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Systematic Review

Competencies of the engineer in industry 4.0 context: a systematic literature review

Walter Rosas Quintero[a*], Julia Eleana Namuche Maldonado[a]
[a]Universidad César Vallejo, Piura, Peru
*wrosasqu@ucvvirtual.edu.pe

Abstract

Paper aims: To analyze the main studies to identify the competencies that engineers must possess in their education to confront the challenges of Industry 4.0.

Originality: The lack of clarity in the existing literature regarding the competencies of engineers in the context of Industry 4.0 reinforces the manuscript's originality.

Research method: Systematic review aimed at investigating the competencies engineers need in their professional education for success in Industry 4.0.

Main findings: There is no consensus on the required competencies for engineers to meet the new challenges posed by Industry 4.0; an ongoing topic of debate among experts in Industry 4.0 and the educational sector.

Implications for theory and practice: The practical and theoretical implications presented in this document are relevant for researchers and academics, as they can serve as a guide for future research and the development of models to close the competency gap in Industry 4.0.

Keywords

Competences. Engineering. Engineering education. Industry 4.0.

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1. Introduction

The concept of Industry 4.0 emerged with the German government at the Hannover Fair in 2011. According to the report "Recommendations for Implementing the Strategic Initiative Industry 4.0" by Kagermann et al. (2013), the implementation of Industry 4.0 will strengthen Germany's competitive position while aiding in addressing global challenges such as energy efficiency, resource management, and tackling organizational and regulatory challenges

Industry 4.0 is characterized by automation, digitalization of processes, and the use of electronics and information technologies in manufacturing (Ynzunza et al., 2017). The Fourth Industrial Revolution, also known as Industry 4.0, brings many disruptive changes, especially in the manufacturing and service industries, due to the interrelation of technologies, with its main elements being cyber-physical systems and connectivity, impacting various organizational functions (Foladori & Ortiz-Espinoza, 2022), (Akyazi et al., 2022). However, the success of Industry 4.0 will depend not only on addressing technological changes but also social changes, including demographic shifts and their implications for productivity, learning, and work (Kagermann et al., 2013). Rapidly changing work environments require cultivating a competitive workforce equipped with essential knowledge and skills in Industry 4.0.

Industry 4.0 imposes significant changes with increasing uncertainty and complexity. It faces challenges not only within the industry but also impacts the economy, society, and education. Companies manufacture, improve, and distribute their products while influencing consumer behavior and business models (Jiménez et al., 2019). Decision-making becomes ambiguous (Allendes, 2020), and globalization and rapid technological development demand that organizations confront disruptive innovation. This compels them to meet the expectations of such changes, not solely relying on technological investments but also embracing a paradigm shift regarding the new organizational context. However, Industry 4.0 also brings new opportunities and creates value for societies. Human talent must face the challenges and opportunities in this context, successfully matching themselves with the labor market processes. Thus, there is a pertinent need that demands new competencies from professionals in various knowledge areas fields to address the aspirations of Industry 4.0. This creates new challenges for education, especially in the field of engineering.

In this sense, universities and/or Higher Education Institutions, as responsible for the education of engineers, face a dilemma associated with the rapid transformation of Industry 4.0 and society. Consequently, they must constantly seek new ways to organize learning and research to address the challenges and the current context.

The education of engineering professionals demands competencies for increasingly changing work and social environments. This is compounded by scientific evidence revealing that knowledge is not static but a dynamic process characterized by high levels of competencies, short product life cycles, and constant testing of new processes, products, and services (Mendes et al., 2020). Hence, there is a growing concern among universities to provide education that responds to the needs of Industry 4.0, where human talent and technology converge to create new opportunities in a creative and innovative manner, seeking solutions, solving various problems, and exploring different possibilities for innovation (Fuertes et al., 2021). The purpose of the research is to identify and analyze the competencies that engineers must develop to effectively adapt to Industry 4.0, environment. The main question posed is: What competencies must engineers develop to adapt to Industry 4.0? The specific questions include: What are the fundamental technological pillars of Industry 4.0, and what competencies must engineers possess to successfully work with these technological pillars? Additionally, what challenges does engineering education face in incorporating these competencies and preparing students for the changes imposed by Industry 4.0? These inquiries will guide a detailed analysis of the skills necessary to confront the new challenges and opportunities presented by Industry 4.0.

2. Literature review

2.1. Industry 4.0

The term "Fourth Industrial Revolution" or "Industry 4.0" has been extensively explored and defined from various perspectives by multiple authors such as Kagermann et al. (2016), Schwab (2016). It represents a profound digital transformation that is impacting industrial operations and the global economy, enhancing business capabilities through the integration of emerging technologies (Grabowska & Saniuk, 2022). Industry 4.0 is fundamentally revolutionary within organizations, as it has the potential to catalyze fundamental changes in business processes and organizational adaptation. This technological integration enables faster decision-making based on precise, real-time data, promoting the transformation towards intelligent and highly efficient manufacturing environments (D'Orazio et al., 2020). Key technological pillars such as the Internet of Things (IoT), cyber-physical networks, automation, among others, have triggered a true revolution not only in the way production processes are carried out but also in business models, allowing holistic connectivity across different stages of the value chain (Nitlarp & Kiattisin, 2022). A detailed description of the main technological pillars is provided in Table 1, highlighting their significance in Industry 4.0.

2.2. Engineering education

To equip future engineers for the challenges of Industry 4.0, educational institutions must cultivate well-rounded professionals, endowing them not only with robust technical knowledge but also with a diverse set of competencies and attitudes aligned with this industrial revolution. Engineering education is undergoing a profound transformation, marked by the convergence of disruptive technologies, digital interconnectivity, advanced automation, and artificial intelligence, all of which are reshaping industrial processes and business models (Lu et al., 2019). Addressing these challenges necessitates a significant transformation in engineering education to produce highly skilled professionals. In this regard, accreditation emerges as a paramount concern, adopting evaluation frameworks to gain international recognition for engineering programs (Narong & Hallinger, 2024).

International accreditations play a crucial role in ensuring and promoting the quality of engineering programs. Accreditation is generally a review process undertaken by an institution or academic program to demonstrate

Table 1. The pillars of Industry 4.0 Key enabling technologies in the industry 4.0 paradigm.

