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What does Industry 4.0 mean to Industrial Engineering Education?

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Abstract

Due to Industry 4.0 (I4.0), the Industrial and Systems Engineering (ISE) undergraduate programs are changing; likewise, the complexity in organizations is increasing. Moreover, international competition, rising market volatility, and the demand for highly customized products are challenging enterprises. Against this scenario, the ISE educational programs should develop creative ways to quickly adequate new requirements. Beyond using advanced technologies, a discussion about the evolution and development of new competences in the ISE field is opened. Thus, this work analyzes the I4.0 impact on the ISE professionals' desired skills by performing a literature review analysis and developing a cross-reference with the ISE skills. As a result, possible curricular innovations are identified to endeavor the current needs of the profession, and a new "ISE Education 4.0" framework is proposed, which includes five main pillars providing an overview of the new courses, strategies, and components driving the I4.0 education for ISE curricula.

Keywords: Industrial Engineering; Industry 4.0 Skills and Competences; Educational Innovation; Higher Education; Professional Education.

1. Introduction

Industry 4.0 (I4.0) has been a transformative initiative for organizations over the last decade. Initially proposed in 2011 by the German Government [1], I4.0 comprehends the usage of advanced technologies, such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), Big Data and Analytics, Autonomous Robots, Simulation, Cloud Computing, Augmented and Virtual Realities (AR and VR, respectively), Additive Manufacturing, Machine Learning, Cybersecurity, and Horizontal and Vertical Systems Integration [2]. These technologies support human activities by facilitating real-time monitoring, analysis, and decision-making, resulting in improved processes, increased competitiveness, and ease in meeting market volatility and changing demand for customized products [3].

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Even though I4.0 brings significant benefits to organizations, it represents a challenging journey for people to face digital disruptions, act on their own initiative, and manage complexity [4]. Regarding this, organizations need to identify the new talent for today's reality, which must be made up of workers capable of interacting with other humans and enabling technologies, adapting to new changes, and, most importantly, having self-development capabilities [5].

New tasks are needed based on the I4.0 initiative requirements, mainly performing cross-functional activities where digital skills are fundamental [2]. Following this, engineering professionals take an important role since they need to adapt I4.0 technologies to their daily tasks. In particular, Industrial and Systems Engineering (ISE), being one of the most selected engineering careers globally, opens an opportunity for universities to re-engineer the ISE curricula, seeking to fulfill the students' development challenges. In this sense, updating the educational contents will embrace ISE students to work cross-disciplinarily and develop the competences (i.e., skills, knowledge, and abilities) needed in I4.0. Besides, the contents will prepare them for their professional lives by gaining I4.0 knowledge and experience, especially in using advanced technologies and interacting with "smart" devices [6].

The remainder of this work is organized as follows. Section 2 details the relevant literature on new educational opportunities for the ISE curricula due to I4.0 challenges. Then, in Section 3, the problem that motivated this research is defined. Section 4 explains the methodology followed in carrying out the research. Moreover, in Section 5, the results are depicted by firstly discussing the main findings regarding the competences needed in ISE students and the educational models that universities have designed, and secondly, by providing a framework for the new ISE educational revolution aligned with I4.0 requirements and focused on students' development. Finally, Section 6 presents the conclusions and suggests future work.

2. Related Research

Following the need for an innovative and restructured education oriented toward I4.0 and the development of the required skills and competences, the "Education 4.0" initiative [7] refers to the future of learning in which I4.0 concepts, technologies, and applications are studied and put them into practice. This initiative distinguishes eight characteristics (see Fig. 1) to determine high-quality lifelong learning while dealing with I4.0 challenges.

