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Industry 4.0 Technologies in Industrial Engineering Courses: A Faculty Survey in Brazil*

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Industry 4.0 represents the digital transformation of industrial production, characterized by intense automation and digitalization of manufacturing and management processes, bringing new technologies such as Big Data Analytics, Industrial Internet of Things, Cloud Computing, and Additive Manufacturing. This transformation changes how processes are organized, demanding a new profile of engineers. This article presents a survey with professors of undergraduate courses in Industrial Engineering about the inclusion of i4.0 technologies in these courses. The research is guided by five questions about the importance, maturity, challenges, strategies, and impacts of these technologies in Industrial Engineering courses. A total of 95 professors responded to the survey, representing 17.9% of the total number of invited professors. The results show that, although most of these technologies are considered necessary for the new profile of the industrial engineer, the degree of maturity in teaching these technologies, in most cases, is still in the early stages of adoption. In addition, challenges related to capacity, infrastructure, and resources need to be overcome for successful innovation. In this sense, some strategies were pointed out in the survey. An evident limitation of the work is that it reflects the reality of a given country, which also presents significant regional differences. An extension of the present work would be to replicate and compare the results of this survey with those of other countries at different stages of Industry 4.0.

Keywords: industry 4.0; enabling technologies; industrial engineering; engineering education

1. Introduction

Industry 4.0 (i4.0) was born in 2011 from a German government initiative, which sought technological solutions for greater automation and digitization of its industry. The aim was to achieve higher productivity and efficiency in German manufacturing companies [1].

For this, Industry 4.0 relies on automation and digitalization of the manufacturing and management processes. It is based on enabling technologies such as Big Data Analytics, the Internet of Things, Cloud Computing, and Additive Manufacturing.

The dissemination of these technologies and new production practices generates the need for professionals with new skills, especially in engineering. This demand has made educators dedicate themselves to identifying these competencies and how to develop them [2].

Analysing the operations management literature, we identified a few articles on changes in engineering education towards i4.0 in other countries. Some papers present case studies on the inclusion of i4.0 topics in the engineering curricula [3–5]. Other studies addressed strategies for including i4.0 topics in engineering curricula through surveys with students, teachers, and companies [6–8]. Finally, based on literature reviews, some authors analyse the skills of i4.0 professionals and explore strategies that some institutions are adopting to achieve this objective [9, 10].

Although i4.0 is still not a reality in Brazil, Santos and Oliveira [11] point out that digital transformation will soon impact industrial engineering in our country, as it happens in more developed countries. As a result, some engineering schools are already moving to adapt their curriculum.

This study aims to survey the opinion of Brazilian industrial engineering professors about teaching i4.0 technologies in their undergraduate courses. The survey addresses five issues: importance, maturity, challenges, strategies, and impacts, which are translated into the following five research questions:

RQ.1 How important is the inclusion of i4.0 technologies in Industrial Engineering courses?
RQ.2 What is the degree of maturity in teaching i4.0 technologies in Industrial Engineering courses?
RQ3. What are the challenges of including i4.0 technologies in Industrial Engineering courses?
RQ4. What are the best strategies for including i4.0 technologies in Industrial Engineering courses?
RQ5. What are the impacts of digital transformation on Industrial Engineering?

This article is structured as follows. Section 2 presents the theoretical framework of the article. Section 3 details the research method. In section 4,

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the analysis and discussion of the research results are carried out. Section 5 closes the article with conclusions and suggestions for future research.

2. Background

In this section, we provide an overview of the enabling technologies of i4.0, which are the focus of this research. In addition, we present an overview of the new skills required of engineers and, finally, a topic on learning practices in engineering education.

2.1 Industry 4.0 Enabling Technologies

According to [12], Industry 4.0 is characterized by automated and digitized processes, which make intensive use of information and automation technologies. Mittal et al. [13] highlight that the high degree of digitalization is one of the main factors differentiating the fourth industrial revolution from its predecessor.

The Boston Consulting Group [14] defined nine technologies considered pillars of i4.0: (i) Big Data Analytics, (ii) Autonomous Robots, (iii) Simulation, (iv) Horizontal and Vertical System Integration, (v) Industrial Internet of Things, (vi) Cybersecurity, (vii) Cloud Computing, (viii) Additive Manufacturing, and (ix) Augmented Reality.

Several authors [15–18] also consider artificial intelligence an enabling technology for Industry 4.0. Thus, this article considers the ten enabling technologies presented below.

Big Data Analytics (BDA) makes it possible to collect and analyse information in real-time from large corporate databases, which are relevant for decision-making in different areas of management, such as marketing, logistics, production, purchasing, etc. [19, 20].

