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Towards Industry 4.0: an overview of European strategic roadmaps

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Abstract

New achievements in information and communication technologies (ICT) are drastically influencing several industrial sectors. The provision of connectivity, networked entities, real-time data, and pervasive information is shifting paradigms in industries. However, this rapid evolution requires a proper comprehension and definition by scholars and practitioners in order to achieve a broad dissemination of the technological progress. Today, the trend towards a digital revolution in manufacturing is known as "Industry 4.0". However, the footprint of these evolutions, the technological borders, and the application frameworks are not yet specified. Therefore, the adoption of this paradigm change still requires more research to further develop the knowledge about the drivers and accomplishments of Industry 4.0. Towards this goal, this paper reviews some major EU industrial guidelines, roadmaps, and scientific literature that led to the depiction of the term Industry 4.0, and explores how key technologies and concepts have been addressed over time.

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Keywords: Industry 4.0; technology roadmap; convergence

1. Introduction

The increasing number and complexity of technologies being developed to cope with the societal challenges of the 21st century calls for structured methodologies for technology management. For this purpose, technology roadmaps, whether on an industrial, national and even supra-national levels, have been designated to support the delineation of strategic research agendas [1].

In the advent of the fourth industrial revolution, namely Industry 4.0, and its potential to disrupt the entire conventional approaches to manufacturing [2], European countries have been announcing their Industry 4.0 strategy; which is leading to the development of technology roadmaps and research agendas. As information and

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communication technologies (ICT) facilitate the networked manufacturing systems, implying interoperable systems, information interchange, and decentralized control and decision-making [3], the need for coordinated efforts among industries and countries is more important than ever. In particular, Industry 4.0 is expected to have an impact on five key areas: Transport, Energy, Well-Being, Industry and Infrastructure [4]. This paper explores the Industry dimension of those five.

Here, an overview of a number of technology roadmaps and strategic research agendas is presented first and their adherences to the main concepts of Industry 4.0 are examined. The objective is to provide an analysis on the convergence of the evolutionary paths, identifying the topics that have been discarded from more recent roadmaps, and to discourse on the reasons for this discontinuity.

This paper is organized as follows: section 2 presents the literature review, which discusses about the main concepts of Industry 4.0 and the role of technology roadmaps. Section 3 describes the research methodology used and documents reviewed in this study, then section 4 presents the results and discussions from these analyses. Finally, section 5 presents the conclusions.

2. Literature review

2.1. Industry 4.0 – key concepts and impact in European manufacturing

According to the German Federal Ministry of Education and Research[1], the term Industry 4.0 was coined in 2011 as part of a strategic manufacturing roadmap to promote the digitalization of manufacturing [5]–[8]. Industry 4.0 - the fourth Industrial Revolution - is a comprehensive concept as well as a new trend in manufacturing (and relevant sectors) based on the integration of a set of technologies that enable ecosystems of intelligent, autonomous as well as decentralized factories and integrated product-services [9, 10]. Its pervasiveness has produced several conceptualizations and been contributing to lack of clarity and definition. Fig. 1 presents the technologies and concepts that have been frequently linked to Industry 4.0, based on the literature reviewed in this paper.

Industry 4.0 aims at the purposeful collection and application of real time data and information by means of networking all individual elements, in order to reduce the complexity of operations, while increasing the efficiency and effectiveness with a long-term cost reduction target. It is supposed to guide European countries to a new era of modern manufacturing [11]. Industry 4.0 is anchored in the expansion of research in ubiquitous applications of ICT and aims at operationalizing the promising results on Internet of Things (IoT), Distributed and Decentralized Control, Embedded Systems, Cyber-Physical Systems (CPS), and Big Data in manufacturing. The multitude of technologies and their integration is characteristic to the concept of Industry 4.0.

