2.0, Industry 3.0, and Industry 4.0 respectively [3] as shown in Figure 1.
Since then, the term was spreading in almost all human life sectors from engineering, natural science, social science, health science, commerce, and et cetera. Hence, an enormous number of research papers have been published in different scientific databases. However, only a small number of papers discussed the concept and basic understanding of Industry 4.0. In fact, a formal academic definition that comprehensively describe what Industry 4.0 actually means cannot be found. Furthermore, it is also essential to know what subject areas that most contributed to Industry 4.0 research. The main aim of this research is to provide an inclusive review of Industry 4.0 research. In this paper, we are addressing three research questions as follow:

1. What is the formal academic definition of Industry 4.0?
2. What are the enabling technologies that driven Industry 4.0?
3. What research areas are the most contributed to Industry 4.0?

To find the solutions, we performed a literature survey using four literature databases, i.e. Scopus, Web of Science, ScienceDirect and IEEEXplore. We also used analytical tools provided by Scopus and Web of Science to drive our findings. The original contributions of this paper are threefold. First, a comprehensive definition of Industry 4.0 based on recent literature. Second, determine a new list of Industry 4.0 technology enablers. Lastly, define a map of Industry 4.0 research areas. That new knowledge will be a foundation for further research.

The rest of the paper is structured as follows. Section 2 described detail methodology implemented in this research. Section 3 presented the result, and Section 4 discussed the findings. Subsection 4.1 reviewed the past definition of Industry 4.0 and proposed a new definition. Subsection 4.2 and 4.3 discussed various technologies driving Industry 4.0 and the main research areas respectively. Finally, Section 5 concluded the findings and research contributions, also defined further research direction.

2. Methodology
This research follows a literature survey method to retrieve information from academic databases. The process of this approach is shown in Figure 2. There are four main databases investigated, i.e. ScienceDirect, IEEEXplore, Scopus, and Web of Science. Since ScienceDirect does not provide the number of citation for each paper, also does not have search result analysis tools, it excluded for further steps.
3. Results

Based on the search on the databases using the term “Industry 4.0”, Scopus has the largest number of papers, following by ScienceDirect, Web of Science, and IEEEXplore. After the screening process based on the number of citation, we explored 19 papers in detail. Table 1 shows the list of the papers.

Table 1. Most cited papers.

| Research Topic                  | Reference | Number of Citation (rank) | Scopus | Web of Science | IEEEXplore |
|--------------------------------|-----------|---------------------------|--------|----------------|------------|
| CPS architecture               | [4]       | 1019 (1)                  |        |                |            |
| Concept                        | [5]       | 527 (2)                   | 361 (1) |                |            |
| Smart analytics                | [6]       | 476 (3)                   | 340 (2) |                |            |
| Design principle               | [7]       | 458 (4)                   |        |                | 304 (1)    |
| Smart factory                  | [8]       | 299 (5)                   | 204 (4) |                |            |
| Automation network             | [9]       | 252 (6)                   | 179 (5) | 252 (2)        |            |
| Sustainable manufacturing      | [10]      | 246 (7)                   | 154 (6) |                |            |
| Smart manufacturing            | [11]      | 227 (8)                   | 152 (7) |                |            |
| Technologies                   | [12]      | 225 (9)                   | 145 (9) |                |            |
| CPS                            | [13]      | 204 (10)                  | 151 (8) | 143 (3)        |            |
| CPPS                           | [14]      |                           | 290 (3) |                |            |
| IIoT                            | [15]      |                           | 142 (10)|                |            |
| Technologies                   | [16]      |                           |        |                | 120 (4)    |
| Human-machine interaction      | [17]      |                           |        |                | 114 (5)    |
| Fog computing                  | [18]      |                           |        | 88 (6)         |            |
| Concept                        | [19]      |                           |        | 64 (7)         |            |
| Concept                        | [20]      |                           |        | 63 (8)         |            |
| IoT                            | [21]      |                           |        | 56 (9)         |            |
| Standardization                | [22]      |                           |        | 51 (10)        |            |

By using analytical tools provided by Web of Science and Scopus, the number of subject areas and the source of publications can be mapped. Figure 3 shows that engineering has dominated the research on Industry 4.0 followed by computer science and business economic. Going further in the engineering field, we found Procedia Manufacturing, which is a collection of conference proceedings organized by CIRP (the international academy for production engineering), has dominated the publication source. Another CIRP publication, Procedia CIRP, also placed as the third most Industry 4.0 publication source.