Enabling Technologies	Description
Integration Systems	Horizontal and vertical integration systems forming a value-added chain; they allow integrating operational technologies with information and communication technologies.
Autonomous Machines and Systems (Robots)	Use of robots with greater cooperation, flexibility, autonomy, and human-machine interaction capabilities. Additionally, intelligent machines that automate tasks previously limited to human domain.
Internet of Things (IoT)	Connects devices, machines, environments, and objects through sensors and artificial intelligence. Enables multidirectional communication between machines, people, and products, facilitating decision-making.
Additive Manufacturing	3D printing system that allows manufacturing parts by overlaying layers of different materials based on a previous design, without molds, directly from a virtual model.
Big Data and Analytics	Systematic and digitized computational architecture with greater capacity to process and analyze large datasets accurately and immediately. These data can be reported by machines and equipment, sensors, cameras, microphones, mobile phones, production software, and can come from various sources such as companies, suppliers, customers, and social networks.
Cloud Computing	Service oriented to store data virtually in one place, improving processing performance, cost, and communication efficiency.
Virtual Environment Simulation	Simulates physical processes, machines, and products in the virtual realm, providing greater accuracy in decision-making and resource optimization.
Artificial Intelligence	Based on the development of algorithms that allow computers to process data at an unprecedented speed, also achieving machine learning
Cybersecurity	Strategic systems with IT governance standards, ensuring the security and reliability of communications and data transactions.
Augmented Reality	Allows complementing the real environment with digital objects. It involves systems that combine simulation, modeling, and virtualization, enabling new formulas for product design and process organization, providing flexibility and speed in the production chain.

Source: Dos Santos & Leon, 2020; Toprak et al., 2021b; Ynzunza et al., 2017.

compliance with established quality standards. In engineering education, accreditation is a rigorous evaluation and recognition process that certifies academic programs as meeting quality standards set by internationally recognized accrediting bodies. The essence of engineering education accreditation lies in ensuring that programs adhere to quality standards, aiming to develop competent professionals ready to practice engineering in a global and dynamic environment (Zhang et al., 2023). However, it is essential that both faculty and students adopt a positive attitude towards this accreditation process, considering the necessary changes in teaching methodologies, evaluation systems, and quality management (Haro et al., 2023).

Accreditation bodies such as the Accreditation Board for Engineering and Technology (ABET) and EUR-ACE (EURopean ACcredited Engineer), among others, play a vital role in guaranteeing the quality and relevance of engineering programs worldwide. ABET, based in the United States, sets comprehensive standards for engineering and technology programs, evaluating key aspects such as curricula, faculty quality, and available resources. Meanwhile, EUR-ACE, backed by the European Network for Accreditation of Engineering Education (ENAEE), focuses on harmonizing and ensuring the quality of engineering programs in Europe, promoting student and professional mobility within the region. These systems, along with others such as the Japan Accreditation Board for Engineering Education (JABEE) and the Institute of Engineering Education Taiwan (IEET), are fundamental in maintaining the excellence and relevance of engineering education on a global scale (Haro et al., 2023; Jalali et al., 2022; Olvera et al., 2021).

2.3. Competence

The term “competence” has undergone significant evolution, now encompassing a multifaceted blend of knowledge, skills, aptitudes, and personal traits that facilitate effective performance in specific contexts (Hlavac, 2023). In the professional realm, competence is defined as the amalgam of capabilities and skills essential for an individual to effectively meet job demands and excel in their professional environment (Salman et al., 2020). According to Bischof-dos-Santos & De Oliveira, 2020), supported by Souza et al. (2020), competence is not limited merely to technical skills but encompasses a comprehensive combination of knowledge, skills, attitudes, and motivations. The European Union defines key competencies as a combination of essential skills, knowledge, and attitudes necessary for the full development of citizens in today’s society (European Commission, 2019). These competencies are designed to prepare individuals for the challenges of a globalized and constantly changing world, enhancing their employability, active citizenship, social cohesion, and personal fulfillment. According to several authors such as Roll & Ifenthaler (2021a), Hadiyanto et al. (2022), and Ralph et al.

(2022), key competencies that engineering graduates must possess before entering the job market include both technical and soft skills that are essential for addressing modern challenges in engineering. Accreditation bodies for engineering programs—such as the ABET (Engineering Accreditation Commission, 2021), the ENAEE (European Network for Accreditation of Engineering Education, 2021), and the JABEE (Japan Accreditation Board for Engineering Education, 2019) are crucial in ensuring educational quality and preparing students for the professional environment. They define competencies comprehensively, covering both technical knowledge and soft and management skills. Their goal is to ensure that engineers are well-prepared to meet the challenges of the modern industry and contribute effectively in their professional roles. These bodies ensure that engineering training programs encompass technical, soft, and management competencies, preparing for the challenges of Industry 4.0. Table 2 provides a summary of how accreditation bodies define and categorize competencies to successfully address current job and technological challenges.

Table 2. Competencies of Engineers for Industry 4.0.

Competencies and Skills	Description of Competencies for Industry 4.0 According to Various Accreditation Bodies.
Hard Competencies	Hard competencies in engineering encompass crucial technical knowledge such as mathematics, basic sciences, and engineering principles, necessary for solving complex problems and designing systems. These include designing innovative solutions under constraints and the ability to stay at the technological forefront in Industry 4.0 (Engineering Accreditation Commission, 2021; European Network for Accreditation of Engineering Education, 2021; Japan Accreditation Board for Engineering Education, 2019).
Soft Competencies	Soft competencies include interpersonal and communication skills essential for professional success, such as effective communication in international contexts. The ability to work in multidisciplinary teams and adapt to multicultural environments is crucial for solving complex problems. Professional and ethical responsibility, considering the impact of work on society and the environment, is also fundamental (Engineering Accreditation Commission, 2021; European Network for Accreditation of Engineering Education, 2021; Japan Accreditation Board for Engineering Education, 2019).
Competitive Competencies	Competitive competencies are essential for engineers to excel in Industry 4.0. Adaptability and continuous learning are crucial to keep up with technological advancements. Project management and leadership, along with an entrepreneurial mindset and problem-solving capacity, are vital for developing innovative solutions and new business models (Engineering Accreditation Commission, 2021; European Network for Accreditation of Engineering Education, 2021; Japan Accreditation Board for Engineering Education, 2019).

Source: Engineering Accreditation Commission (2021); European Network for Accreditation of Engineering Education, (2021); Japan Accreditation Board for Engineering Education, (2019); Bischof-dos-Santos & Oliveira, (2020); Souza et al., (2020); Roll & Ifenthaler, (2021a); Hadiyanto et al., (2022); Ralph et al., (2022).

The analysis of the literature reveals a significant gap in understanding the competencies necessary for engineers in Industry 4.0. Although the World Manufacturing Foundation (2019) highlights the importance of education and skills for global competitiveness, there is still a lack of detailed assessment of the specific competencies required to address the challenges of Industry 4.0. Trevelyan & Williams (2019) identify a disconnect between engineering education and the routine activities of engineers. Furthermore, reports from United Nations Educational, Scientific and Cultural Organization (2021) and the World Economic Forum (2022) emphasize the need to adapt education to new technologies, but do not address how these adaptations translate into practical competencies. This underscores the urgency for research that defines the competencies necessary for success in Industry 4.0.