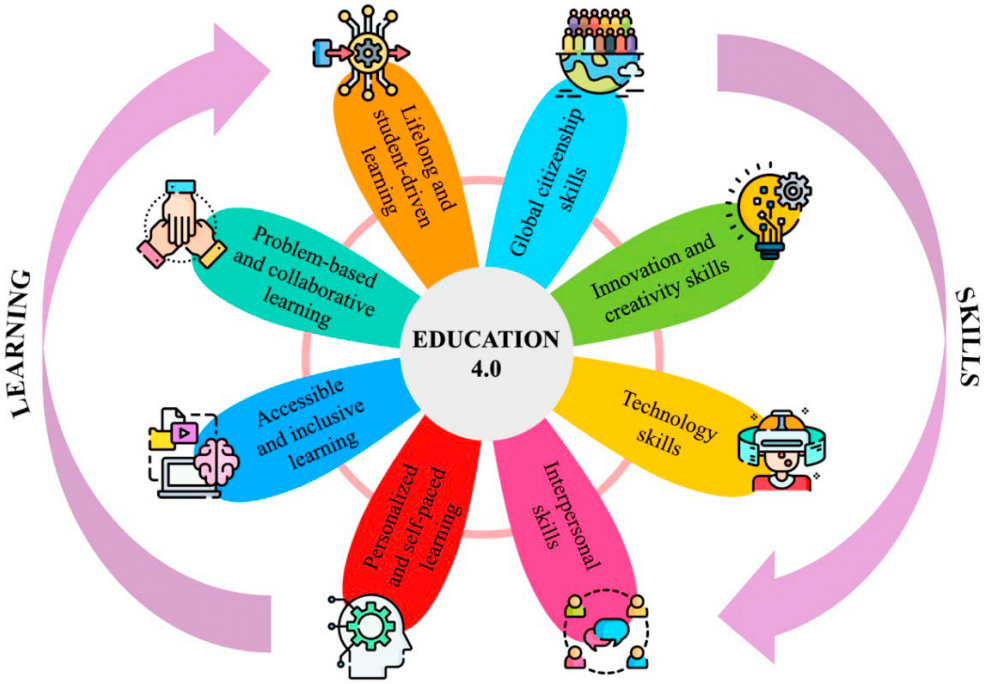

Fig. 1. The Eight Characteristics of "Education 4.0" (Authors' elaboration based on [7], using icons made by Freepik from [8]).

Following the I4.0 education, the authors Cevik Onar, Ustundag, Kadaifci, and Oztaysi [2], proposed a classification of four groups for its content, which are the following:

1) Data and computing technologies: Data Modeling and Big Data, Data Analytics, Cloud Computing, and Machine Learning.
2) Value-added automated operation: Automation, Robotics, Smart and Embedded Systems, and Additive Manufacturing.
3) Up-to-date domain knowledge: State-of-the-art of I4.0 applications and requirements.
4) Innovation and entrepreneurship: Innovative materials and tools, and innovation/entrepreneurship business models.

These criteria recognize the main elements that must be considered in the I4.0 education's content, from data usage and value-added operations to knowledge and innovation.

Furthermore, the authors Gueye and Exposito proposed the concept of "University 4.0," which refers to the ability of universities to manage learning processes by integrating I4.0 technologies in their courses and improve current learning; therefore, being part of a new educational revolution [9]. Based on the need to adapt educational models, universities' interests must focus on integrating the physical and digital worlds into their programs. In this sense, students will acquire knowledge, develop skills and competences, and be prepared for professional life.

Universities around the world, including the Massachusetts Institute of Technology (MIT), the National University of Singapore (NUS), Universidad Carlos III de Madrid (UC3M), the University at Buffalo (UB), the State University of New York (SUNY), among others, have designed new programs that contain I4.0 concepts, technologies, and their applications to meet this initiative requirements.

Similar to these undergraduate, graduate, and certificate learning models, online educational platforms that offer I4.0 courses are available on the Internet. On the one hand, online learning (e-learning) platforms, such as LinkedIn Learning, Coursera, Udemy, and edX, provide valuable learning experiences throughout educational courses, allowing students to learn and develop new skills. On the other hand, online course platforms, including LearnWorlds and Thinkific, offer the opportunity for professionals to update their knowledge based on training and development programs [10]. These two schemes represent a fructiferous approach to keeping synchronized education with industrial and technological trends, sustaining lifelong learning, and continuously developing talented workers. Hence, considering the need for updated and flexible educational programs where the cooperation between universities and industries is fundamental to enhance the skills and competences development desired in I4.0 [11].