According to [21], the traditional data processing methods are not suitable for big data due to the large volume and diversity of data. Therefore, special techniques and methodologies are needed for analysis, curation, sharing, storage, transfer, visualization, and privacy of information to perform predictive analysis and extract value from data.

Autonomous Robots are essential for smart factories to achieve the desired level of flexibility. Through artificial intelligence, this class of robots can make some decisions and perform some tasks autonomously, without operator intervention [1].

Simulation, a well-known decision support tool in Industrial Engineering for years, has gained new applications with software development, which allows simulating the new configurations of production systems in a very realistic way.

The simulation is "a technology that mirrors the physical world data such as machines, products and process in a virtual world aiming for simplification and affordability of the design, creation, testing and live operation of the systems" [17, p. 4].

Horizontal and Vertical Integration refers to systems integration in i4.0. Horizontal integration consists of integrating systems for exchanging information between companies, being the basis for close and high-level collaboration. Vertical integration is the basis for exchanging information and cooperation between the different hierarchical levels of the company through the digitalization of all processes [1].

The Industrial Internet of Things is a network technology to connect shop floor agents to company systems. The data collected can be analysed and used in decision-making [22].

Cybersecurity is a critical aspect of i4.0, as systems (communication infrastructure, network protocols, application servers, database servers, human-machine interfaces, program logic controllers, and remote terminal units, among others) have become more vulnerable to cyber-attacks, which can cause significant losses for the business [23].

In this way, cybersecurity technologies aim to protect systems from these threats through countermeasures such as firewalls, the application of multiple layers throughout the network, and remote access [23].

Cloud Computing is an architecture that allows the allocation of computing resources in real-time, with minimal interaction with the server, greater data sharing, and reduced physical distances, in addition to increasing computing power [19].

Additive Manufacturing or 3D printing is the technology that allows the construction of a three-dimensional object in layers from a digital model [24, 25]. With Additive Manufacturing, it is possible to create prototypes faster and reduce the design time of products and processes [1].

Augmented Reality is one of the technologies that allow the interaction between humans and machines and between humans and intelligent manufacturing systems through visualization devices, sensors, tracking, data processing, and user interface [26].

In the past, Augmented Reality was used mainly in the entertainment field. However, according to [27], this technology has gained importance and applicability in the industry in several areas, such as maintenance, remote technical assistance, training, quality control, work safety, design, and logistics.

Artificial Intelligence (AI) is a science that develops intelligent algorithms that emulate reasoning, learning, communication, and perception, which allow controlling physical objects [28].

Artificial Intelligence supports processing large amounts of data provided by big data. Based on the processing of this data, it can make associations, identify differences, and expand pattern recognition ability. These correlations, links, and inferences help managers in decision-making [28].

2.2 Competencies of Engineers for Industry 4.0

The term competence, in the context of education, is defined as a set of knowledge, skills, and values, whether general or specific, that an individual needs to develop throughout their professional trajectory, to work in different environments, and to follow the constant changes in the labour marketplace [9].

According to [29], competence is the proven ability to use individual, social and technical knowledge, and skills in professional and personal development. Therefore, competence can be understood as a combination of knowledge and experience.

General competencies point to transversal skills that apply to various environments and professional situations, emphasizing teamwork and communication skills [30]. On the other hand, specific competencies refer to the acquisition of knowledge and skills in a particular specialization, such as using techniques and tools for corrective maintenance or collecting and analysing data for preventive maintenance [31].

As presented in section 2.1, i4.0 implies big data processing. Thus, statistical tools, artificial intelligence, and other technologies that enable i4.0 must be included in the engineer's set of skills, at least their fundamentals, as a minimum requirement [32].

With the diffusion of the enabling technologies of i4.0, companies will demand more qualified, creative, articulate professionals with a strategic vision to manage more complex manufacturing systems [33]. Industry 4.0 professionals need to have the knowledge and skills to face a highly technological and interconnected environment, requiring the development of specific and general skills. The main general competencies include: (i) interdisciplinary thinking, (ii) agility in decision making, (iii) problem solving, (iv) intercultural relationship skills, and (v) commitment to lifelong learning [3].

The main specific competencies in the field of engineering are related to (i) systems development, (ii) technology integration, (iii) embedded systems programming, (iv) mobile and network technologies, (v) machine-to-machine communication, (vi) interaction with intelligent systems and (vii) machine learning [34, 35].

The engineer must diagnose problems and adopt scientific methods to solve them, aiming to increase production efficiency, improve product quality, reduce process costs, and increase business profitability. Therefore, engineering encompasses technical and management skills [9]. In addition, [10, 36] consider that engineers must be prepared for technological changes and the decrease in product life cycles and processes and adapt to new environments and work relationships.