3. Research methodology

The research was a systematic literature review characterized by synthesizing the best available evidence to answer a research question through the location, identification, selection, and critical evaluation of relevant studies. Additionally, it involved the extraction and analysis of data from the studies included in the review, which may or may not have included meta-analyses and statistical techniques to summarize and integrate study results. This study was based on a systematic literature search in the scientific databases: Web of Science, EBSCO, ScienceDirect, and Scopus, which were selected for their extensive multidisciplinary coverage, rigorous publication selection, and advanced search tools (Gusenbauer & Haddaway, 2020)

3.1. Research question

The process for a systematic review began with the formulation of a specific and structured research question, which determined the terms used in the search across databases and the types of articles relevant to answering the question., According to Martinez et al. (2016) and Nishikawa-Pacher (2022), the PICOT format is the most widely used tool for developing research questions in a clear and structured manner, integrating fundamental elements: population (P), intervention (I), comparison (C), outcome (O), and time (T). It facilitates the research process and enhances the likelihood of accessing the most relevant scientific evidence, essential for informing and supporting decision-making across various research domains (Sánchez-Martín et al., 2023). Table 3 displays the basic components for crafting an appropriate research question identifying the research topic and the gap or deficiency it aimed to address, expressed in the form of a question: "What are the required competencies that engineers must possess to achieve success in Industry 4.0, and how do these competencies impact the education of engineers in university settings?"

Table 3. PICOT Approach.

P	Population or Problem of Interest	Engineering education
I	Intervention	Industry 4.0
C	Comparison	University
O	Outcome	Engineer's Competencies
T	Time or Type of Study	2018 al 2023

Source: authors.

3.2. Search strategy

To define search keywords and validate the search string, we combined different keywords related to the research questions (Bártová et al., 2022). The list of keywords used is presented in the search algorithm defined as follows: (Engineering or University) AND ("Industry 4.0" or "smart industry") AND (Education or Learning) AND (Competencies or Skills).

3.3. Selection strategy

The methodological strategy adopted for this systematic review was based on the PRISMA 2020 protocol, recognized as an updated and rigorous guide for conducting and publishing systematic reviews (Page et al., 2021). The study selection process was structured in the following key stages:

Record Identification: In this initial stage, an exhaustive search was conducted in selected databases to gather all records relevant to the study topic. A total of 910 records were identified from various sources: 115 from Web of Science, 286 from EBSCO, 51 from ScienceDirect, and 458 from Scopus.

Record Filtering: At this stage, the initial sample was refined to ensure that the selected articles met specific inclusion criteria. The criteria applied included belonging to open-access scientific journals and publication within the period from 2018 to 2023. After applying these filters, 521 records were selected, as detailed in Table 4. This initial refinement helped to focus the review on contemporary and accessible works.

Table 4. Search paths*.

Database	Search terms	2018	2019	2020	2021	2022	2023	TOTAL
Scopus	TITLE-ABS-KEY ((engineering OR university) AND ("Industry 4.0" OR "smart industry") AND (education OR "Learning") AND (competencies OR skills)) AND (LIMIT-TO (OA, "all")) AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018))	12	32	38	32	41	17	172
ScienceDirect	(Engineering or University) AND ("Industry 4.0" or "smart industry") AND (Education or "Learning") AND (Competencies OR Skills)	0	1	3	4	4	6	18
Web of Science	(Engineering or "University") AND ("Industry 4.0" or "smart industry") AND ("Education 4.0" or "Learning") AND ("Competencies" OR "Skills") (All Fields) and Open Access	2	5	15	24	22	8	76
EBSCO	(Engineering or University) AND ("Industry 4.0" or "smart industry") AND (Education or "Learning") AND (Competencies OR Skills)	17	21	55	61	68	33	255
	Limiters - Academic publications (refereed); Date published: 20180101-20230731; Hidden Net Library Holdings Expanders - Apply equivalent subjects	**31**	**59**	**111**	**121**	**135**	**64**	**521**

Source: authors.
* Date of consultation conducted from December 1, 2022, to July 25, 2023

Duplicate and Ineligible Record Removal: In this phase, the list of records was cleaned by removing 96 duplicate records that appeared in multiple databases. Additionally, 19 records were discarded by automation tools due to criteria of automatic ineligibility. Four records that were in languages other than English and Spanish were also removed.

Record Screening: During this stage, a detailed review was conducted to exclude records that were not relevant to the research topic. The authors independently evaluated the titles and abstracts of each article to determine their relevance to the research topic. A total of 296 records that did not meet the established criteria were excluded, of which 147 were not scientific articles, 63 records had titles not aligned with the research topic, and 86 whose abstracts did not appropriately correspond to the research. Additionally, 7 records that could not be adequately retrieved were removed. This screening stage ensured that only relevant and quality articles advanced in the review process.

Eligibility Assessment: In this phase, the authors conducted a thorough review of the 98 articles to confirm that they met all inclusion criteria. Only records that directly addressed the research questions were included, discarding 59 articles that did not provide relevant information on the competencies of engineers in the context of Industry 4.0. This stage ensured that the selected articles effectively contributed to the research objectives.

Results Synthesis: Finally, a detailed analysis of the selected studies was performed to assess their quality and the robustness of the evidence presented. An in-depth analysis of the 39 selected articles was carried out. Figure 1 presents the PRISMA flowchart, detailing the process of identification, screening, eligibility assessment, and final selection of the studies included in this review.