In 2019, Coşkun, Kayıkcı, and Gençay [12] proposed a generic framework for I4.0 engineering education, aiming to deal with the need for new educational models. It determines three interconnected stages (i.e., curriculum, laboratory, and student club) based on "Kolb's Experiential Learning Theory" and the I4.0 concepts and technologies to describe the enhancements needed in universities' curricula. Based on this framework, in 2020, Aichouni, Kolsi, and Aichouni [13] developed "The Engineering Innovation Club Model (KSA 2030 for Industry 4.0)". This model helps determine the requirements for creating an engineering innovation club where students can acquire the skills, knowledge, and abilities for their engineering background regarding I4.0.

I4.0 educational characteristics and current frameworks were studied from the literature presented, recognizing key concepts and contributions. Considering the findings, there is a need for a new ISE educational framework for which possible program innovations must be identified to endeavor the profession's current social and digitalized requirements. Hence, the main characteristics of Education 4.0 and the reviewed existing frameworks were taken as a reference to incorporate their concepts into a new framework proposal for ISE professionals. Such that this study develops a new ISE education perspective incorporating trends related to developing I4.0 skills and competences. It provides a new proposal for how to evolve the I4.0 program for ISE, showing the relevance of solving complex problems through multidisciplinary processes and digital-technological knowledge, where developing competences and encouraging lifelong learning are the basis. Similarly, placing the curricula at an intersection of learning and perspective, where students can experience internal and external perspectives from their study environment across different theoretical and experiential learning scenarios.

3. Problem Description

I4.0 is a transformation journey for organizations, which requires adopting advanced technologies, changing methods and processes into real-time interconnected ecosystems, promoting virtual- and real-world scenarios, and enhancing workers' skills and competences development [14]. Following this, implementing I4.0 technologies promotes a smart exchange of information, triggering actions, and controlling each other. The communication and integration of these technologies are considered necessary to reach an intelligent manufacturing environment [15].

Thus, the complexity and requirements of the organizations have progressively increased, which impulse them to innovate in developing new business models. The product life cycle has been reduced by factors such as the growth of international competition, the rising market volatility, or the demand for highly customized products, which present severe challenges to enterprises. It looks as if current methods of value creation are not well-matched to deal with the increasing requirements regarding cost efficiency, flexibility, adaptability, stability, and sustainability anymore, due to the increment in the manufacturing industry requirements and accelerated technological development [16].

Against this scenario, the ISE undergraduate programs, which have been popular worldwide and are one of the top six engineering professions chosen by students [17], should be adapted due to the world context of digital transformation in which the I4.0 initiative is emerging as an industrial tendency. Most importantly, they should ride the wave of developing creative ways to adequate them more quickly than the common actualization period. Beyond the use of advanced technologies or didactic strategies, the complexity of the current humanity problems requires opening a discussion about the evolution of the ISE field and the best way to develop the new competences of ISE professionals and prepare the ISE talent necessary for I4.0. Mainly because ISE professionals are the classy production job profile in industries, and due to digital challenges, they require developing technological and communication competences [18].

4. Methodology

This paper aims to analyze the I4.0 initiative's impact on the skills desired in an ISE professional and provide a framework where emerging areas in Education 4.0 for ISE are proposed to meet the I4.0 adoption requirements. The previous, by considering competences' development and lifelong learning perspectives and supporting universities in new educational models' structure. To achieve the following, the study is carried out based on the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) Method, which is a recognized process for orienting on selecting the publications that contribute to the research by following four stages: identification, screening, eligibility, and included [19]. This section describes the methodology implemented to develop the study. Its subsections are organized as follows: (4.1) Research questions, (4.2) Search strategy, and (4.3) Data selection, collection, and analysis.

4.1. Research Questions

To accomplish the objective of this research study, which is to analyze the I4.0 initiative's impact on the skills desired in an ISE professional and provide an Education 4.0 framework for ISE aligned to this initiative's requirements, three research questions were established:

- RQ1: What skills and competences do students need to develop in order to face I4.0 working challenges?
- RQ2: What are the new educational models developed by universities?
- RQ3: What are the benefits of updating current educational programs toward meeting I4.0 requirements?

