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ORIGINAL PAPER

Competencies for Industry 4.0

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Abstract

Industry 4.0 is a term that represents the radical transformation of Industry that has resulted from the integration of emerging technologies. It implies that we are witnessing the proximity of the Fourth Industrial Revolution. *Industry 4.0* aims to enable intelligent factories to produce personalized output utilizing greener and more efficient processes. However, to accomplish this, manufacturers must overcome several barriers, such as the lack of qualified talent to develop and manage various high-tech systems. This deficiency means that Industry 4.0 demands a change in the labor market, explicitly requiring trained professionals who have the competencies and skills to thrive in this new environment. What should a set of competencies be in the modern professional profiles? In this work, we review the required competencies, the technologies that aid in developing them, and the methods of assessing them.

Keywords Competencies · Assessment · Industry 4.0 · Smart 4.0 Industry · Smart manufacturing · Educational innovation · Higher education

1 Introduction

Industry 4.0 is a term that represents the radical transformation of Industry that has resulted from the integration of emerging technologies. It implies that we are witnessing the proximity of the Fourth Industrial Revolution. *Industry 4.0* aims to enable intelligent factories to produce personalized output utilizing greener and more efficient processes [63]. The factories can be managed by a central computer that controls all the different units' tasks and activities, from the supply chain to distribution. One critical function is that there must be a constant interchange of data among all the subsystems [62]. The potential of *Industry 4.0* includes faster decision making, better monitoring and control of the shop floor, more efficient use of resources, and better forecasting of demands.

Autonomous Robots, Simulation, Horizontal and Vertical System Integration, Industrial Internet of Things, Cybersecurity, The Cloud, Additive Manufacturing, Augmented Reality, and *Big Data* and *Analytics* are technologies that enable the implementation of *Industry 4.0*. They connect companies that take advantage of the vast amount of data generated by updated processes; this information allows for faster decision-making and flexibility [63].

Autonomous robots are at the core of *Industry 4.0*. This technology's benefits include increased productivity, reducing errors and re-work, and performing high-risk tasks [26]. Soon, these robots will manage (quickly and effectively) an extensive array of objects of various sizes and shapes. Moreover, they will make intelligent and precise decisions [36]. Simulations have been widely used in manufacturing to design products or off-line optimization; their main benefit is saving time and resources [79]. In the *Industry 4.0* context, simulations mimic processes to understand their behavior, make decisions, and improve performance [63].

Horizontal and Vertical System Integration consists of integrating independent production chains and the value-added subsystems of a single company. When it comes to horizontal integration, *Industry 4.0* employs connected networks of cyber-physical and commercial systems that have

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better levels of automation, flexibility, and operational efficiency in the production processes. Vertical integration in *Industry 4.0* aims to unite all the organization's logical layers, from the field layer to research and development. The main benefit of vertical integration is the enabling of autonomy throughout the entire business. *Industry 4.0* has made *Horizontal and Vertical System Integration*, the backbone of smart factories [73].

Th*e Industrial Internet of Things (IoT)* is the network integration of machine sensors, middleware, software, cloud computing, and storage systems in companies' industrial processes. The concept includes integrating smart manufacturing machinery, automation based on *Artificial Intelligence,* and advanced analytics to make all factories and workers more efficient. The *Industrial Internet of Things* is changing manufacturing by enabling the acquisition and accessibility of vast amounts of data, which gets distributed and used to develop advanced analytics, discover insights, and make operational decisions [28]. *Cybersecurity* refers to the protections and actions manufacturers take to avoid attacks on their information systems and devices for theft or manipulation. Such attacks could occur upon actuators, sensors, and information networks [24] that generate unexpected problems, such as production disruptions [4]. The *Cloud* consists of computer resources, applications, and networks accessed through internet servers [3]. *Cloud computing* means storing and accessing data and programs over the *internet* instead of through a local computer's hard drive. The *Cloud* is just a metaphor for the internet. It permits organizations to share information or data in milliseconds, and, in manufacturing, it allows real-time communication for production systems.

Additive Manufacturing is a process in which products are designed digitally and built by depositing layers of material [56]. The tremendous benefits for industry are that this can produce personalized products of high quality, innovative processes can be hastened, and the time to market can be shortened [33]. *Augmented Reality* is a tool used to improve an environment by superposing virtual images onto real objects [54]. AI is used to train operators or as an interface in interactions with robots. The benefits include an increase in productivity, savings in time and costs, prevention of errors, and the enhancement of design and development, among others [17]. *Big Data and Analytics* consist of analyzing significant quantities of data generated by the company's machines, processes, and logistical activities. The main goal is to discover knowledge that leads to better, more informed decisions in real-time [24].

Industry 4.0 offers excellent benefits. Digital production lets customers enjoy higher quality and lower cost products, protects the environment, and makes enterprises more competitive [10]. However, manufacturers must overcome some barriers to materialize these benefits. The principal one is the lack of qualified talent to manage the different systems [50]. The waves of emerging technologies are changing the labor market, especially in the competencies and abilities a person must possess to meet the new environment's demands. As a result, there is a need for new professional profiles [63].

Analysts predict that in 10 years, 3.5 million people will be needed to fulfill specific manufacturing vacancies. However, fewer positions will be filled because of the lack of professionals trained in the required competencies [74]. Such competencies are varied, ranging from managing complex manufacturing systems to having more creativity, strategic thinking, and coordination skills [32]. However, there is no clear consensus on these competencies. Well-qualified human resources will now be more critical than ever. Therefore, universities are already doing their part to educate and train professionals for success in *Industry 4.0*.