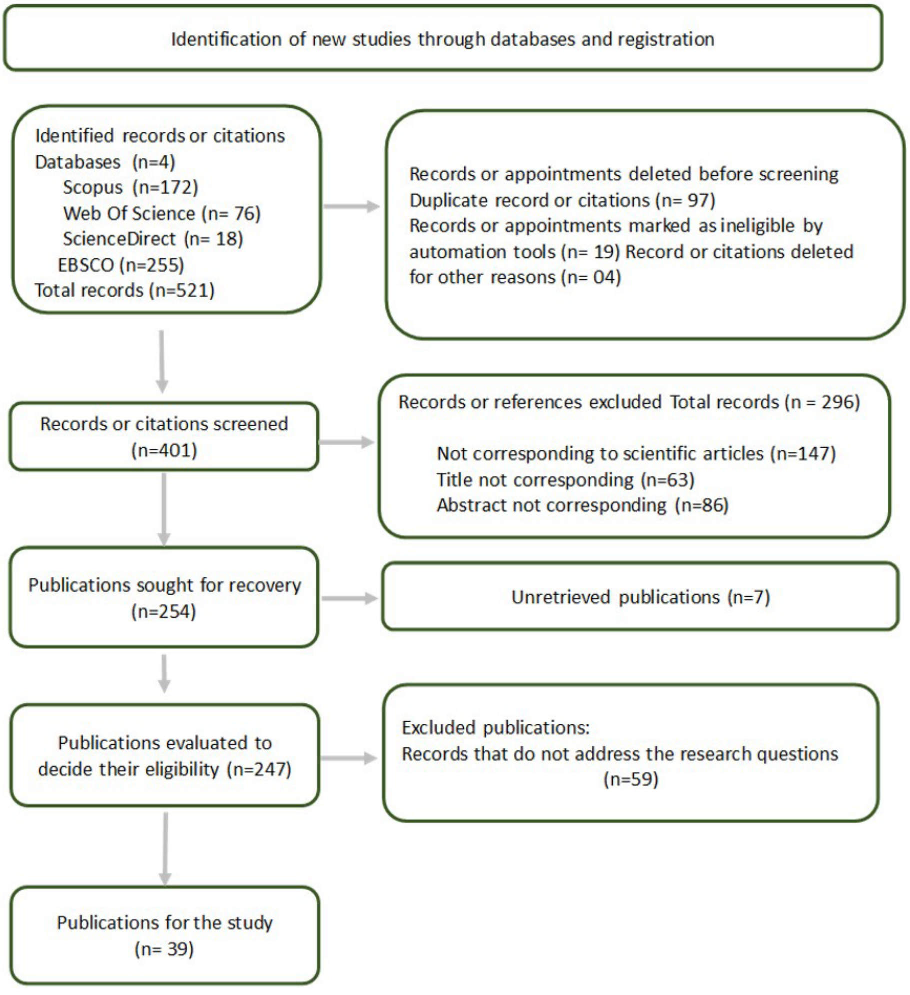

Figure 1. Flowchart of the methodology for the selection process.
Source: authors' adaptation (Page et al., 2021).

4. Results/Findings

4.1. Descriptive analysis of selected articles

The number of articles in this research, classified over the years, is shown in Figure 2. The curve illustrates how the research articles since 2018 have a growing projection, with a significant increase in the number of publications each year, focusing on learning new competencies for Industry 4.0. From this, it can be inferred that this research topic is currently being discussed and studied among researchers worldwide.

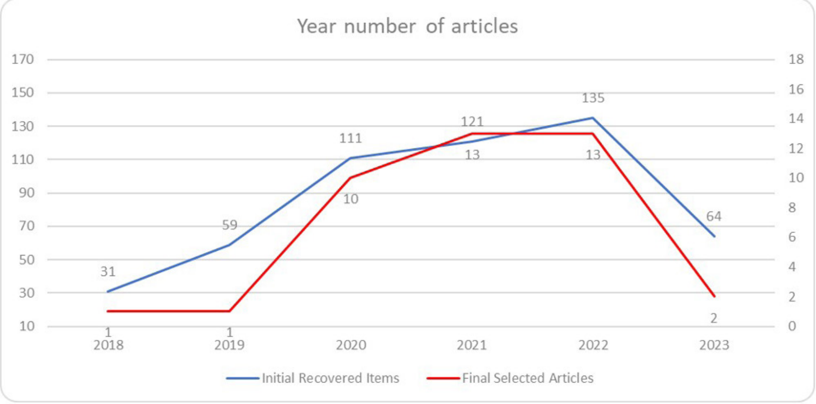

Figure 2. Trends of selected publications over time (Number of articles vs year).
Source: authors.

According to the World Economic Forum, (2018), the well-positioned countries to benefit from Industry 4.0, leading in design and testing, and pioneering emerging Industry 4.0 technologies, are: Germany, Austria, Belgium, Canada, China, Denmark, Slovenia, Spain, United States, Estonia, Finland, France, Ireland, Israel, Italy, Japan, Malaysia, Netherlands, Poland, Czech Republic, Republic of Korea, Singapore, Sweden, Switzerland, and the United Kingdom (González-Hernández & Granillo-Macías, 2020). In Figure 3 of this study, the depicted countries, with the highest number of articles, are Germany, Turkey, Spain, Indonesia, the Philippines, Poland, Russia, Italy, Brazil, Mexico, among others, which are classified as leading countries in the industry 4.0 domain.

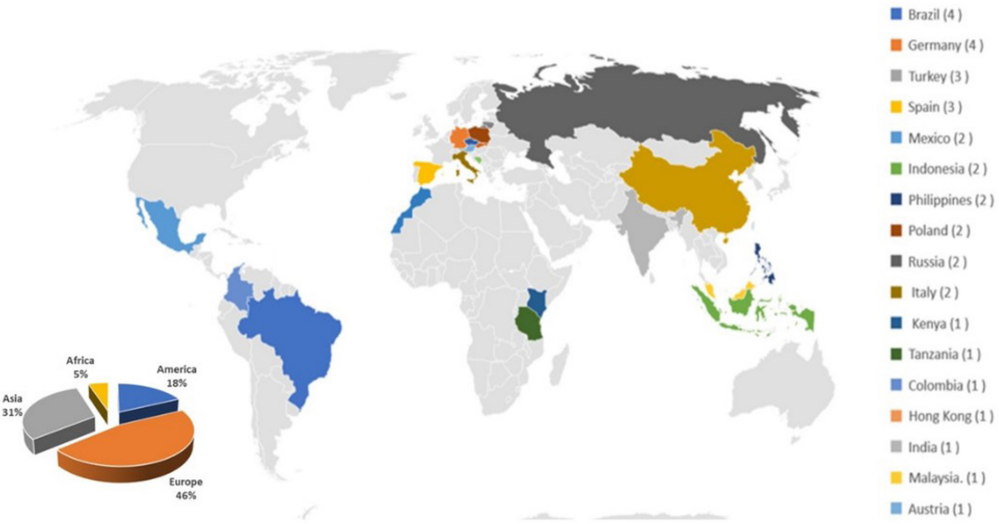

Figure 3. Information on the continent and country of origin of the research
Source: authors.

4.2. Correlation of articles: development of topics

To address the research question regarding the fundamental competencies engineers must possess to succeed in Industry 4.0 and how these competencies impact engineering education. Industry 4.0 represents a disruptive transformation in manufacturing processes driven by the integration of emerging technologies such as the Internet of Things, big data, artificial intelligence, and robotics. These advancements necessitate a reassessment of the competencies engineers need to integrate into this new industrial era successfully. To determine the competencies required in this context, this research will focus on three main themes: firstly, it will analyze the technological pillars of Industry 4.0 and their implications; secondly, it will explore how engineering education in universities should adapt to this new paradigm; finally, it will identify the most relevant competencies engineers need in this new scenario. Across these three areas, the research aims to comprehensively determine the impact of Industry 4.0 on competency demands and engineering education. Table 5 presents the articles to be compared for each research topic.

Table 5. Distribution of articles by topics to be discussed.