4.2. Search Strategy

A literature review was developed to address the research questions, searching for the skills and competences professionals need and students must start developing, updated educational programs in universities oriented toward I4.0 fundamentals, and existing frameworks for an I4.0 education. Scopus and Web of Science were the databases used for this literature review since they are considered leaders in reporting high-quality journals [20]. Moreover, Google Scholar and universities platforms were reviewed. The search string researched was ("Industry 4.0" OR

"Fourth Industrial Revolution") AND ("engineering curricula" OR "engineering education" OR "Industrial Engineering" OR "Industrial and Systems Engineering") AND ("skill" OR "competenc*").

It is worth mentioning that the last search string included "competenc*," denoting the terms competences and competencies in their singular and plural forms (i.e., competency, competence, competencies, and competences). While competences refer to job functions associated with humans' actions, assessments, and performance [21], competencies focus on people's behaviors in performing a task and their ability to have greater job performance [22]. Even though these terms are different based on their definitions, both are significant and contribute to what is sought in this research on the development of workers considering I4.0 requirements.

4.3. Data Selection, Collection, and Analysis

Following the application of the PRISMA Method, 305 documents were identified in Scopus and 69 in Web of Science (see Fig. 2). Additionally, 15 publications were distinguished from other sources, such as Google Scholar and universities platforms. Of these 389 publications, 51 were duplicates. Thus, 338 documents remained such that in the second stage, they were screened according to the inclusion and exclusion criteria described below. The chosen documents were written in English and published in peer-reviewed publications from Journals from 2011 to 2021. This second stage resulted in 269 records being excluded. In the third stage, 69 full-text publications were selected as eligible. A total of 15 publications were excluded considering they do not meet one of the following criteria: (a) describe the main skills and competences needed in ISE students to face I4.0 in their upcoming professional lives, (b) propose or discuss a new model focused on I4.0 education for ISE curricula, or (c) recognize the benefits of updating the current curricula of ISE education. Lastly, 54 documents were considered for the research in the fourth stage, of which 18 records were key to this study since they positively contributed to the research in regard.

New educational models were identified with their respective objectives, courses, and development areas from the records retrieved in the review process. The findings allow the development of an "ISE Education 4.0" framework that considers the models' strengths and areas of opportunity.

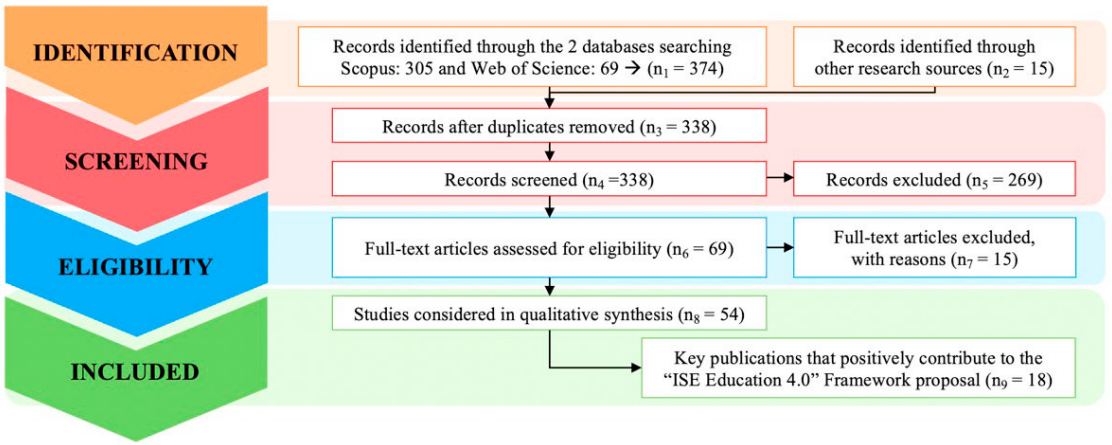

Fig. 2. The PRISMA Flow Diagram Followed for the Literature Review (Authors' elaboration based on [19]).