Industry 4.0 technologies are critical to achieving greater operational efficiency, so organizations will use emerging technologies to improve productivity, eliminate waste, and reduce response time [37]. Therefore, developing appropriate skills represents a significant challenge for higher education institutions. It is up to them to assess the impacts of digital transformation and develop strategies to incorporate enabling technologies into the engineering curriculum.

2.3 Engineering Education 4.0

Digital transformation has also influenced higher education. Education 4.0 expresses a trend of changes in the educational process, provided by the advances in information and communication technologies [3]. Technology makes it possible to combine physical and virtual resources, face-to-face and remote experiences, and synchronous and asynchronous activities, expanding the possibilities of learning that can occur anywhere and at any time [38].

In Engineering Education 4.0, teaching is more personalized, aiming to explore each student's potential. Using student-centred methodologies supported by new digital technologies, students take a more active role, and teachers become mediators of the learning process [39]. These new teaching practices have been called "active learning." Another essential concept is the flexibility of formation paths, allowing students to choose the topics of most significant interest throughout the undergraduate course [40].

In the active-learning paradigm, students are encouraged to carry out activities and reflect on what they are doing, which enriches the learning experiences. [41] highlights four active learning strategies:

(i) Problem-Based Learning (PBL), which aims to develop problem-solving skills.
(ii) Project-Based Learning (PjBL), which explores teamwork, creativity, and communication skills.
(iii) Game-based learning or Gamification, which uses the playful aspect to motivate students' participation in activities.
(iv) Flipped Classroom, which requires the student to do a preliminary study of the content of the class and uses the class time for discussion and application of this content [42].

Olmedo-Torre et al. [43] include the active learning methodology "design thinking," which aims at creative problem solving, using figures, graphics, images, or animations to drive learning. Kumar et al. [44] address blended learning. This modality combines online and offline activities with the use of flexible information and communication technologies, which had widespread use during the pandemic.

Hernandez-de-Menendez et al. [10] emphasize that the new practices of active learning, combined with digital technologies in teaching, should guide the new pedagogical projects in engineering education. In general, and in the specific engineering case, i4.0 technologies may enable virtual laboratories to provide meaningful learning experiences [45].

Examples of i4.0 technologies with the potential to change engineering education include: (1) 3D printers, which provide a better understanding of manufacturing processes; (2) augmented and virtual reality, which better capture students' attention and stimulate connections between learned concepts and its practical applications; (3) cloud computing, which provides students with remote access to learning environments and computing resources; (4) simulation, which allows students to develop modelling and analytical skills; (5) artificial intelligence, which provides a better understanding of problems and resolution strategies using codes [46]; (6) autonomous robots, which capture students' attention and stimulate creativity and (7) the internet of things, which provide an expanded view of the agents that make up modern production systems [47–49].

The different potential applications of i4.0 technologies in engineering education, combined with the adoption of active learning strategies, contribute to developing the engineer's general and specific skills required to work in the new digital corporate environment.

3. The Survey Method

This section presents the research method, a survey with higher education professors. According to [50], a survey consists of (i) collecting information about one or more groups of people (their characteristics, opinions, or experiences) through a self-administered questionnaire, (ii) tabulating the answers, and finally (iii) analysing the data collected to answer the research questions.

In this article, the objective is to raise the opinion of professors about the importance, maturity, challenges, strategies, and impacts of the inclusion of i4.0 technologies in undergraduate courses in Industrial Engineering at the leading Brazilian higher education institutions. As defined in section 1, the study is guided by five research questions:

RQ.1 How important is the inclusion of i4.0 technologies in Industrial Engineering courses?
RQ.2 What is the degree of maturity in teaching i4.0 technologies in Industrial Engineering courses?
RQ3. What are the challenges of including i4.0 technologies in Industrial Engineering courses?
RQ4. What are the best strategies for including i4.0 technologies in Industrial Engineering courses?
RQ5. What are the impacts of digital transformation on Industrial Engineering?

To answer these questions, we prepared and applied a questionnaire to professors of the leading Industrial Engineering courses in Brazil, following the recommendations of [50]. The institutions' choice criteria were the national assessment of graduate programs, a consolidated assessment in the country, and strongly correlated with the undergraduate courses.

The questionnaire has ten questions, seven of which are closed-ended and three are open-ended. We used a 5-point Likert scale to quantify the answers to closed questions. We used the Google Forms survey application to collect and save responses in a spreadsheet.

Before sending the questionnaire, as suggested by [50], we conducted a pilot test with three professors, who evaluated the questions for clarity, relevance, and consistency with the research objectives. Some criticisms and suggestions were incorporated into a new questionnaire, again validated by the three collaborators and the team. The final version of the questionnaire is available at the end of this article.

Next, we prepared a table containing the professors' names, e-mail, and institutions. Based on the criteria mentioned above, we selected 20 faculties to participate in the research, but data from the professors of five of them were not available. Thus, the final table had 15 faculties and 532 professors.