Topic	Definition	References
The pillars of Industry 4.0	Industry 4.0, also known as the connected industry, is related to digital transformation and the introduction of technology into all systems and processes of organizations.	Yüceol, 2021; Dos Santos & Leon, 2020; Romero et al., 2021; Akyazi et al., 2022; Fidalgo-Blanco et al., 2022; Bongomin et al., 2020; Toprak et al., 2021b; Spöttl & Windelband, 2021; Cropley, 2020; Güleryüz & Duygulu, 2020); (Saniuk et al., 2021; Mendes et al., 2020); Išoraitė et al., 2022; Wu et al., 2023
Engineering Education	Engineering education has a strong connection with global economic and social development; therefore, it is important to align engineering education with the socio-economic needs of a region..	Yüceol, 2021; Anisimova et al., 2018; Fidalgo-Blanco et al., 2022; González-Pérez & Ramírez-Montoya, 2022; Spöttl & Windelband, 2021; Costan et al., 2021; De Alburqueque et al., 2021; Cropley, 2020; Miranda et al., 2021; Rekh & Chandy, 2020; Akyazi et al., 2022; Roll & Ifenthaler, 2021a; Toprak et al., 2021a; Jung, 2020; Simeunovic et al., 2022; Vrchota et al., 2020; Ralph et al., 2022; Amini et al., 2023; Souza et al., 2020
Competencies for Industry 4.0	An engineer requires strong interpersonal skills associated with knowledge of engineering sciences and contemporary industry. Due to this, there is a need for current engineers to develop skills and competencies in response to this new vision of the industry 4.0 sector.	Yüceol, 2021; Akyazi et al., 2022; Teplická et al., 2022; Bongomin et al., 2020; Toprak et al., 2021a; Roll & Ifenthaler, 2021a; Roa et al., 2021; Ivaldi et al., 2021; Hadiyanto et al., 2022); Cropley, 2020; Güleryüz & Duygulu, 2020; Vrchota et al., 2020; Ra et al., 2019; Mingaleva & Vukovic, 2020; Hafni et al., 2020; Plawgo & Ertman, 2021; Cazeri et al., 2022; Mudzar & Chew, 2022; Cesco et al., 2021

Source: authors.

4.2.1. The framework of Industry 4.0 and its pillars

The historical developments of industrial revolutions have led to rapid and radical changes that have impacted our society. Industrial advancements that improve technology have resulted in increased production, greater efficiency, and contributed to social improvements. The fact that industrial revolutions strengthen economic development and provide a competitive advantage requires close monitoring and adaptation. According to Fidalgo-Blanco et al. (2022) and Išoraitė et al. (2022), from the first industrial revolution to the fourth industrial revolution, the entire society was affected, changing ways of acting and operating in all areas: economic, labor, social, technological, and educational. Similarly, to the first revolution, it requires an educational model that meets the arising new demands.

According to Dos Santos & Leon (2020), Toprak et al. (2021a), Spöttl & Windelband (2021), Hadiyanto et al. (2022), and Cropley (2020), Industry 4.0 represents a disruptive paradigm shift in industrial processes, driven by the synergistic convergence and integration of various advanced digital technologies. This technological convergence enables a transition towards flexible, personalized, and optimized manufacturing processes, reducing production times and bringing supply closer to the end customer (Cropley, 2020; Saniuk et al., 2021). In this context, engineers must develop a specific set of technological competencies to perform effectively in highly digitalized and automated industrial environments.

According to Yüceol (2021), Akyazi et al. (2022), Fidalgo-Blanco et al. (2022), and Bongomin et al. (2020), the primary technological competencies required include: specialized knowledge in emerging technologies such as artificial intelligence, IoT, and additive manufacturing; the ability to integrate multiple systems and manage real-time data; cybersecurity skills to protect interconnected systems; adaptability and continuous learning in the face of rapid technological advancements; and strong competencies in complex problem-solving and innovative solution development, enabling effective performance in intelligent industrial environments and driving business innovation and competitiveness (Mendes et al., 2020; Güleryüz & Duygulu, 2020).

These specific technological competencies, along with other transversal skills such as interdisciplinary teamwork and critical thinking, form the set of capabilities that future engineers must develop to thrive in Industry 4.0 environment. Higher education in engineering plays a crucial role by being responsible for updating curricula and teaching methodologies to prepare professionals for the challenges of this digitized and technified industrial paradigm. Table 6 outlines the main technological competencies required for Industry 4.0.

Table 6 describes the key technological competencies required for Industry 4.0.

The impact of this technological transformation is such that it is affecting all aspects of the organization, from production to research and development, as well as inventory control, management, customer support, etc. (Akyazi et al., 2022). In the near future, operators will be able to make smarter decisions in less time, thanks to real-time data from intelligent and automated production environments (Simeunovic et al., 2022; Cesco et al., 2021).

Table 6. Key Technological Competencies Required for Industry 4.0.

Technological Competencies	Description
Specialized knowledge in emerging technologies	Engineers must possess a deep and updated knowledge in emerging technologies such as artificial intelligence, the Internet of Things, augmented reality, additive manufacturing, among others. These technical skills enable the design, implementation, and management of interconnected and highly automated systems.
Ability to integrate systems and data.	The ability to integrate multiple technologies and systems is essential. Engineers must understand how to integrate data from various sources and manage complex cyber-physical systems. The ability to work with real-time data and use it to make informed decisions is a crucial skill.
Skills in cybersecurity	With increasing interconnectivity, security becomes a priority. Engineers need to be trained in cybersecurity to protect systems from potential vulnerabilities and attacks, ensuring the confidentiality, integrity, and availability of data
Adaptation and continuous learning skills	Given that technology evolves rapidly, engineers must have the ability to adapt to changes and continuously learn about new technologies and methodologies. A mindset of constant learning is crucial to staying updated in an ever-changing environment
Problem-solving skills	In a highly technological environment, engineers must be skilled in solving complex problems. This involves the ability to identify and address technological challenges, as well as creativity to propose innovative solutions.

Source: Yüceol, 2021; Dos Santos & Leon, 2020; Akyazi et al., 2022; Fidalgo-Blanco et al., 2022; Bongomin et al., 2020.

4.2.2. Engineering education in the context of Industry 4.0

Facing the challenges posed by the transition to Industry 4.0, a profound and rapid transformation is required for higher education to meet the demands of the fourth industrial revolution Ralph et al., (2022). Anisimova et al. (2018) and Plawgo & Ertman (2021) indicate that Industry 4.0 is changing the priorities of education and giving rise to new education models, based on digitalization of education, personalized learning, integration of educational types, and the creation of creative spaces for teamwork. (Hafni et al., 2020) suggest the need to shape professionals who are agile, flexible, and responsive, enabling them to connect and communicate in real-time, anytime and anywhere, constantly learning and continuously improving their skills with high adaptability in various environments, integrating technology.