5. Results

I4.0 is rapidly evolving in industrial scenarios. Since it involves adopting new advanced technologies, it challenges workers in digital scenarios. Considering the three research questions established in the previous Section 4, this section of the research paper has been divided into three subsections to address and present an answer to each of them accordingly. The subsections are depicted as follows: (5.1) skills and competences desired in students and

professionals for I4.0, (5.2) new I4.0 educational models designed by renowned universities, and (5.3) the benefits of ISE Education 4.0.

5.1. Skills and Competences Desired in Students and Professionals for I4.0

According to Hernandez-de-Menendez et al. [23], the main competences needed for I4.0 are the following: technical, methodological, social, and personal. Considering the corresponding skills that the authors defined for each competence and adding those identified by Himmetoglu, Aydug, and Bayrak [24] for students based on the "Education 4.0" initiative, Table 1 integrates the skills and competences expected to meet I4.0 working requirements.

Table 1. Skills and Competences Expected in Students and Professionals Toward an I4.0 Education.

Competences	Skills
Technical-technological:	Media and coding skills, process understanding, state-of-the-art knowledge, and understanding of Information Technology security.
Methodological:	Analytical skills, autonomous learning, conflict- and problem-solving, creativity, critical thinking, decision-making, and entrepreneurial thinking.
Social-communicative:	Ability to work in teams, cooperate and collaborate, cross-cultural understanding, digital and information literacies, share knowledge, as well as communication, intercultural, language, leadership, and networking skills.
Personal:	Ability to work under pressure and adapt, be resilient, compliant, flexible, responsible, and tolerant, as well as keep a mindset focused on sustainability, keep motivated to learn (i.e., lifelong learning engagement), and produce knowledge.

Recognition of the skills needed in I4.0 Education was attained. By comparing them with those traditionally developed in some ISE programs, insights were obtained, allowing the identification of strengths of the current programs to face the I4.0 adoption and opportunity areas to be considered in the near future as part of the evolution of the ISE curriculum.

5.2. New I4.0 Educational Models Designed by Renowned Universities

International universities have designed educational models geared toward the I4.0 initiative, integrating I4.0 concepts and technologies into engineering curricula. Their programs focus on developing new skills and competences needed to face the challenges I4.0 holds in organizations. Table 2 indicates the universities and the educational programs they have proposed, with their corresponding objectives and modules.

Table 2. Universities' I4.0 Educational Programs.

University	Program	Objective	Core/Essential Modules
MIT [25]	Professional Certificate Program in I4.0 (online)	To influence and help professionals obtain a broader vision of I4.0 and carry out their industrial revolution.	Management of Technology, Designing Product Families, Smart Manufacturing, Beyond IoT, and Elective Course.
NUS [26]	Master of Science in I4.0	To prepare students for the emerging I4.0 workplace by equipping them with the skills needed to face technological disruption.	Introduction to I4.0 and Applications, Digital-Physical Integration in I4.0, Data Analytics for Sense-making, Digital Infrastructure and Transformation, Professional Career Development, and Industry Consulting and Application Project.

UC3M [27]	Master in Connected I4.0	To train students interested in working in enterprises that are advancing toward a connected I4.0 scheme.	Introduction to Connected I4.0, Cyber-Physical Systems, Intelligent Networks, Industrial processes and services, Data processing and cyber-security, Internships and Seminars, and Master Thesis.
UB & SUNY ONLINE [28]	Program: Digital Manufacturing & Design Technology (online)	To provide students with an understanding of I4.0 manufacturing and how it is evolving through implementing digital-based technologies.	Digital Manufacturing & Design, Digital Thread: Components, Digital Thread: Implementation, Advanced Manufacturing Process Analysis, Intelligent Machining, Advanced Manufacturing Enterprise, Cyber Security in Manufacturing, MBSE: Model-Based Systems Engineering, and Roadmap to Success in Digital Manufacturing & Design.