The questionnaire was open from July 22 to October 12, 2021. We sent the invitation to participate in three moments (first sending and two reminders). In the end, we received 95 responses to the questionnaire, corresponding to 17.9% of participation. The results are presented in the next section.

4. Results and Discussion

In this section, we present and discuss the survey results. It is divided into seven subsections: quality of answers, respondent profile, importance, maturity, challenges, strategies, and impacts of technologies in undergraduate courses.

4.1 Quality of Responses

Cronbach's alpha coefficient is one of the most used statistics in research to assess the quality of answers to self-administered questionnaires [51]. The alpha coefficient was proposed by Lee J. Cronbach [52] to measure the internal consistency of a scale, that is, to assess the degree of reliability of the answers obtained with a questionnaire.

The input to calculate the alpha is the matrix with the quantified responses to the questionnaire. Each row of the matrix represents a respondent (j), and each column represents a question (i). On the Likert scale from 0 to 5, the original answers are converted into a proportional score from 0 to 1, with responses marked "I don't know" discarded. Then, Cronbach's alpha coefficient is calculated according to Equation 1 [53].

$$\alpha = \frac{\mathrm{k}}{\mathrm{k}-1}\left[\frac{\sigma_j^2 - \Sigma_{i=1}^{k}\sigma_i^2}{\sigma_j^2}\right] \tag{1}$$

Where σ_i^2 is the variance of each column, that is, the variance related to each question, and σ_j^2 is the variance of the sum of each row, that is, the variance of the sum of the responses of each respondent.

In equation (1), k corresponds to the total number of responses, which in this survey was 95. If there is consistency in the quantified responses, then σ_j^2 will be relatively large, causing the α to tend to 1. On the other hand, random answers will make σ_j^2 comparable to the sum of the individual variances (σ_i^2), causing the α to tend to zero.

The reliability of the answers is good if the coefficient is between 0.70 and 0.90. Values below 0.70 suggest a low number of questions in the questionnaire. On the other hand, values above 0.90 indicate redundant issues [54].

The alpha calculated for the questionnaire was 0.84, a value within the acceptable limits established by [54]. The alpha was also calculated by the five dimensions: importance, maturity, challenges, strategy, and impacts. The results obtained were, respectively, 0.77, 0.82, 0.78, 0.39 and 0.79. Except for the "strategy" dimension, the others presented results within acceptable limits. The limited number of response options in this question may explain the low alpha value of 0.39.

4.2 Respondent Profile

This subsection analyses the respondent's profile concerning two aspects: (i) origin and (ii) courses. As highlighted in the previous section, we sent the questionnaire to professors at 15 top universities. We obtained 95 answers from professors in 12 (80%) of them. One respondent did not indicate in which university he works.

Regarding the distribution of these professors by courses, we considered three alternatives: (i) teaching only in the Industrial Engineering course; (ii) in the Industrial Engineering and some other courses; and (iii) only in other courses. The results are shown in Fig. 1.

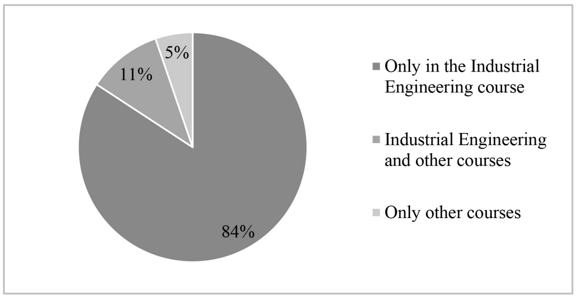

Fig. 1. Frequency distribution by courses.

4.3 Research Question 1 – Importance

The first research question aims to assess how important the inclusion of enabling technologies of i4.0 in Industrial Engineering courses is in the opinion of professors.

First, we sought to validate the list of ten enabling technologies in the questionnaire, asking about the need to include or exclude topics from the list (question 1). Fig. 2 shows that most professors agree with the enabling technologies as presented.

Almost a quarter of the respondents indicated the need to include some technology in this list. Fig. 3 lists the mentioned topics, emphasizing Blockchain, a technology that enables transactions and information sharing between companies in a supply chain.

Some respondents suggested exclusions from the list, most notably the topic of cybersecurity. A comment pointed out that Industrial Engineering

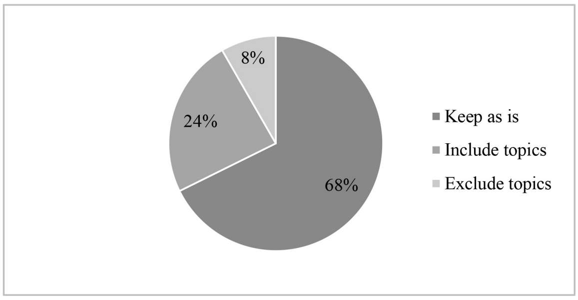

Fig. 2. Respondents' opinion on the list of enabling technologies.