Higher education institutions must work closely with industries, professional clusters, and the government to keep their academic degree offerings up to date, especially per the demands for emerging competencies. In this context, rather than preparing a professional in multiple areas of knowledge, the collaboration (teamwork) of various professionals from different domains of expertise and other skills is desirable. *Industry 4.0* demands collaboration; it "is for people to learn to work with, and complement, the new technology with the most important thing: the human skills that cannot be replaced" [75].

The *Massachusetts Institute of Technology* has three programs to develop graduates with the relevant skills to face *Industry 4.0* challenges. *Makerlodge* is a program in which students learn about *Industry 4.0* technologies such as circuit board manufacturing and *3D* printers. The university offers more than ten makerspaces in which students can practice the abilities acquired. The program's final goal is to develop professionals who are innovators who solve significant problems in society [47]. *MIT Leaders for Global Operations (MITLGO)* is a graduate program that aims to develop professionals who can propose strategic initiatives in manufacturing companies. Leadership is the main competency developed, which is put into practice through internships with partner companies like *Amazon*, *Caterpillar,* and *Boeing* [49]. The *Smart Manufacturing Program* is an online option to learn how to implement *Industry 4.0* in an organization. A *Fiber Extrusion Device* is a piece of equipment that allows students to learn about the subjects, solve problems, and apply the knowledge acquired. The main competency developed is problem-solving [48].

Similar to *MIT, ETH Zurich* created the *Institute of Virtual Manufacturing,* whose primary goal is to develop research on themes related to manufacturing (planning, optimization, failure prediction, etc.). In this school, students apply the knowledge gained in classes in real projects. Technical competencies are the primary ones acquired [22]. The *Workshop on Science, Technology, and Policy: The Future of Work* is a program in which themes related to artificial intelligence, robotics, cybersecurity, and the management of disruptive changes are taught. The end purpose is that students acquire knowledge and competencies to perform future work. The program includes visits to enterprises such as *AI Singapore* and *One North-JTC* [21].

Finally, another example of the actions being implemented in universities to prepare professionals for *Industry 4.0* is *RWTH Aachen University. RWTH Aachen University* has the *Master's Program in Automation Technology,* whose primary goal is to teach participants how to make technical systems and processes work autonomously. The course planning is personalized as each student individually selects the topic of his interest. Competencies developed include teamwork, problem-solving, leadership, and management [67]. Another program offered is the *Master's in Data Analytics and Decision Science;* its principal goal is to teach participants how to handle and analyze large amounts of data. Not only specific technical competencies are developed but also transversal skills like decision making and problem-solving. Students also undertake internships at enterprises such as *DHL* [65]. The *Master's Program in Robotic Systems Engineering* teaches students about robots and trains them to develop robotic systems. Analytical, technological, and problem-solving competencies are developed [64, 66]. Just as these three universities have developed programs to prepare students for the opportunities of Industry 4.0, other entities offer some credentialing that span the range from traditional school programs to programs based on alternative credentials.

In this work, we review the competencies that future professionals need to work effectively in *Industry 4.0*. The report also examines the technologies that aid in developing these competencies and their assessment methods.

The outline of this work is as follows: Sect. 2 presents various models for assessing a company's maturity and its readiness to adapt to *Industry 4.0*. Section 3 has a review of the competencies in this context. Section 4 presents the technologies that assist in developing competencies and includes the assessment methods that determine their effectiveness. Section 5 discusses the conclusions of the work.

2 Enterprise readiness/maturity

There are two important concepts related to the adoption level of *Industry 4.0* among organizations: readiness and maturity. Sometimes these words are used interchangeably because both of them refer to an organization's state of readiness for *Industry 4.0;* one describes the beginning of the process (enthusiasm), and the other refers to specific stages of it (maturity) [69].

Readiness for *Industry 4.0* can be defined as the degree to which an enterprise can exploit and take advantage of the full benefits that *Industry 4.0* technologies offer. The dimensions of integration include the pressures to change existing processes, the willingness to take risks with the technologies, have sufficient knowledge about the technologies, have employees with the right competencies and skills and the motivation to work with these technologies, and have the proper amount of support from top management [72]. On the other hand, maturity can be defined as the *state of being complete, perfect, or ready* and deals with a system that is already running. The goal is to measure achievements at a later stage [69]. There are various ways of assessing the readiness/maturity of a company. The most common measures are based on self-assessment. However, nowadays, more quantitative models are developed, including those that deploy indicators, usually known as dimensions [59]. The majority of the models define the dimensions to measure. The *Industry 4.0 Readiness Online Self-check for Businesses* developed by the *IW Consult and FIR* at *RWTH Aachen University* contains six dimensions: strategy and organization, smart factory, smart operations, smart products, data-driven services, and employees. In turn, these have six levels of measure (outsider, beginner, intermediate, experienced, expert, and top performers) [42].

The *Singapore Economic Development Board* developed the *Smart Industry Readiness Index (SIRI).* It measures three general dimensions (Process, Technology, and Organization) that are broken down into eight sub-dimensions (Operation, Supply Chain, Product Lifecycle, Automation, Connectivity, Intelligence, Talent Readiness, and Structure and Management) [71].