Revising these programs and their curricular structures and trends allowed identifying the best practices. They provided initial thoughts about possible quick hits, innovations, and major changes to adequate the ISE curriculum in order to meet the current requirements. Moreover, the recognition of I4.0 enabling technologies in the new programs was distinguished as relevant for developing capabilities related to the use, implementation, and scope of each. Therefore, a discussion about using several enabler technologies of I4.0, such as AR, Blockchain, and CPS, in courses may close the gap among the current digitalization trend and the academic programs offered.

5.3. The Benefits of ISE Education 4.0

Based on the research and analysis performed regarding (a) the skills and competences needed in ISE students and professionals to cope with I4.0 challenges, (b) the updated educational programs from universities, and (c) the existing frameworks on literature for "Education 4.0", educational areas with their characteristics were integrated into an "ISE Education 4.0" framework proposal that was developed, as shown in Fig. 3.

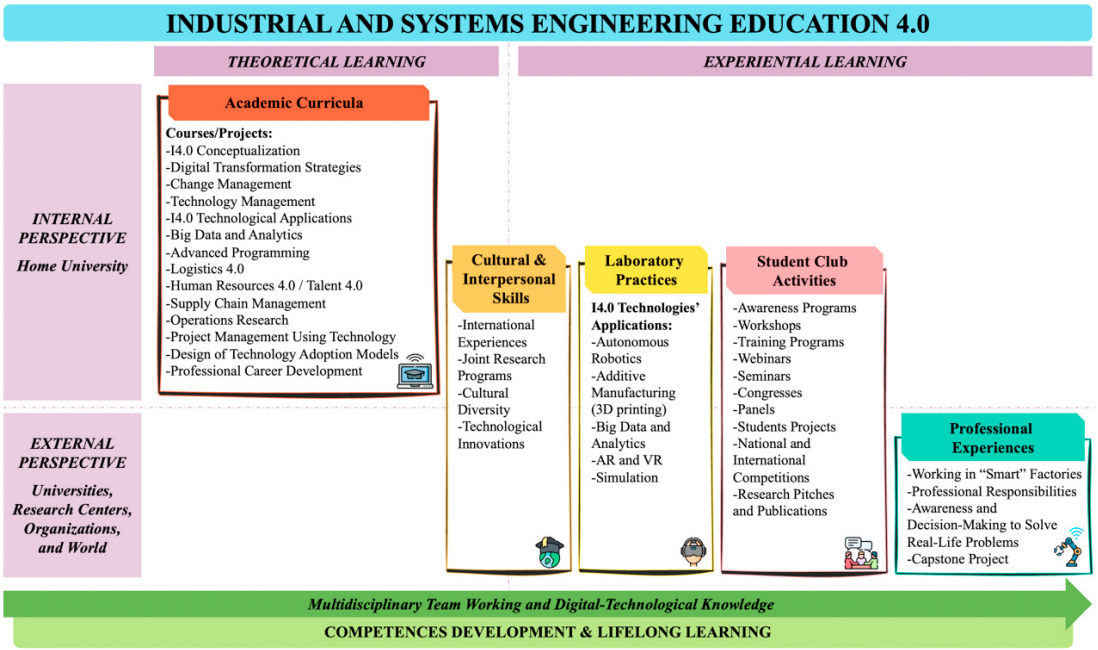

Fig. 3. The "ISE Education 4.0" Framework (Authors' elaboration using icons made by Freepik from [8]).

The framework depicts five main education pillars: Academic Curricula, Cultural and Interpersonal Skills, Laboratory Practices, Student Club Activities, and Professional Experiences. These pillars are interrelated and based on their characteristics, are classified into two categories: learning and perspective. Each category contains two subcategories; their corresponding definitions are depicted in Table 3.

Table 3. Categories and Subcategories of "ISE Education 4.0" Framework.

Learning Category	Perspective Category
Theoretical Learning: It refers to the knowledge learned from professors' lectures, digital media, books, and research publications.	Internal Perspective: It concerns the added value students obtain from the courses taken at their home university.
Experiential Learning: It entails learning by doing and reflecting on the experience, putting knowledge into practice, and developing new skills and competences.	External Perspective: It encourages exploring and gaining new introspections, approaches, and ways of thinking from people in other places, such as international universities, research centers, organizations (industries), and the world itself.