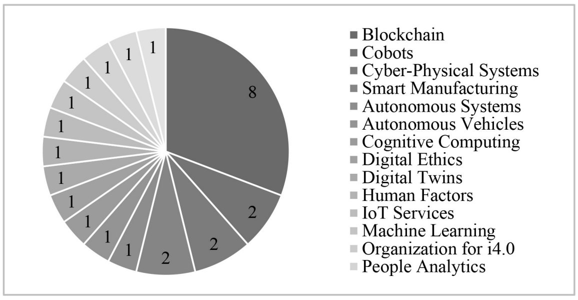

Fig. 3. Technologies that should be included.

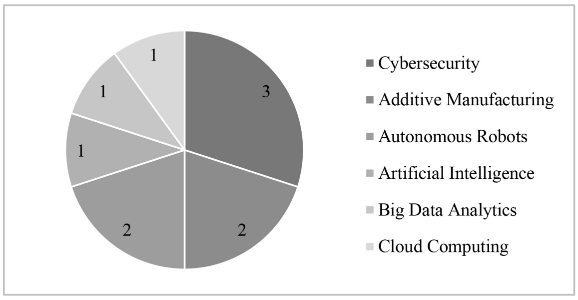

Fig. 4. Technologies that should be excluded.

is a "user" of these complex technologies, not a "developer"; therefore, they should not be part of the curriculum.

The comments pointed out that industrial engineers should only know these more challenging technologies, which other engineering fields will study. Fig. 4 presents the topics cited for deletion.

Analysing the responses from the two previous questions (frequencies and comments), we consider that the original list of technologies is adequate for this research.

Continuing with the questionnaire, question 7 deals with the importance of teaching i4.0 enabling technologies in Industrial Engineering courses. Most professors considered teaching such technologies "very important," as shown in Fig. 5.

In addition, to better understand this question, we asked about the inclusion priority of each technology (question 2). Figs. 6a and 6b show that artificial intelligence, digital simulation, and horizontal and vertical systems integration are highly prioritized for inclusion.

To complement the analysis, we calculated the average priority of each technology on a scale from 0 to 4, considering the answers "none" equal to 0, "low" equals 1, "median" equals 2, "high" equals three, and "very high" equals four. The results are shown in Fig. 7.

4.4 Research Question 2 – Maturity

The second research question analyses the maturity of teaching i4.0 enabling technologies in Industrial Engineering courses. Question 3 of the questionnaire addressed this issue.

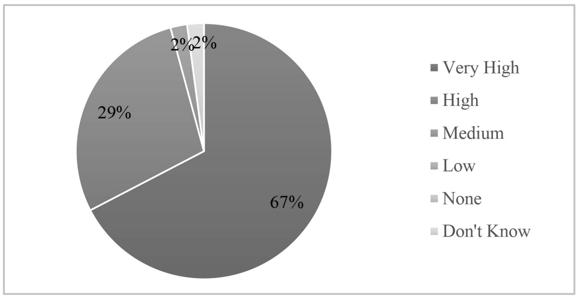

Fig. 5. Importance of teaching enabling technologies.

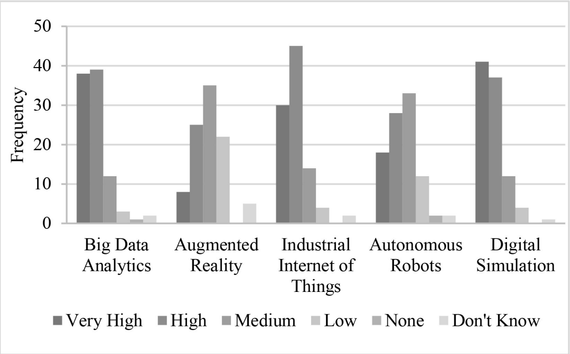

Fig. 6a. Inclusion priority of enabling technologies in Industrial Engineering courses.

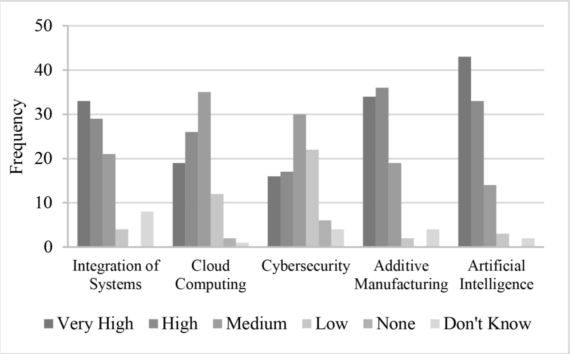

Fig. 6b. Inclusion priority of enabling technologies in Industrial Engineering courses.