The *Ministry of Int Trade and Industry of Malaysia* developed the *Industry4WRD* readiness assessment. It is a program that helps enterprises evaluate their capabilities for adopting *Industry 4.0*. The main goal is to understand their gaps and develop the right strategies to have effective implementation. The general dimensions assessed include technology, process, and people. *The technology* comprises nine sub-dimensions, including enterprise intelligence, facilities intelligence, shop floor intelligence, enterprise connectivity, facilities connectivity, shop floor connectivity, enterprise automation, and facility and shops floor automation. The *people* dimension has five sub-dimensions, namely, personnel competency for Industry 4.0, technology savviness of top management, leadership, collaboration structure, and governance and *Industry 4.0* strategy. Finally, *the process* has seven sub-dimensions: cybersecurity, horizontal integration, product individualization, product lifecycle management, performance management, technology management, and product management [46].

RAMI 4.0 from *BITCON VDI/VDE* is a three-dimensional representation of all the crucial aspects of *Industry 4.0*. It has two axes. The *hierarchy-levels* axis is the right horizontal one and represents the different functions inside a factory, i.e., product, field device, control device, station, work centers, enterprise, and connected world. The left horizontal axis is named l*ife-cycle and value stream* and represents facilities and products' life cycles. It includes development, maintenance/usage, and production. Finally, the vertical axis is divided into layers that represent the properties of a machine. The layers are business, functional, information, communication, integration, and asset. This model classifies all aspects of Industry 4.0. Enterprises interested in implementing *Industry 4.0* can use this 3D map to identify the requirements and prerequisites needed based on national and international standards. Once having done the analysis and determined their readiness for the implementation, the enterprises follow the next steps: (a) Identify the things that need to work autonomously (b) Identify the data required exchange between all the parts involved, (c) Define the synchronization requirements, and (d) Specify the communication connections and protocols [37].

SIMMI 4.0, which means *System Integration Maturity Model Industry 4.0*, is a model that allows an enterprise to construct its IT system landscape with a focus on *Industry 4.0* requirements. It assesses the readiness of a company's IT infrastructure. This model has four dimensions (vertical integration, horizontal integration, digital product development, and cross-sectional technology criteria) and five stages of digitalization (Optimized full, Full, Horizontal and Vertical, Cross-departmental, and Basic) that identify the level of digitalization of the company in each dimension [40].

Industry 4.0/Digital Operations Self-Assessment from *Price Waterhouse Cooper* is an online readiness model composed of 6 dimensions that include Business Models, Product and Service Portfolio, Market and Customer Access, Value Chains and Processes, Information Technology Architecture, Compliance, Legal, Risk, Security and Tax and Organization, and Culture. Three of these six dimensions require consulting services for assessment. The model provides an understanding of an enterprise's position concerning *Industry 4.0*. It measures the actual position versus a desired one and defines the enterprise's actions to achieve the former [58].

Other readiness/maturity models worth mentioning are [5]:

The *APM Maturity Model* from *Capgemini Consulting Group.* Its main goal is to help enterprises manage their asset performance, a key element of digital manufacturing. The model allows organizations to increase their asset efficiency, manage assets' sustainability, improve customer-centricity, and optimize the total cost of ownership. These improvements lead to cost reductions and the management of production plans [12].

Industrie 4.0 MM from *Uni Ankara* helps determine the capabilities an enterprise needs to implement *Industry 4.0* successfully. It acts as a guideline for organizations to identify their weaknesses and the areas in which they have problems. It also includes best practices that help them to transform themselves into an Industry 4.0 enterprise consistently [29].

M2DDM from *Uni Stuttgart* is a maturity model for data-driven manufacturing, which has six levels (Nonexistent information-technology integration, Data and system integration, Integration of cross-life-cycle data, Service orientation, Digital twin, and Self-optimizing factory). The lowest level specifies an enterprise with no integration of data processes; i.e., data is not used or stored for making decisions. On the contrary, the highest level refers to a factory that integrates all the systems, devices, and data to optimize the factory automatically [77].

The Connected Enterprise Maturity Model from Rockwell Automation is a five-stage maturity model that offers the best practices and measures necessary to implement *Industry 4.0* in areas related to technology and organizational culture. The five stages are Assessment, Secure and upgraded network and controls, Defined and organized *Working Capital data*, Analytics, and Collaboration [61]

Firma4.cz from the *Czech Ministry of Industry and Trade* is a self-assessment form that evaluates a company's digital maturity. Its five dimensions are (1) Leadership, human potential, the openness of corporate culture to digitalization, (2) Business model, customer orientation, and digital product, (3) Operating model, digital value creation environment, and digital controls, (4) Technology, and (5) Working with data. Its end goal is to support all the Czech companies that pursue digital transformation [16].

Enterprises' readiness/maturity can also be analyzed from the macro-level, i.e., at the national level. The environmental preconditions are its digitalization and its willingness to innovate. Some indexes that are used to evaluate enterprise readiness at the national level include the Networked Readiness Index (NRI), the Global Innovation Index (GII), the Global Competitiveness Index (GCI), and the OECD scoreboard [6].

As presented in this analysis, adopting technology and the workforce having the right competencies are among the main challenges of the implementation of *Industry 4.0*. From the workers' perspective, the main concern is the lack of the right competencies that *Industry 4.0* demands. From the technology perspective, the main challenge is to remove the "high cost of deployment" paradigm to start reaping the benefits in the long term [52].

3 Competencies

The *Accreditation Board for Engineering and Technology, Inc.(ABET)* considers that successful professionals must have the following abilities: (1) to apply knowledge of mathematics, science, and engineering; (2) to design and develop experiments; (3) to analyze and interpret data; (4) to create systems or processes considering economic, environmental, social, political, ethical, health and safety, manufacturing, and sustainability constraints; (5) to identify, formulate, and solve engineering problems; (6) to understand the impact of engineering solutions in global, economic, environmental, and societal contexts; and (7) to use the techniques, skills, and modern engineering tools necessary for engineering practice. Based on *ABET* accreditation, it can be confident that an academic program meets the standards that produce competent graduates prepared to enter the global workforce.