The "ISE Education 4.0" framework provides clear and comprehensive visualization of the main education pillars, where competences development and lifelong learning are encouraged for students in new educational models. The proposed framework distinguishes the added value internal and external perspectives have in students' growth to interact and work in multidisciplinary teams and face real problems using digital-technological knowledge.

While Academic Curricula focused on the I4.0 initiative provide theoretical learning and an internal perspective from each student's home university, Cultural and Interpersonal Skills from studying at another university, participating in joint research programs, or getting involved in cultural activities, allow students to learn theoretically and experientially from internal and external perspectives being supported by I4.0 technologies. Through these immersions, students perceive new realities from the educational, cultural, societal, and other approaches that open their minds to creative thinking and innovative problem-solving strategies for daily life problems.

In addition to these pillars, Laboratory Practices offer students the opportunity to use and interact with advanced technologies, experience the I4.0 implementation, and perceive its benefits. They broaden the internal and external perspectives to visualize the virtual and real worlds from practice. Moreover, Student Club Activities, like laboratory practices, allow students to have internal and external perspectives since they can interact with national and international people and learn from best practices implemented regarding last trend topics of their interest.

Lastly, Professional Experiences provide experiential learning from an external perspective because students can work at an organization while studying at the university. These bring the opportunity to apply the knowledge obtained from classes to working scenarios. By integrating the five education pillars previously explained, a reinforcement process is achieved so that students can develop the skills and competences needed in I4.0. Hence, engaging organizations in this "ISE Education 4.0" framework is relevant to working collaboratively with other universities, being committed to new learning models, and enhancing students' working practices, allowing them to face challenges and learn from real problems.

This framework adds value to current curricula since it allows universities to use it to improve their programs toward I4.0 preparedness. It responds to the different concepts, technologies, and competences concerned in I4.0, expecting ISE to be able to face this initiative's challenges and contribute to society shortly.

6. Conclusions

Even though the ISE profession has a very good reputation, the current trend of digitalization in today's working scenarios challenges professionals regarding the I4.0 adoption, making it plausible for universities to define new educational models aligned with a digital transformation. Mainly, for engineering education, programs have been restructured in renowned universities. Even though universities have developed educational models, and common characteristics and courses have been identified, new ISE engineering undergraduate curricula are not clearly available nor well-defined. It could be because they mainly depend on the research areas of each university's department.

In this regard, actions must be conducted to accelerate the transition toward an "ISE Education 4.0". Thus, for universities to develop the new I4.0 talent, working collaboratively with governments, organizations, and other universities is crucial. Their synergy will allow the enforcement of training and development programs, where students can develop new skills and competences and excel their current ones to cope with I4.0 challenges.

Additionally, since professionals face challenges when adopting I4.0 and need to develop new skills and competences or reinforce the ones they already have, the continuous improvement and redesign capabilities of ISE academics and practitioners should be applied to the development of programs for the digital era. The development of new business models, the leading of digital transformation efforts in the organizations, and the definition of the new roles of people in digitalized organizations are some examples of value-added activities of the Industrial and Systems Engineer 4.0.

Similarly, lifelong learning is important for ISE professionals since it considers that studying and knowing do not end in university and must remain in the professional life. Therefore, the triple-helix bonding (i.e., university-organization-government) allows students to be part of professional experiences and organizations to offer training programs to their workforce related to the latest trends in digitalization and technological advancements.

Future work is suggested to detail the specific curricula and contents of "ISE Education 4.0" and provide a roadmap to successfully guide universities through this evolving educational journey.

The limitations of this study include the exclusion criteria used while performing the literature review, since they resulted in the removal of non-English papers, which may have ignored existing publications in other languages or key concepts different from the ones defined for this research. Also, the smaller number of universities' programs related to I4.0 education that were studied. In the future, it will be interesting to perform exhaustive research on more educational programs to improve the model and validate it through interviews with experts and case studies.

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