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PRODUCTION & MANUFACTURING | REVIEW ARTICLE

Industry 4.0: Clustering of concepts and characteristics

Zhanybek Suleiman[1], Sabit Shaikholla, Dinara Dikhanbayeva[1], Essam Shehab[1] and Ali Turkyilmaz[1]*

Abstract: The Fourth Industrial Revolution, also known as Industry 4.0, stems from the rapid advancement of digital technologies such as the Internet of Things and Cyber-Physical Production Systems. It has the potential to weave positive changes to firms and impact organizational structure layers. Therefore, it provides an impetus for the collaboration of factories, suppliers, and customers. Nevertheless, due to the difference of Industry 4.0 vision among companies, there is a lack of unified perception and approach of its implementation roadmap. Therefore, many firms in both developed and developing countries that step in the way of digital transformation encounter not only organizational, technological, and operational challenges but are also compelled to cope with a large deal of confusion. Hence, this paper aims to identify the main concepts, characteristics, and technology enablers related to Industry 4.0 to provide stakeholders with a clear understanding of this paradigm. It then clusters and matches the derived concepts and characteristics associated with Industry 4.0. Further, the paper provides an analysis of how these clusters are supported by technology enablers of Industry 4.0, as well as managerial implications.

Subjects: Production Engineering; Manufacturing Engineering; Technology

Keywords: Industry 4.0; digitalization; cyber-physical systems; technology; enablers; clusters

ABOUT THE AUTHOR

The authors of this paper are researchers in the project “Industry 4.0: Roadmap development for Kazakhstan enterprises”. The research aims to promote “Industry 4.0” within enterprises in Kazakhstan, as well as aims to identify the current readiness level of enterprises on a state level and identify more about other aspects. This research study was conducted within this project, as most of the organizations during conduction of stakeholder analysis, points out to the absence of well-organized classification of information about Industry 4.0 related concept, enablers, and characteristics. Therefore, in order to cover this need and to structure a big concept of Industry 4.0 in one paper, this research study was performed.

PUBLIC INTEREST STATEMENT

Industry 4.0 has the potential to weave positive changes to firms and impact every layer of organizational structures while providing an impetus for the collaboration of factories, suppliers, and customers. Nevertheless, due to the difference of Industry 4.0 vision among companies, there is a lack of unified perception and approach of its implementation. Therefore, many firms across the world in the way of digital transformation encounter not only organizational, technological, and operational challenges but also are compelled to cope with a large deal of confusion. Hence, this paper aims to identify the main concepts, characteristics, and technology enablers related to Industry 4.0 to provide stakeholders with a clear understanding of this paradigm. This article clusters and matches the derived concepts and characteristics of Industry 4.0 and provides an analysis on how these clusters are supported by technology enablers of Industry 4.0, as well as managerial implications on that matter.

1. Introduction

The constant technological advancements force organizations to adapt and cope to maintain their position in the market (Schwab et al., 2019). With increasing competition in productivity and quality, business managers should focus heavily on improving their business and manufacturing processes. There are already numerous technologies, such as Internet of Things (IoT), Big Data, Cloud Computing (CC), digital twin, and Additive Manufacturing that help various industries to improve performance and achieve better productivity. These technologies are considered as a part of a wider concept which is called "Industry 4.0" or also known as "The Fourth Industrial Revolution" (Turkyilmaz et al., 2021). It was first addressed by Germany in 2011 when they released a new strategic vector of developing the industry in the country and introduced the "Plattform Industrie 4.0", which has been later followed by "Industrial Internet Consortium" in the USA and "Industrial Value Chain Initiative" in Japan (Issa et al., 2018). Industry 4.0 (I4.0) is the next step of the industrial revolution that can potentially further transform production flow and change the communication between humans and machines as well as the interaction between suppliers, producers, and customers. It consists of nine prospective pillars and, to the addition of the technologies mentioned above, includes autonomous robots, simulation, horizontal and vertical system integration, cybersecurity, and augmented reality and can be further enhanced by artificial intelligence solutions (Rüßmann et al., 2015; Vaidya et al., 2018). I4.0 is based on the concept of integrating virtual and physical systems through cyber-physical systems (CPS; Stentoft et al., 2020). Effective combination of IoT, cloud computing, artificial intelligence, and big data and their integration into business and automation processes will conceivably improve the industry not only on operational but also on economic and environmental scales. In such a structure, machines and equipment become connected to a single cloud, to each other and avoid centralized control systems, but more importantly, will gain full autonomy to make fast decisions once unexpected events occur (Alcácer & Cruz-Machado, 2019).

Additionally, the implementation of digital automation through CPS will improve the customization of products by creating modular and changeable production systems (Tortorella & Fettermann, 2018). It is a concept of keeping mass production while adding individual products to the batch size and allowing room for the last-minute changes if requested by a customer (Beier et al., 2020). Mass customization can be extremely effective for small and medium-sized enterprises (SME) as well as allow less energy and material for production, which again contributes to the sustainability factor (Rüßmann et al., 2015). Thus, there are various opportunities and benefits to implement and move towards the digitalization of current industries.

With increasing levels of prioritization of I4.0 in both academic and industrial spheres, there is a correlated increase in complexity and intricacy in this new industrial revolution paradigm. Therefore, there is a lack of unified perception and approach of its implementation. Moreover, there is a need to develop common understanding of I4.0 between the researchers to overcome any confusion amongst external stakeholders. Even among the established institutions involved in the digital transformation, the vision of I4.0 is different (Hermann et al., 2016). This might be because the research in this area is still in its maturation stage, therefore the voids in the literature are persistent.

This paper aims to extend and explore the understanding of I4.0 knowledge areas so that the consequent steps towards the common understanding of the concepts and paradigms of I4.0 will be made in the research community. In this paper, main concepts, characteristics, and enablers related to I4.0 were identified to provide a clear understanding of the overall concept. Then, identified concepts and characteristics were matched and clustered according to semantic likeliness and closeness. Finally, as a major outcome, these clusters were used to develop a definitive I4.0 concept map and their respective heatmap of technology enablers, providing recommendations for the adoption of enablers of I4.0. As the foundation of the research, the main research questions of this study were

RQ1: What are the overarching concepts related to I4.0?

RQ2: What particular concepts and characteristics are primal to the I4.0 paradigm?

RQ3: How do I4.0 technology enablers support these concepts and characteristics?

2. Research methodology

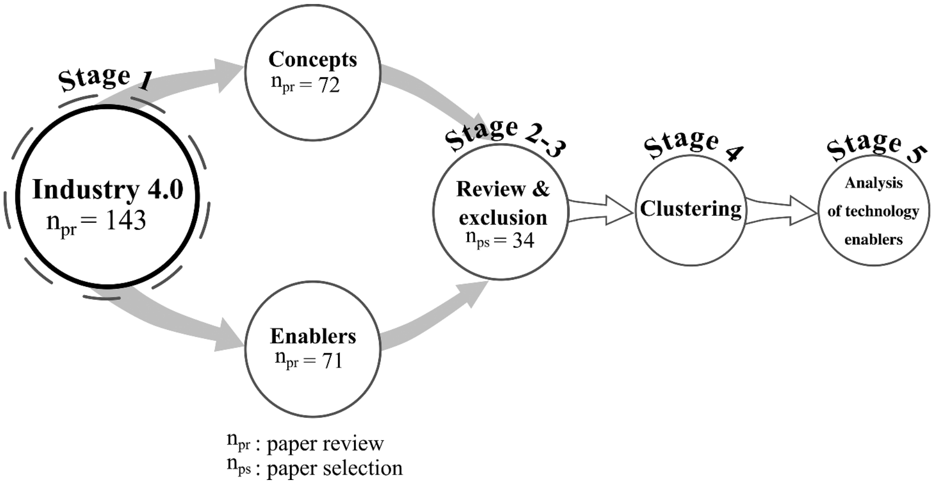
The current study is based on the Systematic Literature Review (SLR) to satisfy the research aims and provide a deep understanding of the I4.0 paradigm. SLR is a useful tool for extracting empirical evidence from the available literature and the analysis tool devoted to supporting research (Dikhanbayeva et al., 2020). The status review of the I4.0 topic was carried out to find out and merge the existing research knowledge on the concepts related to the digital transformation (Circular Economy (CE), Servitization, Smart Manufacturing (SM), etc.), characteristics, and technologies. The methodology of the paper is structured as shown in Figure 1.