Generation Z (people who were born from 1995 onwards) students are now entering the workforce. This generation has distinguishing characteristics that suit the emerging technologies of *Industry 4.0*. Their media consumption habits differ from previous generations; they prefer "cool" products over "cool" experiences, they are entrepreneurial and tech-savvy, and they want to co-create culture. They must have the knowledge and abilities that *ABET* has defined as useful to work in *Industry 4.0* environments, which are characterized as technology-intensive and digitally interconnected. Some of the competencies that these professionals must have include decision making, cultural and intercultural skills, lifelong learning, interdisciplinary thinking, problem-solving [14], and handling of typical *Industry 4.0* technologies [50].

Researchers are working to determine the competencies that future professionals must have to effectively adapt when entering the workforce. Through the development of a literature review, a group of researchers identified competencies that new entrants to the force must have to implement *Industry 4.0*, as shown in Table 1 [32].

Industry representatives and experts suggested in a survey that the competencies and knowledge associated with different required elements of *Industry 4.0* are the following, as shown in Table 2 [75].

Figure 1 shows the different relationships among several technical and engineering elements of *Industry 4.0*. These technological elements influence the products, their lifecycles, and customers (emphasized squares). Similar figures can be generated for business and innovation elements of *Industry 4.0* [75].

Transversal competencies include problem-solving skills, soft (personal) competencies, systems thinking, business thinking, and technological literacy, as shown in Table 3 [75]. Transversal competencies can be applied in various domains; they can be classified as primary, intermediate (built on basic), and high (built on intermediate) competencies.

All of these competencies are interrelated and coupled. *Problem-solving* competencies are critical for the *Industry 4.0* approach. These competencies take in the fundamental sciences, applied sciences, and problem-solving attitude [68]. *Technological literacy* and *scientific processes* help to understand and solve the problems. The development of thinking processes sometimes occurs through *creative experimentation. Soft competencies* allow people to *work in multi-disciplinary teams* and include *leadership*, *networking*, *communication* (*written and oral*), and *assertiveness*. Developing *self-knowledge* demands the personal attributes of *will*, *motivation*, *self-direction*, *self-regulation*, *self-judgment*, *self-awareness*, and *self-regulation*, all of which enrich *life-long learning* [55]. The latter, learning continuously, is associated with openness to change and improvement and learning something new from the academic domain. *Systems thinking* means understanding the process holistically. *Ethics* and *sustainable development* lead to making better decisions. *Social innovation* in *Industry 4.0* relies on the benefits of technology and the need for different views from interested people. *Business thinking* allows for analyzing the commercial side of the products and services. Finally, the knowledge of essential engineering tools, how they function, and how they are used, is the definition of *technological literacy*.

Table 1 Competencies required for the *Industry 4.0* workforce

Technical competencies	Methodological competencies	Social competencies	Personal competencies
State-of-the-Art knowledge	Creativity	Intercultural skills	Flexibility
Technical skills	Entrepreneurial thinking	Language skills	Ambiguity tolerance
Process understanding	Problem-solving	Communication skills	Motivation to learn
Media skills	Conflict-solving	Networking skills	Ability to work under pressure
Coding skills	Decision-making	Ability to work in a team	Sustainability mindset
Understanding IT security	Analytical skills	Ability to compromise and cooperate	Compliance
	Research skills	Ability to transfer knowledge	
	Efficiency orientation	Leadership skills	

Other researchers [8] believe that *Information Technology* professionals will be more critical than ever in companies. *Information technology* jobs for *Industry 4.0* include *Informatics Specialists, PLC Programmers*, *Robot Programmers*, *Software Engineers*, *Data Analysts,* and *Cybersecurity professionals*. Among the competencies needed in these

Table 2 Required competencies and knowledge associated with elements of *Industry 4.0*

Discipline-specific competencies and knowledge			
Engineering	Business	Design	
Data science and advanced analytics	Technology awareness	Understanding the impact of technology	Transversal competencies
Novel human–machine interfaces	Change management and strategy	Human–robot interaction	
Digital to physical transfer technology	Novel talent management and strategy	User interfaces	
Advanced simulations and virtual plant modeling	Organizational structures and knowledge	Tech-enabled product and service design	
Data communications and network	Role of managers as facilitators	Tech-enabled ergonomic solutions and user experiences	
Real-time inventory and logistical optimization systems	Tech-enabled processes: forecasting, planning, scheduling		
Artificial intelligence			
Robotics			
Automation	Business analysis		
Programming	Digital skills		
Information technologies			
Mechatronics			
Cybersecurity			
Augmented and virtual reality			
Knowledge of internet of things, interfaces, communication protocols, understanding systems, cloud solutions, software know-how, sensors and electronics, lean manufacturing			

professions are language skills, responsibility, flexibility, analytical and logical thinking, and problem-solving.

In *Industry 4.0,* there will also be a huge need for individuals with managerial abilities. These are persons who make business decisions and lead others. Eight competencies identified as essential for managers in Industry 4.) are shown in Table 4 [30].

In some industries, such as the automotive industry, the competencies in Table 4 are also considered essential for the workforce, particularly entrepreneurial thinking, analytical competencies, and time management abilities. Entrepreneurial thinking makes people be creative and have a sense of ownership of their jobs. They also tend to perform better. In some countries, the automotive industry considers necessary for implementing *Industry 4.0* competencies such as management of specialized software, knowledge of simulation systems, collaboration in virtual settings, creativity, financial analysis, leadership, and critical thinking [18].