The challenge is to educate and train future professionals in this field with today's knowledge (Vrchota et al., 2020). Technological advancements have allowed new modes of imparting learning (Ra et al., 2019). In this regard, pedagogical approaches are also evolving and reorienting their paradigms towards innovation in their training processes to meet the needs of a technologically advancing society. Miranda et al. (2021), Rekh & Chandy (2020) indicate that higher education should consider that knowledge generation goes beyond pedagogy and andragogy to an approach that combines heutagogy, peragogy, and cyber-pedagogy. According to Yüceol (2021), Anisimova et al. (2018), González-Pérez & Ramírez-Montoya (2022), Costan et al. (2021), Miranda et al. (2021), and Jung (2020), it is indicated that heutagogy promotes self-directed learning based on humanistic and constructivist principles centered on the learner for both learning and teaching. It encourages self-reflection and metacognition or understanding one's own learning process. Peragogy refers to the basis of collaborative learning, involving teaching techniques that promote learning between peers. Additionally, cyber-pedagogy has emerged due to technological advancements and the evolution of the internet, supporting the educational offerings. Cyber-pedagogy is defined as learning strategies promoted by ICT that offer learning experiences beyond the limits of time and space. In Figure 4, we present a summary of the path of education through the industrial revolutions.

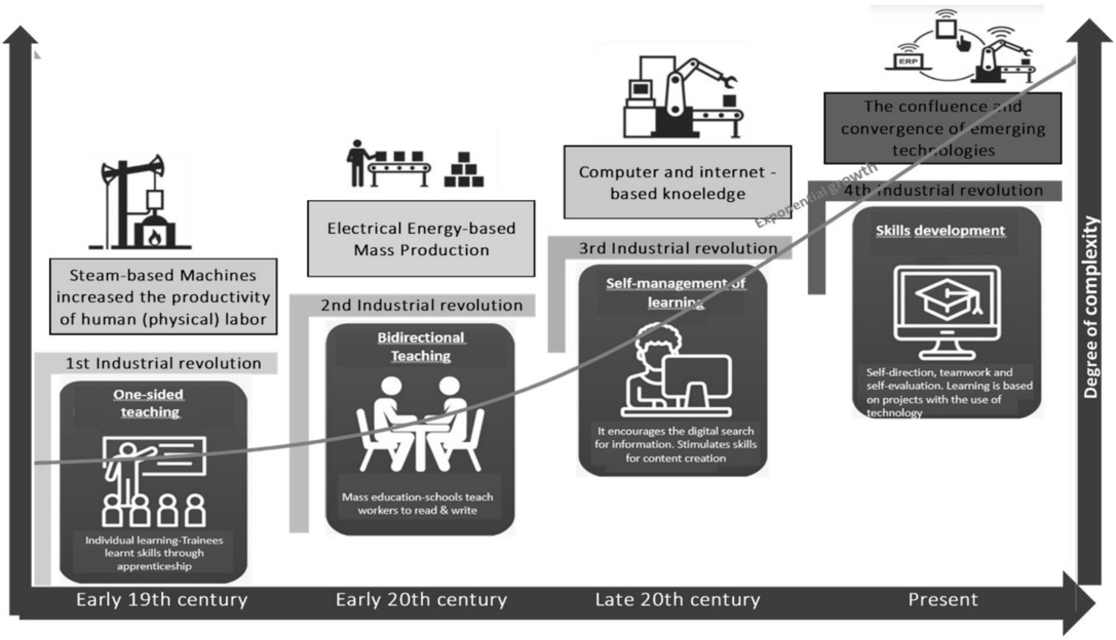

Figure 4. Path of education through industrial revolutions.
Source: adapted from (Yüceol, 2021; Anisimova et al., 2018; González-Pérez & Ramírez-Montoya, 2022; Costan et al., 2021; Miranda et al., 2021).

4.2.3. Necessary competencies for new university professionals in the context of Industry 4.0

The success of Industry 4.0 is driven by human capital, high-performance teams, leadership, and interdisciplinarity. Human talent must adapt to an educational learning model that is characterized by Volatility, Uncertainty, Complexity, Chaos, Ambiguity, Continuity, Co-created, and Connected (VUCCA + CCC), as explained by Roll & Ifenthaler (2021b). The developments of Industry 4.0 require a set of multidisciplinary competencies for professional training, consisting of specific knowledge, motivational aspects, cognitive skills, and abilities to meet the demands of digitally interconnected work situations (Fidalgo-Blanco et al., 2022; Mudzar & Chew, 2022). Industry 4.0 is associated with a set of soft skills, such as creativity, initiative, strategic knowledge vision, analytical thinking, critical thinking, collaboration, leadership, giving and receiving feedback, planning, and networking, as well as complex problem-solving in teams.

According to Costan et al. (2021), De Alburqueque et al. (2021) engineering education has a strong connection with global, economic, and social development. It is essential to align engineering education with the socioeconomic needs of a region, indicating that an engineer requires solid skills in human relations associated with knowledge of engineering sciences and contemporary industry (Bongomin et al., 2020).

The university education model should enable engineering graduates with better social skills, hard skills, and competitive skills to face the complexity and challenges of globalization and Industry 4.0 revolution. According to Hadiyanto et al. (2022), Fidalgo-Blanco et al. (2022), university education should be a model that meets the demands of Industry 4.0. This is achieved by developing competencies during the learning process that will be subsequently used in Industry 4.0 (Roll & Ifenthaler, 2021a; Plawgo & Ertman, 2021; Mudzar & Chew, 2022). It is essential for future professionals to develop the necessary competencies to work and participate in Industry 4.0. Table 7 provides a summary of the three groups of competencies according to the analyzed authors. The university must equip students with these competencies for success in the context of Industry 4.0.

Table 7. Competencies necessary for Industry 4.0.

Category	Competency	Competency Description
Soft or Transversal	Critical Thinking	ritical thinking skills include scientific literacy that helps critically understand the world around us and categorize vast amounts of information.
	Teamwork	Operating effectively as an individual and as a member or leader in diverse teams and multidisciplinary environments.
	Leadership	Ability to motivate and lead others; guiding organizations' digital transformation processes.
	Communication	Effectively communicate complex engineering activities with society.
	Creativity and Innovation	Generating and implementing new ideas and solutions through creativity and innovation.
Hard or Disciplinary	Technical and Specialization Skills	Knowledge of subject matter content, ideas, basic concepts, values, and facts that a graduate acquires within their area of study.
	Hardware and Technical Skills	Ability to research, design, create, and implement new technologies.
	Software and Algorithms Skills	Using emerging technologies and best practices to propose technology-based solutions.
	Digital Problem-Solving	Ability Applying science and engineering knowledge respectively to solve complex technology problems
Competitive Performance	Lifelong Learning	Recognizing the need and being prepared and capable of engaging in independent and lifelong learning within the broader context of technological change.
	Entrepreneurship	Capacity to create, promote, propose, build, and explore new ideas that can benefit businesses and society.
	Design / Development of Solutions	Designing solutions for complex engineering problems and designing systems, components, or processes that meet societal needs
	Research Skills and Efficiency Orientation	Conducting research on complex engineering problems, utilizing research-based knowledge and research methods.