Industry 4.0 is expected to influence four long-term relationship paradigm shifts that are going to change the landscape of the European Manufacturing [12]: 1) Factory and Nature: improvements in resource efficiency and sustainability of manufacturing systems, 2) Factory and Local communities: increased geographical proximity and acceptance, integration of customers in design and manufacturing processes, 3) Factory and Value chains: distributed and responsive manufacturing through collaborative processes, enabling mass customization of products and services and 4) Factory and Humans: human-oriented interfaces and improved work conditions. Consequently, Industry 4.0 aims to increase the digitalization of manufacturing processes and supply chains, facilitating the communications between humans, machines and products, thus enabling real time access to product and production information for participating entities, and the performance of autonomous work processes along value chains [13]. Thereupon, the European manufacturing sector expects to achieve a growth from 15% to 20% by 2030 if it performs the digitization of their value chains [14].

[1] https://www.bmbf.de/de/zukunftsprojekt-industrie-4-0-848.html

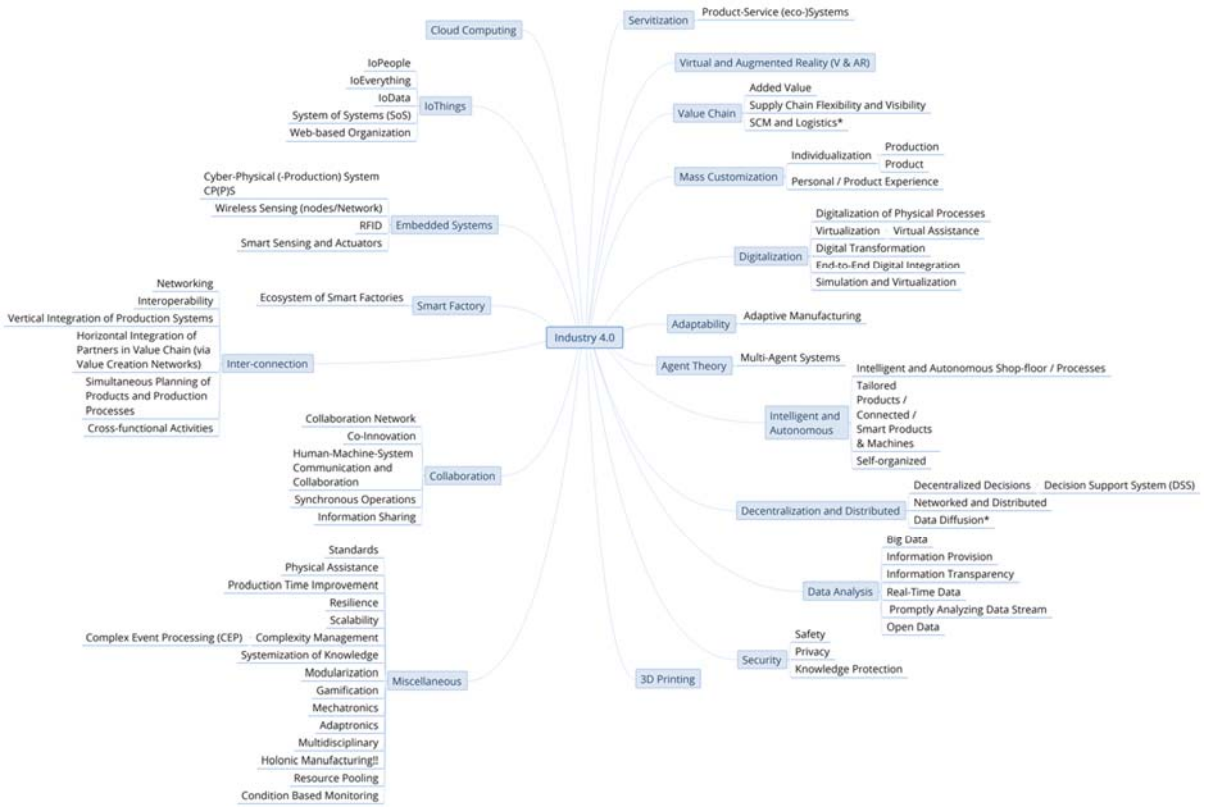

Fig. 1. Review of Industry 4.0 concepts. Source: authors' own elaboration.