The manufacturing industry highly values digital competencies like digital analysis and diagnosis, additive manufacturing skills, and programming/coding abilities. It is noteworthy that in the future, this sector will need persons with hybrid skills who can apply technical, digital, and personal skills and knowledge across a range of contexts and applications [34].

The defined competencies required to adapt to Industry 4.0 reported by the different research projects and various industrial sector surveys differ slightly among themselves. However, the ones in common mainly relate to the ability to use and interact with *Industry 4.0* technologies (e.g.,

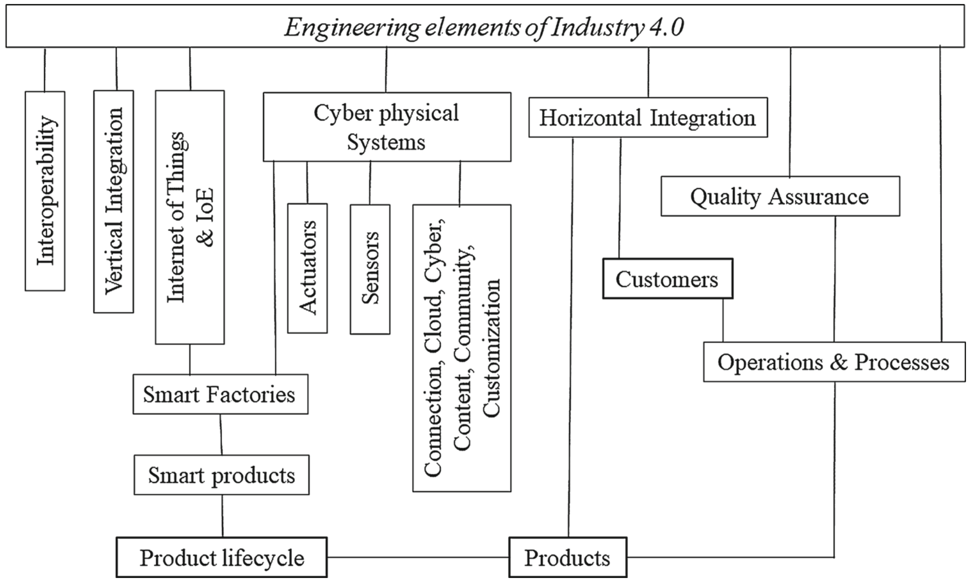

Fig. 1 Engineering elements of Industry 4.0

Table 3 Transversal competencies

Problem-solving	Soft competencies		Systems thinking	Business thinking	Technological literacy
	Interpersonal	Metacognitive and personal attitudes			
Knowledge management	Teamwork	Self-confidence	Ethics		
Experimentation	Leadership	Self-management	Sustainable development		
Creativity	Communication	Responsibility	Social innovation		
Scientific process	Assertiveness	Self-motivation			
		Lifelong learning			
		Self-knowledge			
		Self-direction			
		Self-regulation			
		Self-judgment			
		Self-awareness			

robots and *Artificial Intelligence*), perform data analyses, apply technical knowledge, and use soft, personal skills to advantage. The list of competencies and skills could be exhaustive, and it would be impossible for any future professional to acquire them all. However, the critical competency for all future professionals of *Industry 4.0* is the ability to apply the knowledge that adds value collaboratively in various disciplinary domains. The *Industry 4.0* professional must continually learn from new settings and other professionals with different backgrounds and experiences.

Below is an example of an industry profile that provides practical information generated by the World Economic Forum [78]. Their profile discusses four topics:

1. *Trends driving industry growth* This is an overview of the top socio-economic trends and technological disruptions expected to affect Industry development over the next 5 years positively. According to the share of the survey's respondents from Industry who selected the top drivers of growth for their industry, the rankings are according to the share of the survey's respondents.
2. *Adoption of technology in Industry* as part of growth strategy.
3. *Barriers to adopting new technologies* presents the five most significant perceived barriers to adopting new technologies across the industry.
4. *Workforce (emerging/declining) in the next 5 years* This provides an overview of expected developments in industry-specific job roles. It also offers emerging job roles, indicating their expected total employment share within the industry workforce in the next 5 years (and, similarly, declining job roles).

Table 4 Essential competencies required for *Industry 4.0*

	Competency	Description
a	Creativity	Perceives the world in new ways and proposes innovative solutions
b	Entrepreneurial thinking	Identifies market opportunities and creates strategies to capitalize on them
c	Problem-solving	Involves analytical and creative thinking to find solutions to specific problems
d	Conflict solving	This critical ability requires that the person has emotional maturity, self-control, and empathy
e	Decision making	Process of making choices by identifying a decision, gathering information, and assessing alternative resolutions
f	Analytical skills	Requires that the person evaluate information effectively
g	Research skills	Consist of finding and using reliable sources of information on a given topic
h	Efficiency orientation	Consists of a person who uses the resources in an efficient way

Table 5 shows the industry profile for *Automotive, Aerospace, Supply chain and Transport*. As can be seen, the expected trends (specifically in technology adoption and emerging job roles) in the industrial sector coincide with what had been previously proposed. Robotics appear at the bottom of technology adoption in this industry; indeed, it was divided into four types of robot approaches (stationary robots, non-humanoid land robots, humanoid robots, and aerial and underwater robots).

Figure 2 compares technology adoption trends in two different industries, namely, Automotive, Aerospace, Supply chain and Transport (white bars), and Oil and Gas (black bars). Except for two technologies (autonomous transport and aerial and submarine robots), there are many similarities in adopting the technologies.