First, a comprehensive search and collection of the papers related to concepts, characteristics, and enablers associated with I4.0 were conducted. It was performed among well-known scientific databases such as *Web of Science (WOS), Scopus*, and *Google Scholar (GS)* using the keyword "Industry 4.0" to cover all the journal/conference papers published on the I4.0 research track. During the initial search, which involved skimming the abstracts and content of the publications, 143 journal/conference papers related to I4.0 were identified, among them 72 papers related to concepts and 71 papers about technology enablers.

After the initial screening to uphold the rigorousness of the review, also to eliminate the papers that do not fall into the scope of the study, the following exclusion criteria were crafted:

- **EX1**: A paper is not fully written in English, e.g. abstract and keywords are in English, but the rest of the paper is in the other language;
- **EX2**: The full text of the paper is not available;
- **EX3**: A paper is informal and does not reference valid resources, e.g. a newspaper article;
- **EX4**: A paper does not provide any information on the I4.0 concepts or enablers;
- **EX5**: A paper does not provide a detailed discussion of the particular I4.0 related concepts and their enablers.

Figure 1. Adopted methodology.



In the first iteration of the review, the papers that matched EX1-EX4 and did not add value to the aims of the study were identified and excluded from the pool of the literature. This filtration resulted in the selection of 125 papers for the subsequent review procedure. Then, at the second iteration, the remaining exclusion criterion EX5 was applied, which resulted in the exclusion of 91 papers because of the lack of detailed content on particular I4.0 related concepts, characteristics, and enablers. Finally, the close-up review was terminated upon the selection of 34 journal/ conference papers. The identified I4.0 related concepts, characteristics, and enablers are listed and discussed in Section 3.

At stage four, the identified I4.0 related concepts and characteristics were analyzed based on the semantic likeliness, then aggregated into five distinct clusters. These clusters are expected to cover all layers of I4.0 from the perspective of the concepts and characteristics that are often presented as separate study domains. After that, to provide a helicopter view of I4.0, the concept map of the developed clusters was constructed.

Finally, at stage five, the heatmap of the I4.0 technology enablers with their relative contribution to the formed clusters was synthesized to show how the particular characteristics are supported by the exact set of technologies.

3. Background of Industry 4.0

I4.0 is a trending concept, which promises remarkable results for industries while profoundly changing organizations in many terms. Changes start in the way of setting up business models through the whole production process until the final point when the customer receives the product. However, considering that I4.0 is a newly emerging concept owning a wide range of definitions, there is still a lack of knowledge in concrete steps and only a few scenarios to follow to shift to I4.0 (Pfeiffer, 2017). Especially, this gap hits the companies, leaving them without proper instructions towards the new concept. Although definitions may have substantial differences (Kane et al., 2015), it is important to find out the similarities between them as well as the common ground. In that regard, Mittal et al. (2019) imply that terms such as smart manufacturing, digital manufacturing, and I4.0 are used interchangeably in a huge body of literature due to the lack of a universally accepted conceptual framework for the 4th industrial revolution. As a result, the main research aim of Mittal et al. (2019) was to provide a comprehensive overview on the clustering of technologies related to smart manufacturing as some of them are tightly interconnected between each other, thereby allowing the clustering and identifying the linking factors between those technologies. This approach inspired the authors of this paper to collect all main features (concepts, characteristics, and enablers) related to I4.0 to provide interested parties with an extensive but at the same time structured and classified understanding of this concept. Additionally, this approach helps to narrow the scope of I4.0 and identify the interconnection of concepts, characteristics, and enablers between each other. Moreover, due to different knowledge databases related directly or indirectly to I4.0, a unified understanding of the concepts or ontology is important. Thus, the aim of the collected terms and definitions provided in this paper is to establish unified databases for all interested parties as well as for their easy understanding. Further, an extensive literature review was conducted to identify all related aspects of I4.0.

"Concept" term in the paper context was used as a principle that generalizes similar ideas to simplify them. The number of I4.0 concepts varies due to their complexity, existing variety of definitions, and depending on the authors' perceptions. Lasi et al. (2014) explained seven fundamental and core concepts of I4.0, such as Smart Factory, Cyber-Physical Systems, and Self-organization. In support of this view, Roblek et al., (2016) put forward the claim that with the increase of interest towards I4.0, the extensive list of related concepts is also increasing. Moreover, Roblek et al. (2016) have provided a list of fundamental concepts of I4.0 based on a literature review. It includes the terms such as Smart Product, Cyber-Physical Systems, Digital Sustainability, and Smart City. Salkin et al. (2018) claim that the most important and interconnecting factor between different conceptual approaches towards I4.0 should be the integration of production facilities, supply chains, and service systems to the value creation processes. As a result of the review, an extensive list of 24 concepts was investigated and presented in Table 1.

In addition to concepts, characteristics and enablers were reviewed. However, due to the high number of various characteristics, as well as enablers, in the literature review part, only a few examples have been provided to give a general idea and provide basic knowledge, while the analysis part will include the more elaborated list. Characteristics assume the identification of the term, place, and other by a description of attributes pertaining to the subject (Amiron et al., 2019). For example, according to Majrouhi Sardroud (2012), the combination of several technologies helped to decrease the cost of logistics of construction materials, made a system more efficient, reliable, and less time-consuming. In the study by Krykavskyy et al. (2019), the effect of I4.0 technologies on the supply chain was investigated. As a result, by the survey findings, process optimization, increased flexibility, quality improvements, accurate and transparent data, and mistake reduction were noted. Based on all examples found in the literature review, common characteristics related to the I4.0 concept were underlined and presented in Table 2.

I4.0 is a broad concept covering many dimensions. However, only with the help of technologies, the digital transformation of all processes within the organization is possible. In that term, Issa et al. (2018) introduced the nine pillars of I4.0. According to Issa et al. (2018), application of all technologies separately is possible, but only their integration may transform the traditional manufacturing systems and improve them (Issa et al., 2018). Vaidya et al. (2018) also supported this point of view, where the author provided an in-depth clarification of the I4.0 concept and dimensions. Besides the nine pillars of I4.0, there are many more enablers and tools that need to be considered. A broader view of I4.0 enablers is presented within the analysis part, while the more extensive review of the main nine pillars is provided below:

- Big data: is a complex process of gathering, compiling, cleaning, and analyzing large sets of data to transform raw data into information that can be used for decision-making (Fei et al., 2019);
- Autonomous robots: intelligent machines capable of performing assigned tasks with the minimum involvement of humans (Bahrin et al., 2016);
- Simulation: analysis and testing of a model-based design of the systems, where the computer model imitates the properties of the implemented model (Dalenogare et al., 2018);
- Additive manufacturing: a manufacturing process of producing physical objects based on the 3D models through joining the successive layers of material (Kang et al., 2016);
- Horizontal and vertical integration: vertical integration implies an interaction at different levels of the hierarchical management structure in an enterprise, while horizontal integration assumes all external and internal departments and parties related to the creation of value chain (Dalenogare et al., 2018);
- Internet of Things (IoT): incorporates objects equipped with smart sensors that store, process, analyze, and interchange data between each other. IoT can enable real-time view production, increase in manufacturing efficiency and adaptive decision-making (Roblek et al., 2016);
- Cloud computing: technology that entails the leasing of the IT resources such as CPU or storage on a pay-per-use basis through the Internet (Alcácer & Cruz-Machado, 2019);
- Cybersecurity: a set of technologies, processes, and practices to defend interconnected manufacturing systems from cyberattacks and sensitive data leakage (S. S. Kamble et al., 2018);
- Augmented reality (AR): an enhanced replica of the physical world using computer graphics, sound, and other sensory information (Ghobakhloo, 2018).