The digitalization of supply chain can bring positive benefits in the current sales and operations planning of European manufacturers, such as reducing the time to respond to unforeseen events affecting orders (around 300% improvement), to deliver orders (around 120% improvements) and time-to-market (approximately 70% improvement) [14]. Providers of digital platforms will have an increasing importance in managing complex manufacturing systems, and this can bring data ownership issues.

These issues will pose significant challenges to firms' management structures: cooperation will be critical, as the boundaries of firms will blur in interconnected value networks, turned into "digital ecosystems" [15]. The end-to-end digitalization of value chains have the potential to boost productivity levels, but this requires firms to be horizontally and vertically integrated, to share information and to decentralize decision-making [16]. Additionally, the development of interconnected and interoperable interfaces of manufacturing systems needs to be followed by continuous training, standards for reference architectures, development of comprehensive broadband infrastructures for industries, innovative models of work organization, regulatory frameworks and raising levels of cyber security [16- 18].

2.2. Technology roadmaps

Technology roadmap is a tool used by organizations to provide the necessary information for technology investment decisions through the identification of critical technologies and gaps in need for additional research and development [19]. It is often based (but not always) on structured graphical representations of the relationships between several domains of analysis over time [20, 21].

The European Technology Platforms (ETPs) are forums of industry stakeholders, recognized by the European Commission, formed to support the development of innovation agendas and technology roadmaps for several sectors, at national and EU levels [22]. Manufuture, the ETP dedicated to improve the competitiveness of European manufacturing, launched the European Factories of the Future Association (EFFRA), a Public-Private Partnership (PPP) of industrial associations which regularly publishes strategic technology roadmaps that form the basis for research and technology development call topics. The most recent one, despite not explicitly mentioning the term Industry 4.0, presents the key technologies and research innovation priorities for the 2014-2020 period [12].

Recent research has suggested that existing technology roadmaps for pursuing Industry 4.0 are unclear [23] making it difficult for organizations to understand the implications around the high diversity of technologies and concepts [9] and, consequently, to accomplish its vision and goals [24]. In light of this, this paper examines a number of European roadmaps for the purpose of analyzing evolutionary paths and their degree of convergence towards Industry 4.0 key concepts and underlying technologies.

To accomplish the objectives of a sustainable socio-economic environment, several European manufacturing sectors are developing technology roadmaps to envision R&D and technology needs and goals to foster a new cycle of re-industrialization. Due to their similarities, the terms “technology roadmaps” and “strategic research agendas” have been used interchangeably in several documents issued by European organizations. However, there are differences between them, and usually technology roadmaps are used as inputs for the elaboration of strategic research agendas [25]. Although acknowledging these differences, such documents will be analyzed in the category of “strategic technology roadmaps” for the purpose of this paper.

3. Methodology

Technology has been underlined by European countries as of fundamental importance for addressing the challenges involved in boosting Europe’s economy and to foster job creation. In this context, this study is based on a review of publications about strategic technology roadmaps issued by the European Commission, related organizations and Technology Platforms. In order to ensure an evolutionary perspective, roadmaps prior and after the emergence of Industry 4.0 term (in 2011) are included in this study. Table 1 presents the documents that were analysed.

Table 1. Documents analysed.

Document name	Reference
Manufuture (2006)	[26]
Strategic Research Agenda of the European Technology Platform on Smart Systems Integration (2009)	[27]
Internet of Things Strategic Research Roadmap (2009)	[28]
Factories of the Future PPP – Strategic Multi-Annual Roadmap (2010)	[29]
Factories of the Future 2020': Roadmap 2014-2020 (2013)	[12]
European Roadmap for Industrial Process Automation (2013)	[30]
CyPhERS - Cyber-Physical European Roadmap & Strategy (2015)	[4]
Strategic Research Agenda of the European Technology Platform on Smart Systems Integration (2017)	[31]

A citation analysis performed on publications of both periods enabled an assessment of the evolutionary paths and their degree of convergence towards Industry 4.0. While many technology roadmaps have been issued by the European Commission and ETPS, this study targeted the ones addressing the implications to industry and manufacturing, and was intended as a preliminary analysis on a sample of roadmaps, thus not comprehensive. In addition to this, scientific publications addressing the topic of Industry 4.0 were also reviewed to categorize the drivers and potential achievements of the fourth industrial revolution.