Industry 4.0 is evolving and continuously changing. Enterprises that implement *Industry 4.0* need to understand that their employees must continually acquire new skills. This can be achieved by having a program in which training and education are regularly offered to employees or by hiring external talent with the needed abilities. Learning factories, which are places where employees are connected with digital resources and integrated within a smart factory, are

Table 5 Industry profile: automotive, aerospace, supply chain and transport

Trends driving industry growth	
1	Increasing adoption of new technology
2	Advances in artificial intelligence
3	Increasing availability of big data
4	Shifts in national economic growth
5	Advances new energy supplies and technologies
6	Advances in mobile internet
7	Advances in cloud technology
8	Expansion of affluence in developing economies
9	Advances in computing power
10	Advances in device bridging the human machine divide
Technology adoption in industry	
Machine learning	87%
User and entity big data analytics	84%
Internet of things	82%
Cloud computing	76%
App and web enabled markets	76%
Autonomous transport	74%
New materials	71%
Augmented and virtual reality	71%
Digital trade	68%
Wearable electronics	61%
3D printing	61%
Encryption	58%
Station robots	53%
Non-humanoid land robots	42%
Distributed ledger (blockchain)	32%
Quantum computing	29%
Humanoid robots	29%
Biotechnology	18%
Aerial and underwater robots	18%
Barriers to adoption of new technologies	
Skills gaps, local labour market	59%
Don’t understand opportunities	59%
Skills gaps, leadership	41%
Shortage of investment capital	36%
Lack of flexibility, hiring and firing	28%
Emerging—workforce in next 5 years	
Data analysts and scientists	
AI and machine learning specialists	
Process automation specialists	
Software and applications developers and analysts	
Innovation professionals	
Service and solutions designers	
Product managers	

Table 5 continued

Emerging—workforce in next 5 years
Industrial and production engineers
Supply chain and logistics specials
Declining—workforce in next 5 years
Assembly and factory workers
Data entry clerks
Client information and customer service workers
Accountants and auditors
Accounting, bookkeeping and payroll clerks
Administrative and executive secretaries
Transportation attendants and conductors
Material-recording and stock-keeping clerks
General and operations managers
Business services and administration managers

another way of developing the personnel and staff. In these sites, scenario-based experiences with *Augmented Reality*, the *Industrial Internet of Things*, and *Cyber-Physical Systems* are deployed; learning factories train in data analysis within simulated manufacturing environments [38].

Employees will need to be active learners, be flexible, and be trained in digital *emerging technologies*. Some of the new jobs emerging in the context of *Industry 4.0* are robot coordinators, industrial data scientists, supply chain coordinators, simulation experts, and digitally-assisted service engineers [25]. See Table 5.

4 Technologies and competency assessment methods

To implement *Industry 4.0*, organizations need to transform and adapt their machines to the new needs. The transformation demands a significant investment in the latest technology and original profiles from those engineers who will manage it. For example, information technology professionals will need to program the machines and develop new information technology architectures. Higher education engineers will need to combine various technologies and know about mobile technology, embedded systems, and sensors. They also need knowledge about network technology and *machine-to-machine* communication. Finally, knowledge of robotics, artificial intelligence [57], bionics, and safety-related competencies will be required. Safety is an essential aspect of *Industry 4.0* as processes are not fixed, but they are in continuous movement.

Some examples of *Industry 4.0* professions proposed by some international organizations are (a) *Industrial ICT Specialist* with knowledge in electronics and hardware/software, (b) Industrial Cognitive Science specialists with expertise in sensor/actuator networks, robotics, perception and cognition, and (c) specialists in *Automation Bionics* with knowledge of robotics and perception/cognition from a biological perspective [31]. As can be seen, new professions in *Industry 4.0* are particular regarding the knowledge and, hence, the new entrants' competencies to the labor force must-have.

Technology is a critical factor for the implementation of *Industry 4.0,* and the investment in the correct technologies will lead to a softer, significant acquisition of *Industry 4.0* capabilities. For this to occur, companies need to assess their

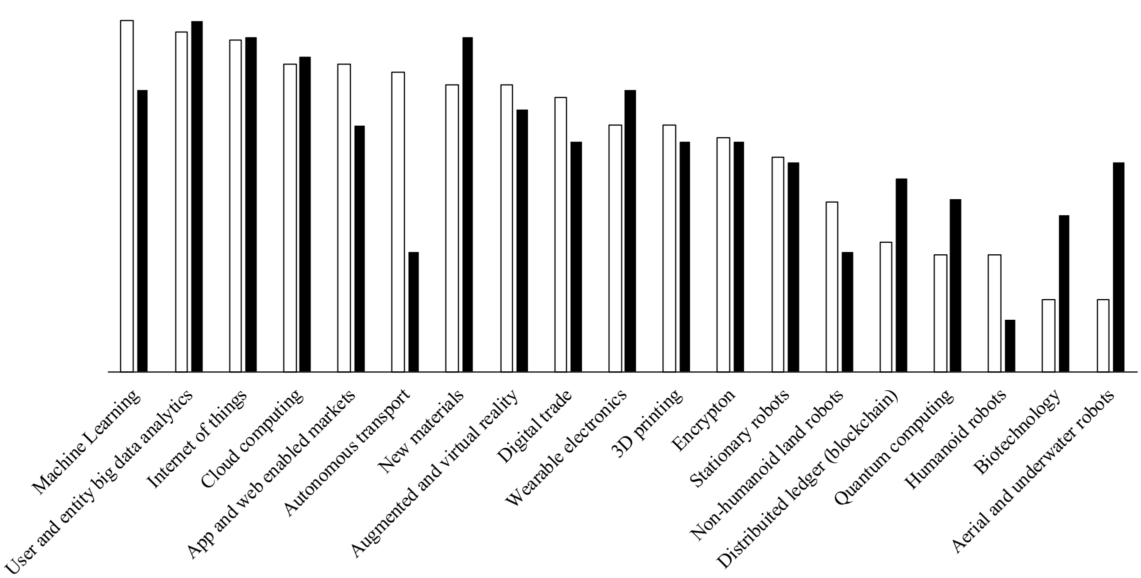

Fig. 2 Comparison of technology adoption in two different industries (white bars: automotive, aerospace, supply chain, and transport; black bars: oil and gas)