Figs. 8a and 8b show that, generally, maturity is low in professors' perception. Considering the most frequent answers, the technologies with greater maturity, Simulation and Additive Manufacturing, were evaluated only as "median" maturity; Systems Integration was rated between "medium" and "low"; the rest were rated "low," except Cyber Security, which was rated "none." None of the technologies were rated as "high" or "very high" maturity. Fig. 9 presents the average level of maturity for teaching i4.0 technologies.

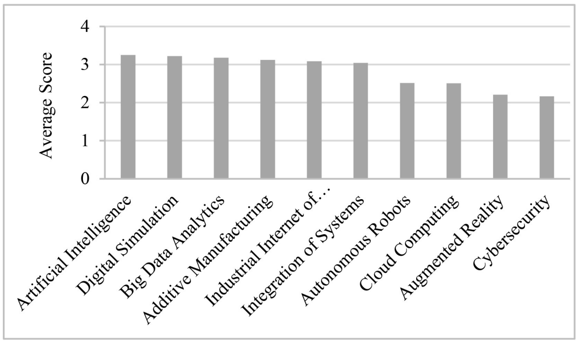

Fig. 7. Average priority of inclusion of enabling technologies.

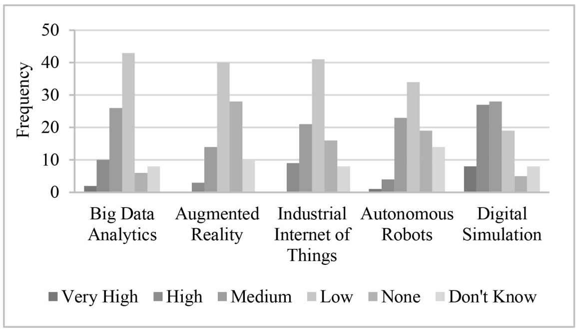

Fig. 8a. Maturity of teaching enabling technologies in Industrial Engineering courses.

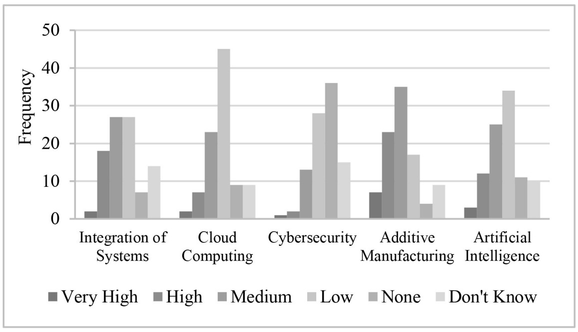

Fig. 8b. Maturity of teaching enabling technologies in Industrial Engineering courses.

4.5 Research Question 3 – Challenges

The third research question addresses the challenges of including i4.0 enabling technologies in Industrial Engineering courses. Questions 4 and 5 address this issue.

In question 4, we evaluated the degree of difficulty in including each of the i4.0 technologies in Industrial Engineering courses. Figs. 10a and 10b show that Autonomous Robots, Augmented Reality, and Cyber Security are the technologies identified with the most significant difficulty for inclusion. On the other hand, Digital Simulation and Horizontal and Vertical Integration of Systems were indicated as technologies of the lowest difficulty for inclusion. Fig. 11 shows the average difficulty level by technology.

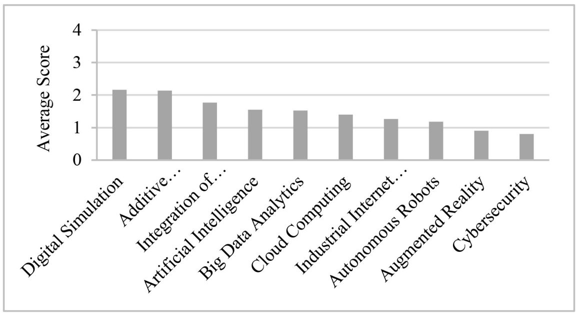

Fig. 9. Average degree of maturity in the teaching of i4.0 technologies.

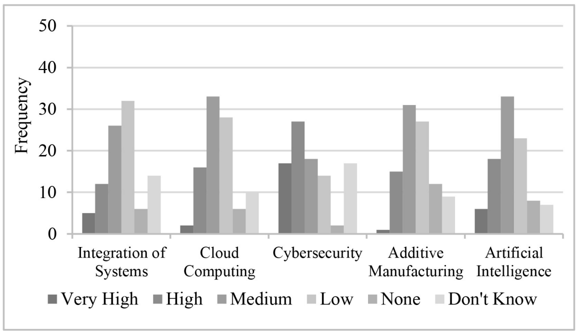

Fig. 10a. Difficulty in including i4.0 technologies in Industrial Engineering courses.