4. Analysis and discussion

The concepts cover some key characteristics of I4.0, however individual concepts are not holistic and omnibus in the determination of I4.0 as a unifying and integrating paradigm. Therefore, to provide an

Table 1. Concepts related to Industry 4.0

#	Concepts	Definition	References
C1	Mass Customization	I4.0 acts as an enabler to provide on-demand services with high reliability, scalability, and availability in a distributed environment.	Y. Yi Wang et al. (2017), 1
C2	Servitization	This concept has a great interface with I4.0 in terms of the demand-pull model and service innovation with the acting technology-push model.	Alejandro Germán Frank et al. (2019), Ennis et al. (2018)
C3	Logistics 4.0	With the growing demand for customized products and services, I4.0 enables the emergence of Smart Logistics systems capable of appropriate planning and control over inbound and outbound logistics operations in companies.	Glas and Kleemann (2016), Alejandro Germán Frank et al. (2019)
C4	New systems in the development of products and services	With the focus on individualized products and services, the new paradigms of open innovation, smart products, and smart factories, the new systems will be required.	Alejandro Germán Frank et al. (2019), Dalenogare et al. (2018)
C5	Adaptation of human needs	Focusing on human needs, I4.0 introduces new human-system interaction with the usage of technological tools such as Big Data and IoT.	Hamada (2019), Sima et al. (2020)
C6	Smart Product	The I4.0 concept changes the standards of products and services offered by introducing technological tools in integrated systems to develop human-machine interaction.	Bilal Ahmed et al. (2019), Nunes et al. (2017)

(Continued)

Table1. (*Continued*)

#	Concepts	Definition	References
C7	Circular Economy (CE)	CE is defined as a global economic model to minimize the consumption of finite resources by focusing on the intelligent design of materials, products, and systems. I4.0 design principles such as decentralization, interoperability, and virtualization are the enablers of CE by allowing reuse, remanufacturing, and recycling of the products.	Rajput and Prakash Singh (2019), Lopes De Sousa Jabbour et al. (2018)
C8	Remanufacturing	I4.0 has a strong interface with this concept as through the remanufacturing of products, and there are opportunities to increase the efficiencies of resources, reduce waste, and support cleaner, more sustainable production.	Kerin and Truong Pham (2019), Shanshan et al. (2018)
C9	Lean manufacturing	Lean and I4.0 philosophies are complementary, and the union field is improvements in productivity, efficiency, quality, and waste management with customer orientation as the main focus.	Sanders et al. (2016), Sachin et al. (2020)
C10	Sustainability	I4.0 enables and supports sustainability by deploying digital technologies and business models with a focus on energy efficiency, pollution control, and value chain optimization.	Ejsmont et al. (2020), Ghobakhloo (2020)
C11	Recycling 4.0	It strongly correlates with CE and sustainability concepts and is one of the key drivers of I4.0.	Poschmann et al. (2020), Theo et al. (2018)
C12	Knowledge Management	I4.0 would enhance knowledge generation and utilization capacities and develop intelligent human-machine communication. This perfectly corresponds to the Knowledge Management concept.	Martin et al. (2020), Alcayaga et al. (2019)

(*Continued*)

Table1. (*Continued*)

#	Concepts	Definition	References
C13	Systems Science	As I4.0 incorporates various sophisticated technologies with a high degree of complexity and integration, Systems Science acts as a catalyzer for analyzing I4.0 complex systems.	Frazzon et al. (2019), Barata et al. (2018)
C14	Innovation Management	The necessary component of I4.0 development strategies and greatly correlates with the Knowledge Management concept.	Meski et al. (2019), Bettiol et al. (2020), (Sansabas-Villalpando et al., 2019)
C15	Business Process Reengineering (BPR)	I4.0 paradigms and technologies enhance not only operation-related process management but also introduce significant changes to business processes.	Ting et al. (2020), Xu 92,020)
C16	Self-organization	One of the core I4.0 design principles, decentralization, implies the development of new business models under which the majority of business operations will be performed in a decentralized form.	Wilkesmann and Wilkesmann (2018), Benitez et al. (2020)
C17	Collaborative Networks (CN)	I4.0 implies the development and enhancement of intra- and inter-departmental communication and integration, which is highly corresponded with the concept of CN.	Yuanju et al. (2019), Potoczek (2020)
C18	Vertical and Horizontal Integration	These concepts are the foundational ones for I4.0 philosophy, which is represented by several design principles.	Barbosa et al. (2018), Zhang et al. (2017)
C19	Flexible Manufacturing (FM)	The core technologies of I4.0 allow us to develop and enhance the business processes in terms of efficiency, productivity, and flexibility. Therefore, the concept of FM is directly related to the I4.0 paradigms.	Camarinha-Matos et al. (2017), Lima et al. (2020)

(*Continued*)

Table1. (*Continued*)

#	Concepts	Definition	References
C20	Agile Manufacturing (AM)	As the main idea behind AM is to acquire capabilities to adapt expeditiously to market changes and to provide customized products and services, it corresponds to the core ideas of I4.0.	Pérez-Lara et al. (2018), Chukalov (2017)
C21	Smart Factory	One of the cores and fundamental concepts of I4.0 and encompasses the features such as a highly integrated network of operations and flexible operational processes.	Margherita and Maria Braccini (2020), Godoy et al. (2018)
C22	Product Lifecycle Management (PLM)	PLM implies the improvement of business performance by integrating organizational and operational processes, technologies, and frameworks. This perfectly correlates with the philosophy of I4.0.	Yli-Ojanperä et al. (2019), Scheuermann et al. (2015)
C23	Digital Transformation	Digital Transformation and I4.0 closely related terms, as the presence of one also implies the presence of another. The commutating part of concepts is the deployment of digital technologies within new business and operation models.	Hozdić (2015), Büchi et al. (2020)
C24	Smart City	The Smart City concept implies the enhancements in several areas of city development such as economy, people, quality of life, government, and the environment by using digital technologies. In that term, I4.0 acts as an essential part of the Smart City concept.	Lom et al. (2016), Prosser (2018), Yun and Lee (2019)

Table 2. Common characteristics of Industry 4.0

#	Characteristics	References
1	Cost savings	Bruemmer (2016); Majrouhi Sardroud (2012)
2	Reliability/transparency of data	Krykavskyy et al. (2019)
3	Autonomous or decentralized decision making	Torn and Vaneker (2019); Sanders et al. (2016)
4	Time savings/reduction of process time, delivery time decrease	Construction (2011); Baynes and Steele (2015); Moeuf et al. (2018)
5	Improving quality	McMalcolm (2015); Allison (2015); Moeuf et al. (2018)
6	Increasing productivity	Müller et al. (2018); Saberi and Yusuff (2011)
7	Improving sustainability/ Better management of resources	Davies et al. (2017); Chou and Chih Yeh (2015); Yuan and Wang (2014); Tang et al. (2013)
8	Agility/flexibility	Daniel et al. (2017); Jasiulewicz-Kaczmarek et al. (2017)
9	Inventory tracking in a real-time	Sanders et al. (2016)

all-embracing and broad-based approach for analysis of I4.0, those fundamental concepts can be grouped or clustered under one dimension, which encompasses and consolidates the main implications on a dimension-view hyperplane. In other words, the clustered dimension can be viewed as juxtaposition and, at the same time, a summary of those similar concepts. In this section, the clustering based on the similarity and closeness of concepts and their implications concerning I4.0 was provided. However, it should be noted that this process is not the only way to cluster them because some concepts may overlap to a great extent so that the blurring of boundaries becomes more apparent. The main aim of this clustering is an attempt to provide the sound and main implications of those closely related concepts. After analyzing the main definitive features of those concepts based on the review of 33 research articles, the clustering of those concepts based on their close relatedness was provided.