current status by analyzing the performance and operational problems before deciding which technologies to invest [43]. The five leading technologies considered to be the pillars of *Industry 4.0* are Smart sensors, the Internet of Things, Cyber-Physical Systems, Cloud manufacturing, and Big data and Analytics [13]. How these five are used in *Industry 4.0* and the competencies needed to manage them are described next.

4.1 Smart sensors

These are conventional sensors that have integrated microprocessors providing intellectual abilities. They are used principally for calculations, self-diagnosis, self-identification, and self-adaptive functions. In the context of *Industry 4.0,* smart sensors are the ones that generate data at all levels of the production process. They can perform self-monitoring and self-configuration. This data is used to improve product quality [19], flexibility, and productivity [70]. Companies need professionals who can create algorithms that discern which data is useful and analyze large amounts of it [39]. The principle of *accessorization* captures this idea [1]

1. *Industrial Internet of Things*

The Industrial Internet of Things is a network of objects with embedded technologies that allow them to interact with each other or the external environment. It supports *Industry 4.0* in monitoring production processes, facilitating maintenance, tracking products, effectively managing inventory, developing innovative solutions, and improving security and quality control [74]. The *Industrial Internet of Things* technology allows products or production machines to connect to a network and collect and share data. This interconnection generates *big data,* which is useful if the companies take advantage of it. Therefore, professionals must have the ability to analyze big data and develop data mining software, algorithms, and interfaced for *enterprise resource planning* [53].

2. *Cyber-Physical Systems*

Cyber-Physical Systems connect virtual and physical worlds to develop a network in which they can communicate and interact. In manufacturing, *cyber-physical systems* are the fusion of sensors, actuators, and excellent connectivity. The interactions with other systems and users on the production floor create a *smart factory*. Teaching factories are built to develop the needed competencies for managing such systems. Problem-solving performed by cross-functional teams results in technical knowledge and development of personal skills [51].

3. *Cloud Manufacturing*

This *emerging technology* allows access to a shared collection of diversified and distributed manufacturing resources to form temporary and reconfigurable production lines that enhance efficiency, reduce product lifecycle costs, and achieve optimal resource loading. In the context of *Industry 4.0, cloud technologies* aid in improving the security of the networks [9]. *Cloud Manufacturing Technologies* (e.g., *Industrial Internet of Things*, cloud computing, and service-oriented technologies) build a multilayer architecture platform, including a resource layer, virtual resource layer, global service layer, and application and interface layer. The system's complexity demands that professionals in charge know how to manage *cloud manufacturing platforms* to guarantee that the processes will perform with the right quality [41].

4. *Big Data and Analytics*

Advanced analytics is used with big data to develop predictive models. Big data has six main characteristics: volume, variety, velocity, veracity, value, and complexity. In the context of *Industry 4.0*, big data helps optimize the quality of production, saves energy, and improves the function of the equipment. The vast amount of data generated, if well managed, supports decision making [41] and enables addressing intractable engineering problems [20].

As can be seen, the generation of data is the most valuable asset in *Industry 4.0*, offering a competitive advantage to companies if they have the right systems for collecting and analyzing it. However, finding the workforce with advanced analytical training is the most critical challenge.

The assessment of competencies is a process in which the proofs that the desired level is attained are based on standardized analysis [2].

The process contains steps such as (a) setting of goals, (b) collection of evidence, (c) comparison of evidence with objectives, and (d) opinion formation. The final goal is to determine which competencies need to be developed with their training strategies. The assessment of competencies is based on standards that include criteria of what is an excellent performance. In this process, there is no comparison among workers; instead, an individual evaluation indicates if the person is or is not competent [76].

Companies use various assessment methods to evaluate the competencies of their workforce; these include tests, questionnaires, interviews, regular observations, descriptions, comparative analyses, simulation methods, and research methods [2]. The most common forms are [44]:

(a) *Interview* This consists of a face-to-face talk between the employee and the leader. The interaction can be performed in an informal way or following a structured procedure.

(b) *Review/Evaluation* These include 360-degree reviews, self-assessments, expert assessment, and special assessment.

(c) *Observation* This method is ideal for assessing technical competencies. A checklist must be used to have an effective process.

(d) *Test* This method is useful for determining functional skills. The data and evaluation obtained are of high quality.

(e) *Assessment center* This refers to a process in which multiple assessment techniques such as job simulations and situational exercises evaluate individual employees.

Below, we review the assessment methods for evaluating the acquisition of *Industry 4.0* competencies.

Industry 4.0 competencies can be divided into soft and hard categories. Soft skills are those personality traits an individual has. In a workplace context, these define how a person behaves in a professional environment. On the contrary, hard skills are the set of technical capabilities that a person has. In Industry, soft skills are commonly assessed with psychological tests. However, these evaluations do not always consider the relevant soft competencies needed in manufacturing, which include interpersonal skills, assertiveness, respect, self-strength, empathy, will, a spirit of perfection, self-discipline, intellectual curiosity, refinement, independence, and creativity [15].