Source: Soft or generic competencies (Yüceol, 2021; Teplická et al., 2022; Roll & Ifenthaler, 2021a; Toprak et al., 2021a); hard or disciplinary competencies (Hadiyanto et al., 2022; Cropley, 2020); competitive performance competencies (Hadiyanto et al., 2022; Ralph et al., 2022).

5. Discussions and eecommendations

5.1. Contribution of the reviewed articles

According to Akyazi et al. (2022), with the integration of artificial intelligence tools such as machine learning, collaborative robotics, or virtual assistants, industrial companies will adopt a more collaborative strategy within work teams, where the interaction between humans and machines will be pivotal. Engineers are expected to take on broader roles with increased responsibility, necessitating multidisciplinary knowledge. Rigid hierarchies will be replaced by agile and flexible structures. These AI tools will facilitate the transition by enhancing productivity. Mudzar & Chew (2022), Dos Santos & Leon (2020), Mendes et al. (2020), Cazeri et al. (2022) indicate that changes in the world of work, with a profound impact on training needs, technology, work organization, and social and ethical dimensions, should also be considered. The employability of future engineers is no longer simply a matter of technical skills application, as students must also possess complementary professional skills, also known as soft skills (Wu et al., 2023). Industry 4.0 will change the job landscape and the way workers perform their tasks, rendering some skills obsolete while creating demand for new skills.

The scenario of Industry 4.0 suggests a new process of professional education for engineers based on the development of skills and competencies. Universities and academic institutions are often considered one of the most important places for the development of pioneering ideas, upon which the progress of societies, their development, economic competitiveness, level of advancement, and many other aspects depend. Professional education for engineers should closely align with Industry 4.0 by introducing innovative learning methods and technological tools to enhance knowledge generation processes and information transfer. This new educational approach should promote (1) both cross-disciplinary and specific competencies that prepare students for the workforce. (2) Incorporation of new learning methods such as critical thinking, cooperation, collaboration, communication, creativity, and innovation, aligning with the changing demands of the modern industry. (3) Integration of Information and Communication Technologies to provide more flexible and accessible programs, offering in-person, distance, and hybrid learning modalities. These teaching and learning methods adapt to technological advancements, allowing the utilization of online resources, virtual laboratories, and collaborative learning platforms. (4) Educational infrastructure also plays a crucial role in education by offering innovative learning environments at both classroom and institutional levels. Classroom designs with advanced technology, as well as the use of suitable physical and virtual infrastructures, reinforce the connection between higher education and the needs of Industry 4.0. It is essential for higher education to evolve to meet the changing demands of Industry 4.0, shaping engineers and multidisciplinary professionals capable of solving complex problems, using disruptive technologies, and working in multidisciplinary teams, within global and technologically advanced environments (Miranda et al., 2021; Romero et al., 2021; González-Pérez & Ramírez-Montoya, 2022; Ralph et al., 2022). Figure 5 illustrates the challenge for universities to successfully implement the necessary competencies in engineering student education and leverage opportunities in the Industry 4.0 workplace.

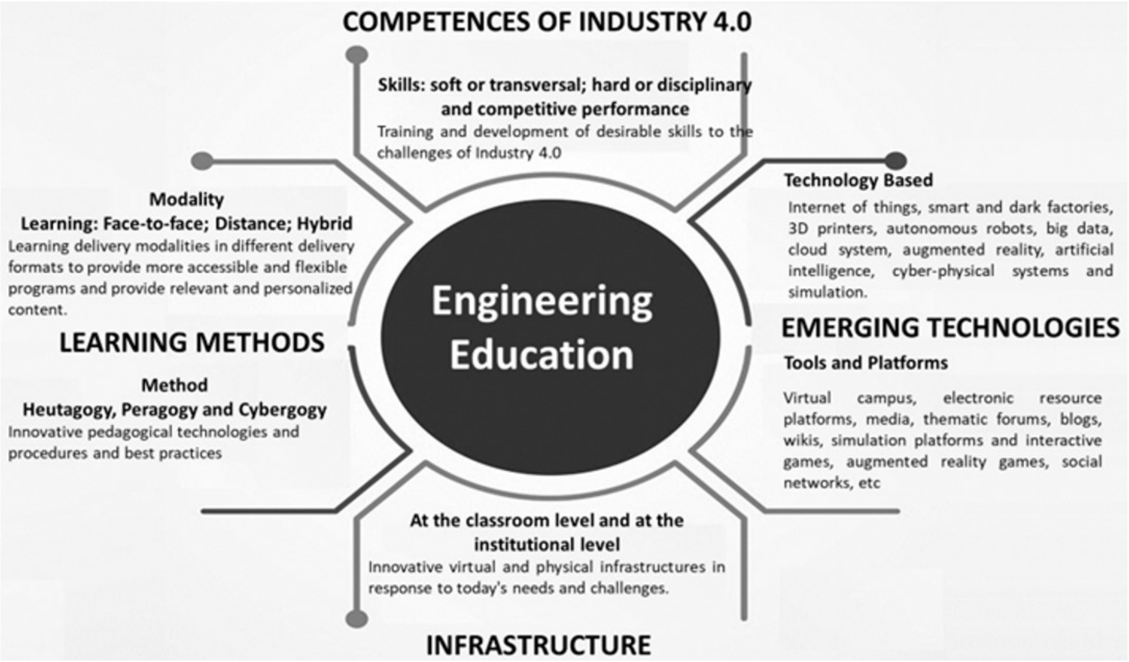

Figure 5. Components of Engineering Education in the Context of Industry 4.0, adapted from (Miranda et al., 2021; Romero et al., 2021; González-Pérez & Ramírez-Montoya, 2022; Ralph et al., 2022).

5.2. Deficiencies, challenges, and research opportunities

Engineering education within the context of Industry 4.0 faces a myriad of deficiencies that may impede the preparation of engineers for the challenges of this new industrial paradigm. One of the most prominent deficiencies is the lack of consensus on a unified framework of key competencies that engineers must acquire to excel in Industry 4.0. Research by Akyazi et al. (2022), Toprak et al. (2021a), and Spöttl & Windelband (2021) highlights this gap, emphasizing the absence of a standardized and widely accepted approach to defining essential competencies. This lack of clarity hampers the alignment of engineering programs with current labor market demands. Additionally, a significant gap persists between the competencies taught in classrooms and those actually required by companies in highly technological and automated industrial environments (Spöttl & Windelband, 2021; Cropley, 2020; Rekh & Chandy, 2020; Akyazi et al., 2022; Jung, 2020; Vrchota et al., 2020). Furthermore, insufficient attention is given to exploring the implications of the Fourth Industrial Revolution on key processes in engineering education and training, limiting educational institutions' ability to adapt effectively to this new environment (Mingaleva & Vukovic, 2020; Hafni et al., 2020; Plawgo & Ertman, 2021; Cazeri et al., 2022).