4. Results and discussion

4.1. Industry 4.0 drivers and potential impact

The drivers for the implementation of Industry 4.0 can be categorized in four types: organizational, technological, innovation and operational [9, 11], [32-34]. The organizational drivers are related to new forms of work and collaboration, while technological drivers result from the convergence of multiple streams. Innovation drivers are forcing the development of new business models and extended innovation networks. Finally, operational drivers derive from the continuous need of organizations to improve their operational performance to remain competitive.

According to Hermann et al. [16] and Qin et al. [23], six major design principles rule the conceptualization and implementation of Industry 4.0: interoperability, virtuality, real-time capability, decentralization, service orientation and modularity. These design principles can support organizations in the identification of the most appropriate solutions for their businesses.

Influenced by those drivers and governed by Industry 4.0 design principles, a number of potential realizations can be envisioned, as illustrated in Fig. 2. These realizations represent potential materializations and possible scenarios for the implementation of Industry 4.0 pilots in companies. Overall, they point to an increasing relevance of collaborative networks, synchronicity between supply and demand, personalization in product and service development, decentralization and extensive data use in driving operational performance.

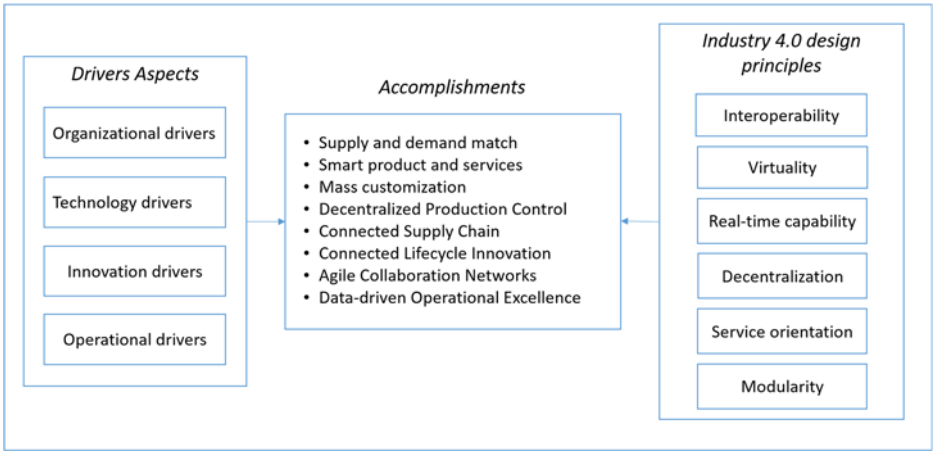

Fig. 2. Potential accomplishments of Industry 4.0.

4.2. Roadmaps and EU projects guidance analysis

This section presents the results of the citation analysis of the documents presented in Table 1. These strategic roadmaps focus on eight key technologies for Industry 4.0: embedded systems, cyber-physical systems, internet of things, sensing, cloud computing/services, agent-based systems, robotic and additive manufacturing. Additionally, the design principles presented in the previous section were also included. Table 2 presents the results of this analysis.

The documental analysis identified relatable themes, and others that have been reconverted in light of Industry 4.0, such is the case of embedded systems and cyber-physical systems (CPS). While embedded systems are seen as the enclosing of information technologies in products and services, CPS takes a more comprehensive approach. CPS are understood as an extension of embedded systems in the sense that propose a closer bridge between the physical and digital worlds by integrating complex information processing from multiple and networked physical elements (people, equipment, machinery, etc.), a concept that resonates with Industry 4.0. As such, CPS are more frequently found in recent roadmaps, and very associated with cloud computing technologies.