Similarly, the five-clustered concepts were elaborated to extract the unique set of characteristics that affect the operation and performance of the businesses. Each cluster reflects in what sense the companies expected to be influenced by the adoption of I4.0 technologies from various facets. In addition, this clustering can contribute to the unification of the I4.0 anthology required for the seamless integration of machines, systems, and processes. In other words, the extracted metrics might facilitate the establishment of the performance indicators for decision-makers that should be tracked while implementing I4.0. After that, these clusters were analyzed on how I4.0 technology enablers support them, according to their mentions in the papers. A detailed discussion of the results of this analysis is provided in the second part of the section.

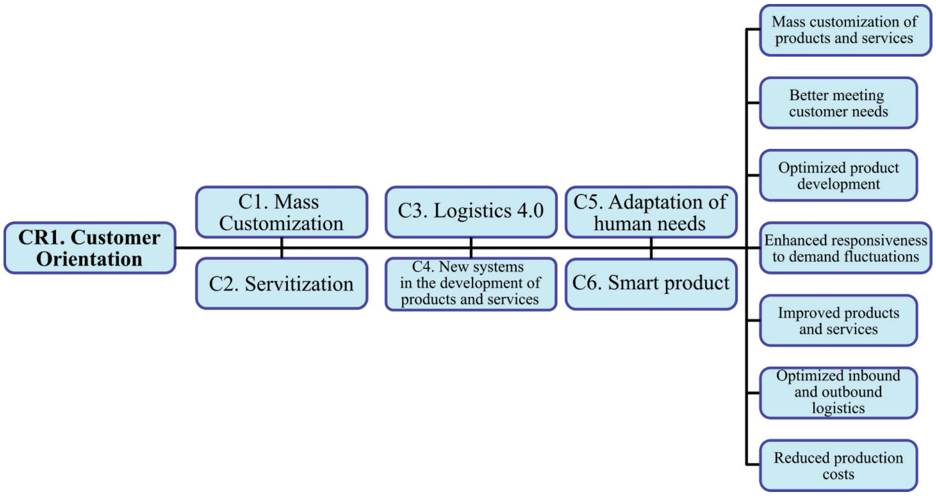
4.1. Industry 4.0 clusters

The first cluster is ***Customer Orientation*** *(CR1)* that includes concepts from C1 to C6. It takes an immense role in the advancement of widespread I4.0 adoption and implementation, as it is considered one of the major driving factors. According to Mihardjo et al. (2019), digital leadership encompassing the foundational features of digital competence and digital culture plays a crucial role in the proper development of business model innovations, as well as constructing the basis of customer experience orientation within the context of I4.0. Moreover, they point out that, as the customer experience orientation is a dynamic and multidimensional field with numerous factors affecting the market conditions, I4.0 acts as a unifying approach for leveraging the advantages of modern technologies towards strengthening customer relationships. In support of this view, Ibarra et al. (2018) put forward the claim that challenges associated with business models such as globalization, volatile market demand, and adaptation towards customer needs can be resolved with the implementation of I4.0. Furthermore, they have provided a holistic view of the different business models, such as service-oriented, network-oriented, and user-driven, and several solutions for providing digital transformation in manufacturing companies based on value capture, creation, and delivery processes. In outline, Ibarra et al. (2018) attempted to underlie the importance of I4.0 as an integrated concept to be a contemporary approach in developing business models with a focus on customer experience. In that regard, concepts C1 to C6 are closely related and clustered accordingly.

As shown in Figure 2, the customer orientation cluster is a combination of seven clustered characteristics. The first two distinct traits of this cluster are the enablement of mass customization of products and services as well as better meeting customer needs. As the infiltration of I4.0 is expected to substantially decrease the cost of product personalization with the help of advanced technologies, it will then highly raise the level of customer satisfaction and contribute to the realization of the production of a batch size of one (Shohin et al., 2020). Next, optimized product development is expected to reduce the time to develop, produce significantly, and release products, which will improve companies' adaptability in adjusting to fast-paced changing customer needs (Arromba et al., 2020). The digital transformation would also influence products and services and their value-added will be substantially increased due to the novel product-service offerings (Paschou et al., 2018).

Furthermore, in terms of supply chain management, enhanced responsiveness to demand fluctuation and optimized inbound and outbound logistics may enable more efficient and dynamic delivery of goods and materials. Moreover, as with the help of modular material flow systems, telematics, and Auto-ID technologies, the logistics operations, including transportation, replenishment, and receipt of materials/products inside and outside the company, are about to be more coordinated, flexible, and accelerated (Hofmann & Rüsch, 2017). Finally, as the last characteristic of this cluster, I4.0 significantly reduces production costs associated with manufacturing processes and product development. This will enable more economic allocation of resources, reduce the number of reworks and inefficiencies, and reshape the established industrial landscape (Arromba et al., 2020; Wijewardhana et al., 2020).

Figure 2. CR1 and related characteristics of Industry 4.0.



The second cluster group is ***Sustainability*** *(CR2)*, which encompasses concepts C7 to C11. With the respective changes towards new industrial paradigms, it is of utmost importance to take into account the increasing number of sustainability challenges. According to Ejsmont et al. (2020), I4.0 can act as a connecting hub between industrial activities and sustainability goals, and therefore, the bibliometric analysis of their relationship was provided in the research work. As the body of literature on that topic is extensive, it was decided to cluster the results of citation network analysis based on the focus of particular research topics on sustainability with I4.0. As a result, Ejsmont et al. (2020) highlight the importance of combining I4.0 realization with sustainability approaches, thereby reinforcing the relationship between these two paradigms. Similarly, Ghobakhloo (2020) features the point that I4.0 implementation could positively impact sustainable economic, environmental, and social development. Moreover, it stated that the process of I4.0 adoption should be mature enough to address the sustainability issues by providing sustainable functions based on digital technologies and design principles. Based on their cause–effect relationship analyses between I.40 and Circular Economy, Rajput and Prakash Singh (2019) determined that I4.0 related technologies provide favorable circumstances to strengthen Circular Economy features, such as remanufacturing and recycling. On these logical grounds, concepts C7 through C11 clustered together.

The sustainability cluster can be described using seven clustered characteristics (Figure 3). First, the extended durability of products describes the I4.0 impact on the lifecycle of products that will be significantly prolonged due to the shift of companies to servitized business models (Bressanelli et al., 2018). Optimized material and energy consumption stands for efficient resource and energy circulation between customers and suppliers that can be achieved with the support of digital technologies (Kerin & Truong Pham, 2020). As for minimized environmental impact and waste, I4.0 technologies uphold the adoption of sustainable manufacturing practices and reduce production waste. However, it should be supported by the appropriate standards and regulations to truly make a difference in dealing with environmental challenges (Kerin & Truong Pham, 2020). Enhanced labor efficiency is another outcome of I4.0 that entails the considerable reduction of the labor force and increased performance thanks to advanced intelligence and networkability of equipment (Shanshan et al., 2018). Also, I4.0 can facilitate the reduction of production emissions and increase the use of recycling and renewable energy with the help of smart grids and smart energy systems that enable real-time monitoring of electricity and resource consumption (Bonilla et al., 2018). Lastly, I4.0 helps organizations meliorate risks and increase financial performance through intelligent decision-making (Amjad et al., 2020).