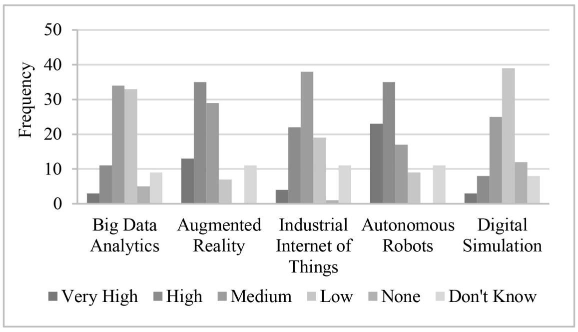

Fig. 10b. Difficulty in including i4.0 technologies in Industrial Engineering courses.

In question 5, we asked respondents to assess some challenges of including these technologies in Industrial Engineering courses. According to Fig. 12, the most significant challenges are getting resources for laboratories and partnerships with companies.

Fig. 13 shows the average difficulty of the listed challenges. Respondents also cited other challenges: (a) create a culture of planning and continuous improvement of curricula; (b) reduce existing subjects to include new subjects in the curriculum; (c) share subjects between different university units; (d) integrate graduate and undergraduate courses, research, and extension activities; (e) adapt laboratory spaces for new undergraduate courses; (f) hire professors with specific skills in some of these

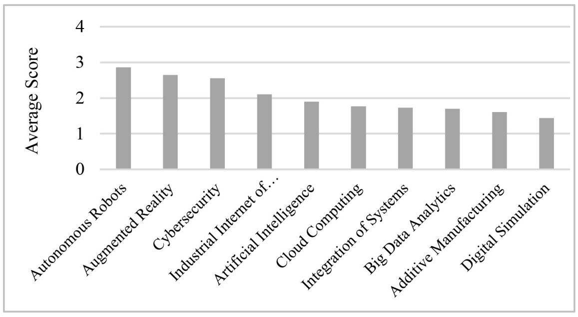

Fig. 11. Average degree of difficulty of including enabling technologies.

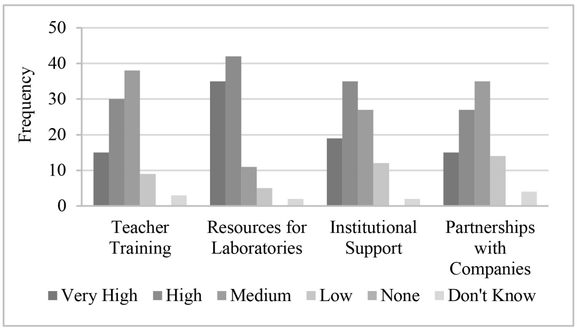

Fig. 12. Challenges of including i4.0 technologies in Industrial Engineering courses.

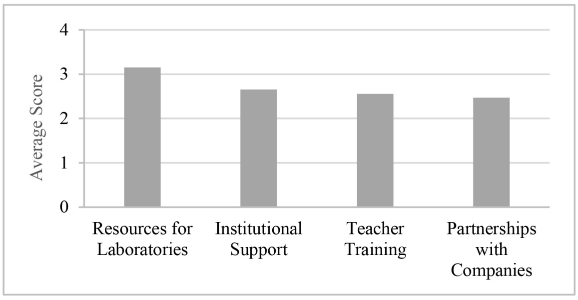

Fig. 13. Degrees of difficulty of the challenges for the inclusion of enabling technologies.

technologies; (g) resistance of the faculty to make significant changes in the courses.

4.6 Research Question 4 – Strategies

The fourth research question analyses the best strategies for the inclusion of i4.0 enabling technologies in Industrial Engineering courses. In question 6, we question the adequacy of some strategies for including i4.0 technologies in the undergraduate course in Industrial Engineering. Fig. 14 shows that all strategies cited are considered adequate.

Fig. 15 shows the average degree of adequacy of these strategies. Two respondents also suggested:

(a) maintain dialogue with companies to monitor the evolution and inclusion of these technologies in engineering curricula.

(b) offer flexibility in the student's education trajectory, aiming at an entrepreneurial and innovation-oriented education.

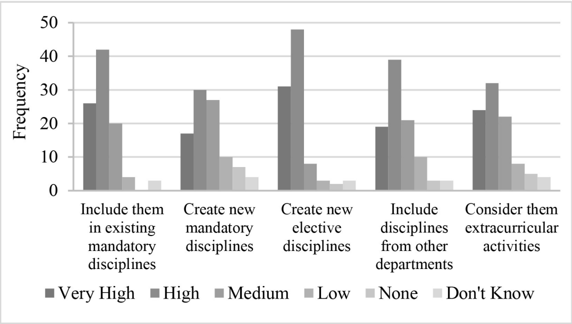

Fig. 14. Strategies for including i4.0 technologies in Industrial Engineering courses.