4. Discussion

This section analyses the results presented in Section 3 to address the research questions.

4.1. Industry 4.0 definition

The definition of Industry 4.0 could not be found on any of the papers listed on Table 1 rather than the 4th industrial revolution. However, each paper has emphasized some fundamental principles of the revolution. Those principles are interconnectivity between physical (hardware) and cyber (software and computational intelligence) [4][13][14], information transparency and decentralized decisions [7], and seamless human-robot collaboration [17]. Other values include the use of smart analytics [6], the
demonstration of smart factories [5][8] and smart manufacturing [11], and the creation of smart products and smart services [23][6].

Based on those principles and values, we propose a comprehensive definition of Industry 4.0 as follow.

“Industry 4.0 is a seamless collaboration of diverse advanced technologies integrating smart visualization and smart analytics of autonomous processes to grasp the vision of smart and intelligent factories as to produce smart connected products and provide smart services through real-time information transparency”.

**Figure 3.** Subject area and publication source

### 4.2. Enabling technologies

Industry 4.0 utilizes many kinds of advanced technologies as enablers to reach the vision of smart factories. In 2015, BCG outlined nine pillars of technological advancement that form the foundation of Industry 4.0. Those technologies are the Industrial Internet-of-Things, the cloud (cloud computing), Cybersecurity, Big data and analytics, horizontal and vertical system integration, advanced robotics, additive manufacturing, augmented reality, and simulation. After four years, some other technologies are gain traction. Those technologies have been introduced few years ago but gained considerable attention recently from academia and industry people. Therefore, based on our literature survey, we added three more advanced technologies, namely knowledge graph, blockchain, and digital-twin. Figure 4 shows the overall 12 technologies as enablers of the Industry 4.0.

Only those three new technologies discussed in this subsection. First, knowledge graph. Graph technology has a significant role in developing interoperability between different systems. Machine learning uses learning power to extract knowledge from data, whereas knowledge graph uses reasoning power to generate new knowledge from existing knowledge. Semantic web technology, ontology engineering, and linked data are the basis of knowledge graph development. Second, blockchain. Blockchain is a new data protection technology that uses peer-to-peer network validation
to maintain a growing list of data (blocks) [24]. Third, digital-twin. Digital-twin can be seen as the next generation of CPS. CPS take data from physical objects and use computational intelligence to optimize its operations. Digital-twin adding those functionalities by providing 3D modelling and 4D visualization of the physical object.

Figure 4. Advanced technologies driving Industry 4.0 vision

4.3. Research areas
One of our findings, as shown in Figure 3 and stated in Section 3, Procedia Manufacturing and Procedia CIRP, which both organized by CIRP, have dominated the publications in Industry 4.0 research. It is shown that production engineering or manufacturing becomes the main subject area of research related to Industry 4.0. However, manufacturing is not the only standing research since computer science also leading the research. An in-depth exploration of the literature has shown that computer science contributes on the fundamental research of new technologies or new tools. Subsequently manufacturing use those tools to renovate production processes to become more effective, lower cost, environmentally friendly, energy-efficient, and enhance productivity. This finding also confirms that the current development is still aligned with the initial vision of Industry 4.0 as to create smart factory of the future.

5. Conclusion and Future Work
To conclude this paper, we emphasize the main contributions. First, a comprehensive definition of Industry 4.0 in this paper encompasses the values and principles that stated in different literature. Second, 12 advanced technologies are determined as the enablers of Industry 4.0. Third, manufacturing and computer science are the two most leading research area contributed to Industry 4.0 development. This research only defines the technologies. For future research, we will study each technology and find how those technologies interconnected each other.

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