The third cluster group is ***Knowledge Management*** *(CR3*), which includes concepts C12 to C15. According to (Bettiol et al., 2020), Knowledge Management plays an important and pivotal role in developing an organization in volatile environment conditions and embraces processes such as creation, elaboration, and transfer of knowledge. This can be supported by researchers in different fields. For example, Sansabas-Villalpando et al. (2019), in their work search for the best method to evaluate the critical factors that will help to strengthen the organizational culture in innovation with the main accent on sustainability and I4.0. From that standpoint, I4.0 introduces new approaches for organizational learning framework development such as Business Process Reengineering (BPR) and Enterprise Resource Planning (ERP). Moreover, it mentioned that the challenges associated with Knowledge Management, such as the ability to translate data into knowledge, the inclusion of external actors for innovation processes, and systematic knowledge database management, can be also addressed by the I4.0 paradigm. This view is supported by Wilkesmann and Wilkesmann (2018), which maintain that I4.0 implementation will automate the knowledge management processes to be both effective and efficient and provide opportunities for the innovation creation processes to be at the forefront of the business model development. Similarly, Benitez et al. (2020) provide the view that the ecosystem approach applied within the context of I4.0 could potentially foster value creation and innovation management processes in the organization, with a special focus on small and medium-sized enterprises. Thus far, concepts C12 to C15 are in one cluster group.

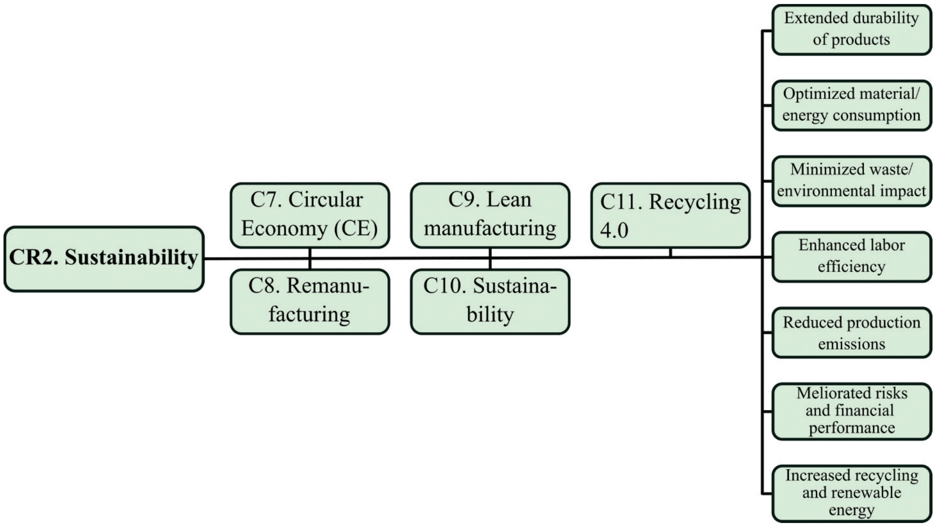


Figure 3. CR2 and related characteristics of Industry 4.0.

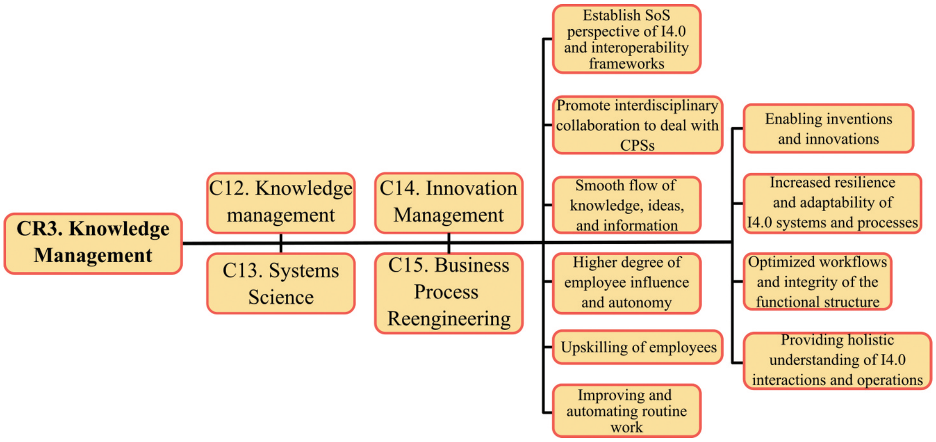


Figure 4. CR3 and related characteristics of Industry 4.0.

Knowledge Management cluster incorporates 10 clustered traits that pertain to I4.0 (Figure 4). First, its implementation enables inventions and innovations in companies because intelligent knowledge management systems and digital devices facilitate horizontal communication between the people engaged in decision-making, thus enhancing their skills and stimulating intrinsic motivation, which is favorable for the emergence of innovations (Wilkesmann & Wilkesmann, 2018). From the perspective of System Science, this cluster also provides a holistic understanding of complex I4.0 interactions and establishes the System of Systems (SoS) perspective of I4.0 and interoperability frameworks. Since the integration of CPS systems, which is a core of I4.0, implies a complicated and intertwined connection between machines, processes, and people, tools to drill down this intricacy and provide its in-depth understanding are required (Li Da, 2020).

Along the same lines, it promotes interdisciplinary training and collaboration to deal with CPSs. It is expected to incite the reforms in the curricula of universities to prepare specialists that conform with

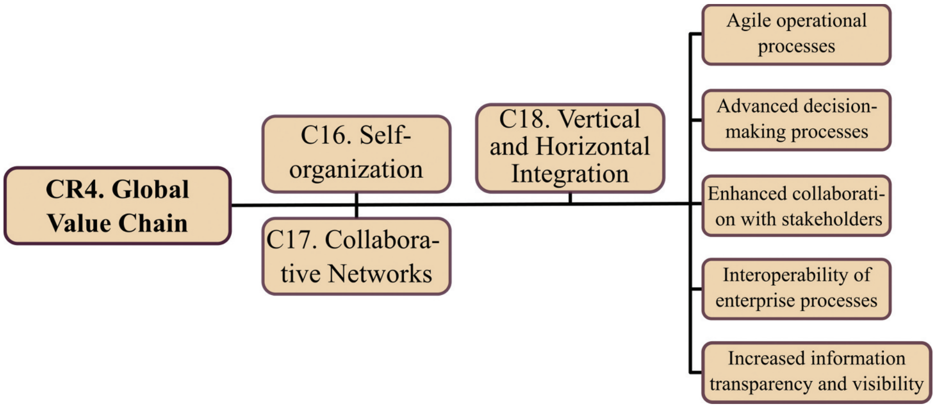
I4.0 requirements and, most importantly, contribute to the development of system science needed to design and engineer CPSs (Li Da, 2020). This will, in turn, make the traditional manufacturing systems and processes more resilient and adaptable to changes, which corresponds to the aims of I4.0. Another crucial feature is the smooth flow of knowledge, ideas, and information in smart manufacturing systems that can help companies to achieve the adaptability and integrity of their management processes (Yuanju et al., 2019). Moreover, in terms of employees, they will experience a great deal of upskilling owing to on-job training using knowledge management systems. As routine work is reallocated to machines, the complexity of tasks for humans will increase to the degree of their autonomy and influence (Wilkesmann & Wilkesmann, 2018). At last, I4.0 promises the optimization of workflows and overall integrity of the functional structure involving redesigning the strategic value-added business processes for improved productivity (Yuanju et al., 2019).