On the other hand, the challenges faced by engineering education in this context are multifaceted and complex. The rapid evolution of emerging technologies, such as artificial intelligence and the Internet of Things, necessitates constant adaptation of curricula and teaching methodologies to keep pace with disruptive technological advancements (Hadiyanto et al., 2022). This challenge is particularly pertinent given the growing gap between the competencies acquired by engineering students and the skills demanded by Industry 4.0 (Roll & Ifenthaler, 2021b). Additionally, there is a need to restructure engineering programs to effectively integrate practical and experiential learning, preparing future engineers for the challenges of industrial automation and smart manufacturing (Mudzar & Chew, 2022). In this regard, the adoption of active and innovative pedagogies, such as project-based learning and immersive teaching with virtual reality, emerges as a crucial strategy to facilitate the development of technical and transversal competencies aligned with the demands of the Fourth Industrial Revolution (Amini et al., 2023; Ralph et al., 2022).

Industry 4.0 presents a range of economic, social, technological, environmental, and political challenges that require specific competencies to be addressed effectively (Cropley, 2020; Ivaldi et al., 2021). In this context, engineering education must tackle challenges such as globalization, constant innovation, process complexity, virtual and collaborative work, climate change, and the need to meet legal and safety standards. This necessitates the development of a diverse set of competencies, ranging from intercultural skills, entrepreneurial thinking, and problem-solving abilities, to technical, analytical, and coding skills, along with transversal competencies such as teamwork, effective communication, and a sustainability mindset (Plawgo & Ertman, 2021; Roa et al., 2021). Table 8 consolidates the challenges of Industry 4.0 and the required competencies to address them according to the analyzed authors.

Table 8. Challenges, competencies, and key characteristics for Industry 4.0.

Challenges	Characteristics	Required Competencies
Economic Challenges	Globalization	Intercultural skills, language skills, flexibility in time, networking skills, and process understanding
	Innovation	Entrepreneurial thinking, creativity, problem-solving, ability to work under pressure, cutting-edge knowledge, technical skills, research skills, and process understanding.
	Service Orientation	Conflict resolution, communication skills, negotiation skills, and networking skills.
	Cooperative and Collaborative Work	Teamwork, communication skills, and networking skills.
Social Challenges	Demographic and Social Value Change.	Knowledge transfer, tolerance for ambiguity, flexibility in time and workplace, and leadership skills.
	Virtual Work	Flexibility in time and workplace, technological skills, multimedia skills, and understanding of IT security
	Process Complexity	Technical skills, process understanding, motivation for learning, tolerance for ambiguity, decision-making ability, problem-solving, and analysis skills.
Technological Challenges	Exponential Growth of Technologies and Data Utilization	Technical capabilities, analytical capabilities, efficiency in working with data, coding skills, understanding of security and IT compliance.
	Creation of Collaborative Work on Platforms	Teamwork, virtual communication skills, media skills, understanding of IT security, and collaboration ability.
Environmental Challenges	Climate Change and Resource Scarcity	Sustainable mindset, motivation to protect the environment, and creativity to develop new sustainable solutions.
Political and Legal Challenges	Standardization	Technical capabilities, coding and process understanding, data security and privacy awareness, understanding of IT security.

Source: adaptation from challenges in society in Industry 4.0 source (Ivaldi et al., 2021; Plawgo & Ertman, 2021; Roa et al., 2021)

6. Analysis and discussions

According to Verma & Pradesh, (2024) Industry 4.0 faces significant limitations, particularly in the lack of integration of the human component and the excessive reliance on automated systems that do not adequately address creativity and emotional intelligence. This situation has driven the transition towards Industry 5.0, which emerges as a response to these deficiencies. According to Grabowska & Saniuk (2022) and Raja Santhi & Muthuswamy (2023), Industry 5.0 is characterized by the incorporation of the Human Cyber-Physical System concept, which seeks a more complete integration between humans and intelligent production systems. This new approach aims to combine automation with human cognitive skills, not only to enhance productivity but also to promote job creation in emerging fields such as artificial intelligence and robotics.

The equitable lack of access to educational resources and the generational gap in adopting technological skills pose crucial challenges in engineering education for Industry 4.0. According to Saniuk et al. (2021), Bischof-dos-Santos & Oliveira (2020), these analyses emphasize the absence of universal educational standards and the difficulties in evaluating acquired competencies, indicating serious barriers in preparing engineers for this new industrial paradigm. Overcoming these deficiencies demands more agile, inclusive educational strategies focused on developing diverse engineering skills, alongside a more comprehensive and adaptable evaluative approach. However, further research is needed to thoroughly explore the competencies required in new contexts, particularly in the effective integration of automation with human cognitive capabilities. Nevertheless, these investigations face limitations due to the lack of consensus on assessment standards and the scarcity of long-term data supporting the effectiveness of proposed educational strategies.

7. Conclusions

Within the framework of Industry 4.0, where the integration of disruptive technologies redefines the interaction between machines and processes, it is essential for engineers to develop new competencies and skills to address the challenges of this industrial environment. This research has identified the fundamental competencies that engineers must possess to perform effectively, including advanced technical skills in automation, robotics, and artificial intelligence, as well as interpersonal and management skills to adapt agilely and creatively to technological and organizational changes. Industry 4.0 offers an opportunity to rethink engineering education, promoting a competency-based approach necessary for future industrial production. It is crucial for educational institutions and businesses to collaborate closely, strengthening the links between academia and the industrial sector, to ensure training that meets the real demands of the labor market and prepares engineers to lead and advance in the context of Industry 4.0.

Engineering education plays a pivotal role in forming future professionals with the competencies required to thrive in the digital era. Higher education institutions in engineering bear the responsibility of rethinking and updating their pedagogical models, curricula, and teaching methodologies to integrate technical and transversal competencies in a balanced manner, thus contributing to the development of innovative engineers equipped to face the multidisciplinary challenges demanded by Industry 4.0.

The scientific debate on the necessary competencies for an engineer to successfully integrate into Industry 4.0 organizations remains open, highlighting the importance of future research in this field. There are significant deficiencies and challenges that offer a valuable opportunity to conduct studies focused on the evaluation and optimization of teaching and learning processes, as well as to develop innovative strategies and methodologies to transform engineering education.

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