A survey in which more than 500 managers in the manufacturing sector participated found that companies are already investing in training resources in *Information Technology* skills. However, interviews reveal that the areas of scheduling, production planning, and control are the ones that need special attention. Explicitly, in the production area, respondents stated that lifelong learning, interdisciplinary thinking, and information technology are the skills required [27]. Many organizations use *Learning Management Systems* to train employees in specific competencies. They measure the significant acquisition of skills through certifications and *training management*. They also build practice centers to improve the acquisition of the desired abilities [35]. Other companies use learning cells on the production floor. These are short training sessions with dynamic activities such as short videos, posters, and simulation games that aim to teach specific themes (e.g., methods of lean production) and develop specific competencies. Learning factories are also an acceptable means for developing competencies such as problem-solving [11].

There are manufacturing enterprises that offer their workforce on-the-job instruction using *Augmented Reality,* and they complement this with classroom instruction. The assessment methods vary from self-assessment to observation by the trainers [60]. International organizations also have ways of assessing the acquisition of *Industry 4.0* competencies. The *Programme for the Int Assessment of Adult Competencies* with its *Survey of Adult Skills* assesses adults' proficiency in vital information-processing skills (literacy, numeracy, and problem-solving). It gathers information and data on how adults use such skills. The *European Digital Competence Framework for Citizens* is a self-assessment tool that job seekers can use to evaluate their digital competency and have it described in their curriculum vitae. It is a reference in Europe for employability, development of strategic policies, assessment of student performance, and teachers' professional development [23].

The *Microsoft Digital Literacy Test* is an assessment tool used to evaluate *information communication technology* skills. The test includes assessing the following areas: computer basics, the internet, and the World Wide Web, productivity programs, computer security, and privacy and digital lifestyles. Each assessment area has its companion course, and certification is given at its end [45].

Competency Management Systems are used for managing competencies in industrial settings. These systems assess competencies by collecting evidence and comparing it with a standard. Also, certifications by third parties are used; this option gives objectivity to the evaluation and reduces the effort required for doing such a process [7].

Other methods that can be used to assess workers' competencies include standardized assessment approaches such as surveys or monitoring the employees' activities. It is essential to mention that this task needs to be performed by experienced persons to minimize biases and obtain consistent results [32]. Companies need to retrain and frequently assess their workforce as *Industry 4.0* evolves fast and incorporates new advances into manufacturing systems [13].

5 Conclusions

The main goal of *Industry 4.0* is to make factories more efficient and flexible to adapt to future demands. There are diverse technologies that allow the implementation of this approach. These include *Autonomous Robots, Simulation, Horizontal and Vertical System Integration, the Industrial Internet of Things, Cybersecurity, The Cloud, Additive Manufacturing, Augmented Reality, and Big Data and Analytics*. All of these allow enterprises to get connected and take advantage of the vast amount of information generated for making better decisions.

Different readiness/maturity models aim to analyze the state of preparedness of an enterprise to implement *Industry 4.0*. These include Smart Industry Readiness Index (SIRI), Industry4WRD, RAMI 4.0, SIMMI 4.0, APM Maturity Model, Industrie 4.0 MM, and M2DDM. Based on their analyses, we see that the adoption of technology and the workforce training that has the right competencies are among the challenges enterprises must overcome to implement Industry 4.0 correctly. Universities are doing their part by offering programs aimed at training individuals in *Industry 4.0* topics. On the other hand, enterprises also provide training programs for their workers to adapt to new demands. However, some issues need to be considered. From the workers' perspective, they could refuse to adopt the approach. From the technology perspective, decision-makers could believe a high economic risk in investing in these advances. In conclusion, the benefits of transitioning to *Industry 4.0* are not readily available and, therefore, well perceived.

There is a vast literature that reviews the competencies needed in *Industry 4.0*. The common ones could be considered those related to the ability to use and interact with *Industry 4.0* technologies, data analysis, technical knowledge, and the need for personal skills. However, there is no consensus regarding the competencies needed for sufficient work in Industry 4.0 environments. A critical competency that future professionals must have is the ability to exploit their knowledge in different collaborative realms in a way to add value. The *Industry 4.0* professional must continually learn from new settings and other professionals with diverse backgrounds and experiences. Enterprises must consider that employees need to be always acquiring new competencies. This can be achieved by having training programs that continuously promote the development of their competencies.

Technologies that assist the implementation of *Industry 4.0* on the production floor are *smart sensors*, the *Internet of Things*, *cyber-physical systems*, *cloud manufacturing,* and *Big Data and analytics*. All of these need workers that have specific abilities to manage them efficiently. The generation of data is the most valuable asset in *Industry 4.0*; to get the most out of it, enterprises need people who can manage vast amounts of information and have the ability to analyze it.

Enterprises have different modes to determine if their workforce has the required abilities. These included *learning management systems*, *competency management systems*, certifications, self-assessments, observations, surveys, and employees' activities monitoring and testing. For the latter, the Microsoft Digital Literacy Test, the Programme for the Int Assessment of Adult Competencies, and the European Digital Competence Framework for Citizens are among the instruments used by enterprises for continuous evaluations of their employees to check their alignment with *Industry 4.0* demands.

Industry 4.0 has already been implemented in enterprises in countries at the vanguard, such as Germany and the United States. The technologies supporting *Industry 4.0* are always changing. Therefore, it is of paramount importance for organizations to track them, so they maintain their operations technologically-updated and have full access to the Fourth Industrial Revolution's proposed benefits.

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