The fourth cluster group is ***Global Value Chain*** *(CR4)* and includes concepts C16 to C18. Strange and Zucchella (2017) propound the view that the emergence of newly developed industrial paradigms and concepts is already having a considerable impact on activities and strategic decisions made by companies and organizations with the main focus on value creation processes. Moreover, the implementation of digital features, such as IoT, Big Data and analytics, robotics, and additive manufacturing in production and manufacturing processes will enhance the elaborative nature of value creation in the organization and influence its performance in the global market. Furthermore, Chen (2019) highlights the difference between conventional value chains and those that are based on information and communication technologies and implies that the latter will be a widespread foundational standard for global supply chains. In the case of Taiwanese textile manufacturing, the implementation of IoT ecosystems was analyzed and results obtained have shown that production efficiency and customized CPS services are enhanced, thereby supporting that I4.0 implementation could potentially create great business opportunities by consolidating Global Value Chains. Similarly, Camarinha-Matos et al. (2017) suggest Collaborative Networks be one of the core enablers of I4.0 that directly impact the strategic directions and actions taken in an organization. The author also provides the point that six dimensions of I4.0, such as vertical integration, horizontal integration, and new business models, can be used to modify and enhance collaborative organizational structures, processes, and mechanisms. Therefore, concepts C16 to C18 are grouped into one cluster.

The global value chain cluster comprises five clustered characteristics (Figure 5). The application of I4.0 and its technologies affect the processes within the organization and optimize and enhance the whole supply chain. That is the reason that six out of seven characteristics are connected with the improvement of processes. First, the increased information visibility and transparency achieved through sensors, IoT, CPS, and other tools create more accurate data, having minimal errors (Camarinha-Matos et al., 2017). This, in turn, positively affects the decision-making processes, which in the current fast-changing environment requires good observation of the situation and fast decisions (Zhang et al., 2017). Improved or advanced decision-making approaches have several impacts. If, in one case, it increases the interoperability of the enterprises' processes at all levels (Zhang et al., 2017), on the other side enhances the collaboration with stakeholders, thus improving the general value creation process (Pérez-Lara et al., 2018). As a consequence of improved integration of the value chain, the agility of the operational processes can be achieved, taking into account the tools, which allow sharing more accurate data or even real-time monitoring. Finally, as a result of enhanced flexibility and improved communication between stakeholders in the supply chain, increased adaptability to the mass customization of products and services needs to be mentioned (Zhang et al., 2017). In conclusion, all mentioned characteristics consequently improve the overall business performance of any enterprise through the better usage of resources, optimization of the product lifecycle, and improved risk management (Marques et al., 2017).

The fifth cluster group is ***Smart Factory*** *(CR5)* and maintains concepts C19 to C23. In a massive body of literature, Smart Factory is considered as one of the foundational pillars of I4.0. For instance, Büchi et al. (2020) claim that the definition of I4.0 is multi-faceted, so that there are multiple definitions for that, such as Digital Manufacturing, Smart Factory, Digital Factory and

Figure 5. CR4 and related characteristics of Industry 4.0.



Production 4.0. However, as these terms might have a different perspective on I4.0 and the underlying concepts, they still have certain common elements that can assist in determining the foundational concepts and features of the I4.0 paradigm. Authors have analyzed and identified that those common features are automation and CPSs, digitalization, IoT, and changes in the relationship with stakeholders. Furthermore, in their research, Chen et al. (2017) have elaborated on Smart factory architecture and pointed that it is based on the concept of adaptive and flexible manufacturing. In addition, they state that some of the common features of Smart Factory include the ability of perception, interconnection, and data integration, as well as dynamic reconfiguration, production optimization, and enhanced controllability. With the same approach, Osterrieder et al. (2020) provided a thorough literature review on Smart Factory and categorized similar features and concepts into 8 cluster groups that highly correlate with the aforementioned definitions. They also suggested new concepts such as digital twin, data-driven decision-making, human-machine interaction, and cloud manufacturing. As it has noticed that these topics are highly relevant to the concept of Smart Factory. Therefore, concepts C19 to C23 are grouped together.

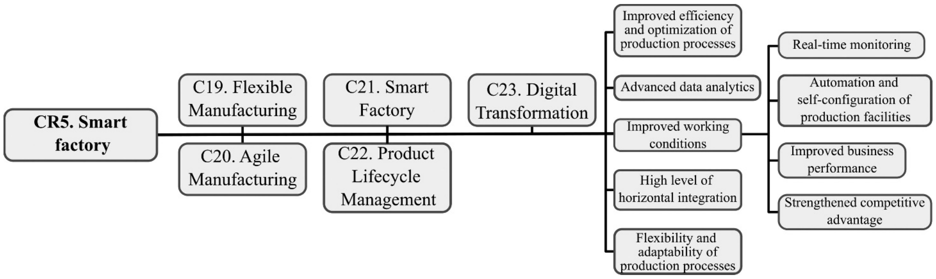
Smart Factory cluster is considered as the biggest by the scope within all mentioned clusters and consists of nine clustered characteristics (Figure 6). This cluster can be regarded as the final goal of digitalization, representing the well-integrated shop floor, including the equipment, machine, and devices communicating and continuously exchanging the data between each other. Therefore, it is not wondering that included characteristics contain elements from all previous clusters. The first five clustered characteristics are related to the inner production processes. Real-time monitoring of the data is important, resulting in increasing the transparency of the data within the organization and the whole supply chain (Chen et al., 2017). Moreover, large amounts of data produced during the production processes require powerful and, at the same time, fast advanced data analytic tools to receive only the relevant data anytime, and this can be enabled by Big Data (Zaki, 2019). Furthermore, tools of I4.0 and basic principles of digitalization assume increased automation of the processes and self-configuration of the production facilities, thus permitting enhanced controllability of production processes (S. Shiyong Wang et al., 2016; B. Chen et al., 2017). The combination of these characteristics results in improved efficiency and optimization of all processes (Margherita and Braccini 2020), and at the same time increasing the interoperability level of the vertical integration (Adamik and Nowicki 2018; B. Chen et al., 2017). The next combination of seven characteristics represents the improved customer orientation as a result of the merge of the previously mentioned ones. Real-time monitoring, advanced data analytic tools, and others positively affect the general flexibility and adaptability of the production processes (S. Shiyong Wang et al., 2016) and the better integration on a horizontal level (Margherita and Braccini 2020). This allows business processes to be more customer-oriented (Margherita and Braccini 2020; Adamik and Nowicki 2018), which assumes increasing customer satisfaction and quick response to their needs. Following that, as a result of the changes in the whole processes such as better optimization of the products' design and improvements in value creation processes results in mass customization (Adamik and Nowicki 2018; Yli-Ojanperä et al., 2019) as well as in improved quality and value of products and services (Nabass & Bahjat Abdallah, 2019; B. Chen et al., 2017). Consequently, general improvements in business performance can be achieved and strengthen the competitive advantage (Margherita and Braccini 2020; Yli-Ojanperä et al., 2019). The last combination of characteristics related to sustainability includes two aspects. Optimization and increased efficiency of all processes allow transfer to more sustainable value generation processes (Margherita and Braccini 2020; B. Chen et al., 2017), which additionally adds a significant positive social impact. Additionally, automatization of processes in organizations, smart devices, and increased control and monitoring results in improved working conditions (Margherita and Braccini 2020), which can also be considered as a positive and sustainable impact.

The last cluster group is Smart City, which is C28. In the majority of literature available, the concept of Smart Cities is considered massive and wide-ranging, and it has common characteristics with I4.0. For instance, Lom et al. (2016) propose that the main components of Smart City are CPS, IoT, Internet of Service, Internet of People, Internet of Energy, and FOG computing, which highly correlates with the phenomenon of I4.0. In other words, the authors highlight the point that I4.0 is considered as a building block of the Smart City concept, thereby increasing the scope and focus of the first one. In that regard, Prosser (2018) has provided the analysis of the Smart City concept through the prism of I4.0 enabling factors such as cloud services and real-time business intelligence, and distinguishes these two concepts based on their main focus: I4.0 is efficiency-oriented, whereas Smart City is focused on citizen/business satisfaction. Another viewpoint is provided by Yun and Lee (2019) by considering Smart City from the perspective of open innovation. They have identified the core enablers of Smart City, such as IoT, cloud technologies, Big Data, and blockchain, which are the core technological base of I4.0. Therefore, concept C28 is considered a self-sustained cluster group.