Table 2. Analysis of strategic roadmaps.

		Before 2011				After 2011			
	Reference	[26]	[27]	[28]	[29]	[12]	[30]	[4]	[31]
Technologies	Embedded Systems	x	x	x	x	x	x	x	x
	Cyber-Physical Systems			x			x	x	x
	Internet of Things		x	x	x	x	x	x	x
	Sensing	x	x	x	x	x	x	x	x
	Cloud Computing/Services			x		x	x	x	x
	Agent-Based Systems			x				x	x
	Robotic	x	x	x	x	x		x	x
	Additive Manufacturing					x			x
Design principles	Connectivity		x	x	x	x	x	x	x
	Virtuality	x	x	x	x	x	x	x	x
	Real Time Analysis and decision-making	x	x	x	x	x	x	x	x
	Decentralization			x	x	x	x	x	x
	Service orientation	x	x	x	x	x	x	x	x
	Modularity	x	x	x	x	x	x	x	x

Internet of Things, robotic and sensing technologies were also found in roadmaps before 2011, suggesting that the adoption of such technologies was not particularly propagated by the emergence of Industry 4.0. Agent-based systems and additive manufacturing technologies are more frequently found in recent roadmaps, although not extensively, perhaps because of the specificity of their applications.

Relevant insights are extracted from the comparison between the evolution of two roadmaps issued by the European Technology Platform on Smart Systems Integration – EpoSS - ([27] and [31]) and EFFRA - ([29] and [12]) before and after 2011. The most recent roadmap from EPoSS [31] acknowledges the emergence of CPS and cloud computing, thus aligning with Industry 4.0, and even addresses the relevance of agent-based and additive manufacturing technologies. On the other hand, the roadmaps from EFFRA do not address CPS, though referring to cloud computing and additive manufacturing technologies. Given that these roadmaps are particularly directed to manufacturing, the reasons are difficult to be speculated, and can only be related to the year of publication (2013) which is near to 2011. Despite this, EFFRA has recently announced that the strategic discussions for the next work programme have initiated, which is currently named "Factories 4.0 and Beyond"[2], and it is expected that will be more related to Industry 4.0.

Finally, the analysis revealed an important observation concerning the design principles. Except for decentralization and connectivity, every design principle is found in all roadmaps, both before and after 2011. This suggests that such design principles have been discussed for some time, but could only be enabled when it became possible to integrate several technologies that have reached a mature state for application, now materialized under the concept of Industry 4.0.

5. Conclusions

This study presented a review on the European strategic roadmaps and assessed their degree of convergence with the concepts of Industry 4.0. Besides, an illustrative framework that depicts the main concepts and technologies regarded relevant to this revolution by the literature was also developed. It has been witnessed that the move towards Industry 4.0 has presented new and reconverted some relevant concepts; which has partially been either substituted or

[2] http://www.effra.eu/index.php/research-a-innovation-65/factories-of-the-future-2020

improved by some new technologies. This shed light on a new strategic perspective of the industrial evolution facing some fundamental changes and technological breakthroughs.

However, the relatively reduced number of the analyzed roadmaps is a limitation of this study. The task of reviewing every strategic roadmap issued by the European Commission and related organizations would require a comprehensive and structured review, something that was outside the scope of this study. From an academic point of view, it makes a generic judgment difficult to ensure that European roadmaps have been converging towards Industry 4.0 over time. A more thorough reading of such documents accompanied with the citation analysis techniques can enrich this analysis.

Despite these limitations, this study contributes to the consolidation of the whole concept behind Industry 4.0, particularly in terms of technologies and design principles. Besides, this work gave a better overview on the trajectory of Industry 4.0 for identifying and following its major roadmap. Future studies should address a wider sample of publications and consider the impact of the implementation of technologies.

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