4.2. Analysis of technology enablers

To understand momentum for I4.0 concept formulation and use case deployment and appliances, one should consider not only the conceptual paradigm with related characteristics but also the impact of technology enablers that are relevant to I4.0 clustered concepts and characteristics identified. For the analysis of technology enablers, the same approach was taken as in the previous part. To determine the nature of the relationship of technology enablers with clustered concepts, the linkages of those enablers with I4.0 concepts were firstly analyzed. From the same literature corpus used for the I4.0 concepts, the list of corresponding enabling technologies was formed. Then, the total number of technology enablers under each clustered group (CR1 to CR5) was calculated. Consequently, all technologies were clustered according to their nature of operations. Based on that, the relative frequency of presence (or presence intensity) of each enabling technology cluster was calculated. The results of that enabling technology presence intensity for each clustered group can be seen in Table 3, which is developed in the form of a heatmap. In particular, the vertical axis shows the clusters of enabling technologies investigated, while the horizontal axis shows the I4.0 clustered groups.

Figure 6. CR5 and related characteristics of Industry 4.0.



By looking at Table 3, the first thing that stands out is that each cell has its corresponding color pallet: the higher the presence intensity of some particular enabling technology, the darker and dense colors will be. It also should be taken into account that under the column of each clustered group CR1 to CR5, the presence intensity of all technology clusters sums up to 100%, which is logical in calculating the relative frequency of each technology.

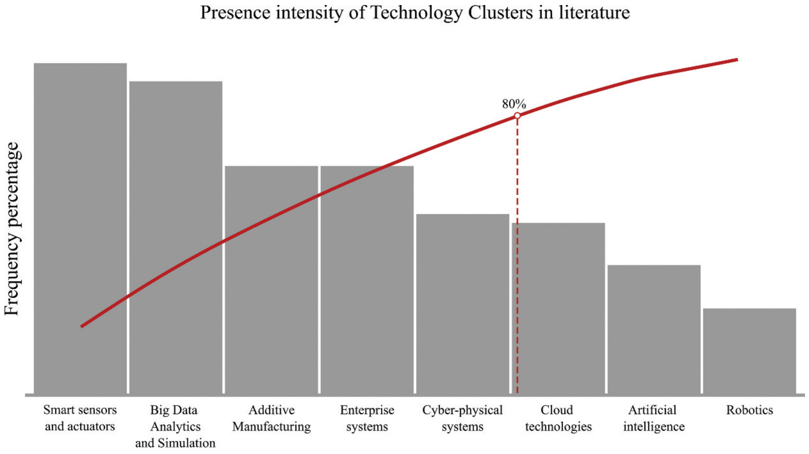
Before the analysis of results obtained, the process of how enabling technologies were clustered is provided. While providing the in-depth analysis of enabling technologies in the particular set of designated literature corpus, an extensive list of over 40 technologies was developed. Since the heatmap analysis on this list of technologies would not reveal useful insights about relations of I4.0 clustered groups with different enabling technologies being analyzed on particularly limited literature corpus, it was decided to cluster and group those technologies based on their nature of operations. The first set of technologies is *Additive Manufacturing* which focuses on enabling the production of products from different types of material such as plastic, metal, and concrete using 3D visualization techniques. It contains technologies such as 3D printing, Computer-Aided Design/ Computer-Aided Manufacturing (CAD/CAM), Augmented Reality (AR), and Virtual Reality (VR). The second set of technologies is devoted to structuring, managing, and analyzing enormous amounts of data generated (*Big Data*), thereby enabling the *digital simulation* of real objects and processes. Moreover, data transparency should be maintained during the process of developing digital infrastructure to maintain self-sustainable and continuous development. This group encompasses technologies such as Big Data Analytics, Data Mining, Digital Twin, and Blockchain. The third set of technologies is dedicated to the management of *enterprise systems* and involves items such as Enterprise Resource Planning (ERP), Manufacturing Execution System (MES), Business Intelligence (BI), and so on. The fourth set of technologies is grouped concerning *Artificial Intelligence (AI)* and incorporates Machine Learning and Neural Networks technologies. The fifth set named *Smart sensors and actuators*, which group together technologies such as the Internet of Things (IoT), Radio Frequency Identification (RFID), and smart material and workpieces. The sixth set is devoted to providing automation of enterprise systems and processes through the usage of *robotics* and includes technologies such as mobile robots and collaborative robots. The seventh set is named as *Cyber-Physical Systems* and aimed towards developing a communicative interface between digital and real-world through the integration of computation, networking, and physical processes. The last, eighth set is devoted *to Cloud technologies* and includes cloud computing and edge computing.

First, by analyzing the heatmap column-wise, the related enabling technology group with higher presence intensity can be identified for each clustered group. For CR1, Big Data Analytics and Simulation, Additive Manufacturing, and Cloud technologies are the most related technology groups according to the heatmap. As the main theme of CR1 is customer orientation, these digital technologies greatly support the characteristics of that cluster, such as optimized product development and improved product and services. Following that, under the CR2 column, the main enabling technology groups with higher presence intensity are Smart sensors and actuators, Big Data Analytics and Simulation, and Additive Manufacturing. The high correlation between these technologies and CR2 (Sustainability) is apparent because they notably support its corresponding characteristics, such as optimized energy consumption and minimizing waste. Next, for the CR3 (Knowledge Management) column, the highly related technology groups are Enterprise systems, Smart sensors and actuators, Additive Manufacturing, and Artificial Intelligence. They remarkably comply with clustered characteristics of CR3, such as improving and automating routine work and optimized workflow and integrity of operational processes. Thereafter, a similar picture emerges for CR4 (Global Value Chain), with related technology groups being Big Data Analytics and Simulation, Smart sensors and actuators, Additive Manufacturing, Cloud technologies, and Cyber-Physical Systems. By analyzing the associated characteristics of CR4, such as agile operational processes and enhanced collaboration with stakeholders, it can be identified that those enabling technologies are complementary and tremendously harmonized with underlying conceptual traits. Finally, CR5 (Smart Factory) maintains a similar pattern as previous clustered categories by having a high presence intensity of technology groups, such as Big Data Analytics and Simulation, Smart

Table 3. Heatmap of presence intensity of enabling technology groups in Industry 4.0 clusters

#	Enabling Technology Groups	CR1	CR2	CR3	CR4	CR5
1	Additive Manufacturing	18%	18%	11%	13%	9%
2	Big Data Analytics and Simulation	27%	18%	9%	20%	20%
3	Enterprise systems	9%	6%	31%	10%	11%
4	Artificial Intelligence	6%	6%	11%	7%	9%
5	Smart sensors and actuators	12%	30%	20%	20%	18%
6	Robotics	3%	3%	9%	3%	7%
7	Cyber-Physical Systems	9%	12%	6%	13%	13%
8	Cloud technologies	15%	6%	3%	13%	13%

Figure 7. Relative frequency (presence intensity) of enabling technology groups in literature corpus.



sensors and actuators, Cloud technologies, and Cyber-Physical Systems. As CR5 maintains several characteristics, among which are advanced data analytics, automation, and self-configuration of production facilities, identified enabling technologies are found to be in primary concordance with those conceptual traits.

In turn, from Table 3, it can also be seen that technology groups such as Robotics and Artificial Intelligence are less debated in the literature corpus analyzed. In other words, these particular enabling technologies were found to have a less correlated impact on I4.0 clustered groups, which is indicated in the heatmap available in Table 3. However, it should be taken into account that this hypothesis maintains tight limitations as it was analyzed based on a particular set of literature corpus. Moreover, this finding should not be explicitly stated in the term that those technology enablers have less impact on I4.0 omnibus paradigm compared to other ones, but rather as an attempt to analyze the nature of the relationship between enabling technologies and I4.0 clustered groups.

Analysis of the relationship between enabling technologies and I4.0 provides an overview of technological trends in that sphere, but it is provided in the limited hyperplane dimension of each clustered group. To comprehend the momentum for technology enablers in the context of I4.0, the panoramic view of those technology groups from the literature corpus is provided in Figure 3. By summation of references for enabling technologies in literature and thereby calculating the presence intensity of each technology enabler, one could analyze the overall trend of technologies in the context of the literature corpus on I4.0. Figure 7 develops as a Pareto chart from which it can be seen that frequently encountered sets of technology groups in the literature are starting from Smart sensors and actuators up to Cyber-Physical Systems are composing 80% of total technology references from the literature corpus. As an attempt to provide a broad sense of the nature of the impact of technology enablers on the I4.0 paradigm, it can be seen that the set of technologies is not limited to those presented in this study. But rather, it is an analysis of trends from a technological perspective on evolving and maturing concept of I4.0.

5. Conclusion and implications for future research

This research article identified the overarching concepts, characteristics, and enabling technologies of I4.0 that are devoted to establishing a common understanding among a variety of digitalization stakeholders. The results of this study might complement the research on the development of the I4.0 ontology. In other words, metrics critical for decision-makers of firms should be considered in the process of digital transformation. To provide a structure that makes sense for this kind of study, the systematic literature review of the I4.0 related concepts, characteristics, and enabling technologies was conducted. Amidst the critical review, three research questions were defined and answered. As the initial part of the analysis, 24 encompassing concepts related to I4.0 were defined. Thereby, answering RQ1, the concepts encoded as C1 to C24 with their definitions that reflect the current research directions and sub-studies of I4.0 are listed in Table 1.

Overall, based on the analysis of I4.0 related concepts and characteristics were formed five distinct clusters, namely Customer Orientation (CR1), Sustainability (CR2), Knowledge management (CR3), Global value chain (CR4), and Smart factory (CR5) that, in turn, can be broken down into 40 clustered characteristics composed of numerous smaller items mentioned in the reviewed articles. Thus, answering RQ2, the compiled clusters and characteristics primal to the I4.0 paradigm are presented in the concept map (Appendix) and explained in Section 3.

Furthermore, the heatmap of I4.0 technology enablers concerning their relative contribution and the frequency of presence in the reviewed literature corpus was constructed. Based on the analysis of enabling technologies and the clustered concepts and characteristics, thus answering RQ3, the most related cluster-wise enabling technologies are as follows:

- Customer Orientation (CR1) is mainly supported by Big Data Analytics and Simulation, Additive Manufacturing, and Cloud technology groups because they focus on such characteristics as optimized product development and improved products and services crucial for increased customer satisfaction.
- The most related technology groups of the Sustainability (CR2) cluster include Smart sensors and actuators, Big Data Analytics and Simulation, and Additive Manufacturing due to their high correlation with such characteristics as optimized energy consumption and minimized waste.
- Knowledge Management (CR3) cluster is in congruence with Enterprise systems, Smart sensors and actuators, Additive Manufacturing, and Artificial Intelligence, which aim to automate routine work, optimize and digitise workflow, and increase the integrity of operational processes inside the firms.
- The Global Value Chain (CR4) cluster is intended to provide companies with agile operational processes and enhanced collaboration with stakeholders. This can be realized through the implementation of such technology groups as Big Data Analytics and Simulation, Smart sensors and actuators, Additive Manufacturing, Cloud technologies, and Cyber-Physical Systems.
- Smart factory (CR5) represented by Big Data Analytics and Simulation, Smart sensors and actuators, Cloud technologies, and Cyber-Physical Systems that enable advanced data analytics as well as automation and self-configuration of production facilities.

The main findings of this analysis have shown that many of the existing characteristics that I4.0 can potentially equip companies. However, it should be noted that due to the focus on a certain set of papers, the overlapping between clustered characteristics is significant. Therefore, the provided clusters of I4.0 can be interpreted differently, as one may argue that a certain characteristic might be placed in another cluster. Although this clustering reflects the overall picture of I4.0 characteristics, it might be not feasible for organizations to attain all of them because it depends on which particular technologies are adopted. That is why, depending on business targets, firms should set priorities in their digital transformation to pursue their own goals. This is especially relevant for small- and medium-sized enterprises (SMEs), as incorrectly chosen I4.0 technology might inflict financial losses rather than benefits. That is, due to the relatively high complexity and high adoption costs of I4.0 technologies, SMEs need to focus on quick wins and invest in digital projects with the lowest expense but the highest added value. Unlike large firms that aim to increase business efficiency through the digitalization of operations, SMEs are advised to marry new business models with cutting-edge technologies. Since having a shorter chain of command, SMEs are more agile in nature, and they can introduce innovative products faster than incumbents and tap into new market niches, thereby changing the competition. Applying digital technologies in product development can improve the performance of SMEs and provide a long-term competitive advantage via products that address unique customer needs (Turkyilmaz et al., 2021). Hence, SMEs need to conduct a comprehensive and well-thought-out cost–benefit analysis of I4.0 technologies based on their sector, and product development strategy. In that regard, SMEs might refer to developed I4.0 clusters and technology analysis to facilitate decision-making.

Another finding of the analysis has revealed that the identified technology trends in the I4.0 literature corpus are consistent with other similar studies. However, since the analysis was completed within a limited scope of papers, the results might also vary from reality.

The major limitation of this study is that it is solely based on the literature review. Since the I4.0 research in certain dimensions is still in its infancy, the results of the study may change as the knowledge base in the area unfolds. In addition, the analysis involved a manual review of the papers clustering decisions based on the perspective and knowledge of the authors, which again presume some deviations. Therefore, future studies may include the extension and revision of clustering using a more systematic and technical approach as text mining with the help of advanced software and technologies.

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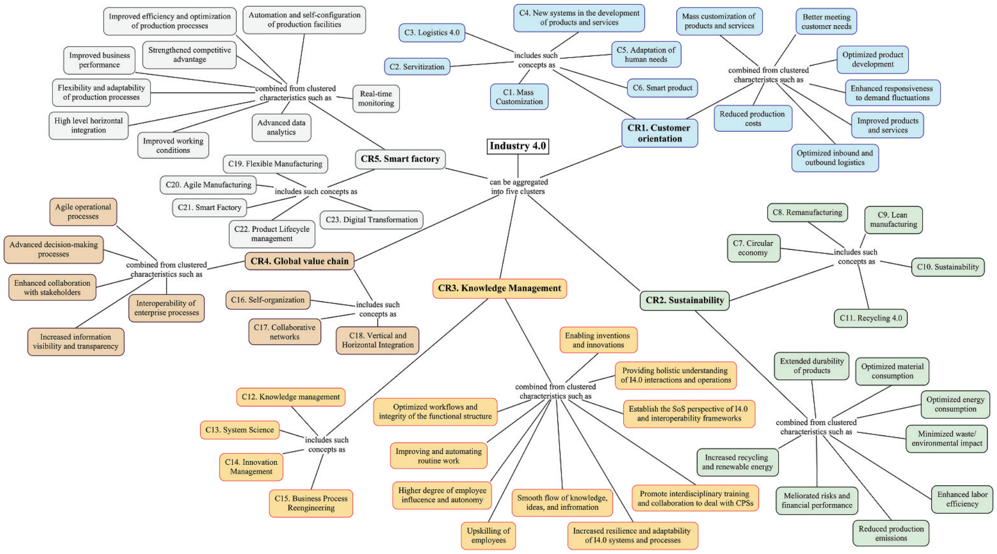
Appendix



"Industry 4.0: clustering of concepts and characteristics"

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