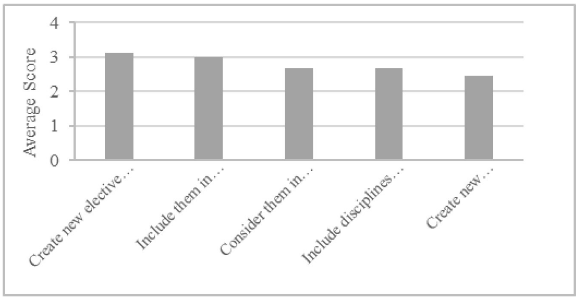

Fig. 15. Average degree of adequacy of strategies for the inclusion of enabling technologies.

4.7 Research Question 5 – Impacts

The last research question aims to analyse the impact of digital transformation in Industrial Engineering. For this, we formulated questions 8 and 9 of the questionnaire.

In question 8, professors evaluated the impact of digital transformation in Industrial Engineering, using the definition of areas presented by the Brazilian Association of Production Engineering (www.abepro.org). According to Figs. 16a and 16b, except Economic Engineering, all areas will have a high or very high impact caused by digital transformation. Fig. 17 presents the average degree

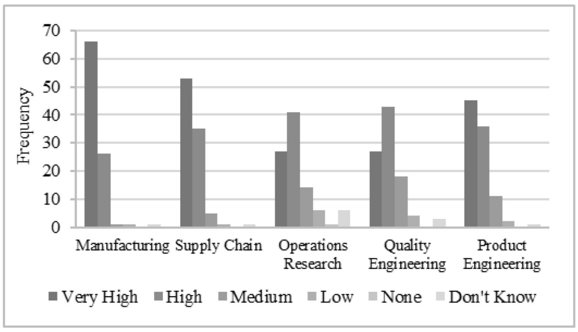

Fig. 16a. Impact of digital transformation in the areas of Industrial Engineering.

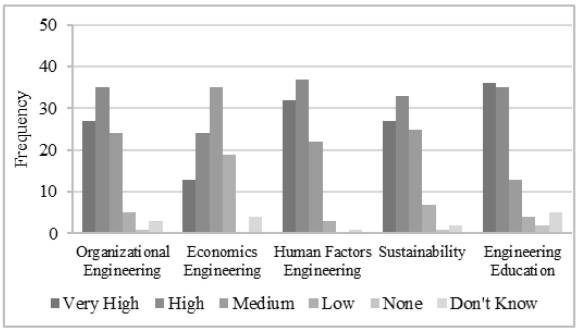

Fig. 16b. Impact of digital transformation in the areas of Industrial Engineering.

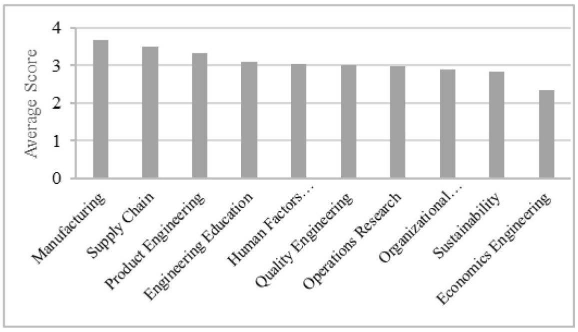

Fig. 17. Average degree of impact of digital transformation in the areas of Industrial Engineering.

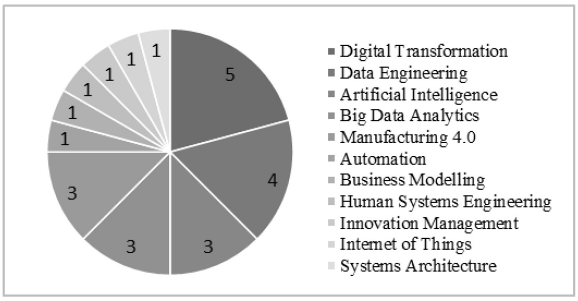

Fig. 18. Topics that should be incorporated into the field of Industrial Engineering.

of impact in the opinion of respondents. In question 9, professors indicated topics to be incorporated into Industrial Engineering. Fig. 18 lists the cited topics.

Finally, the last question was for general comments from respondents, among which we highlight the following: (a) “we must seek a curriculum that combines traditional disciplines with new contents from digital transformation so that industrial engineers keeps their abilities to approach organizations in an integrated way.” (b) “create alternative paths so that students can specialize in specific topics of digital transformation.” (c) “promote a national discussion on the updating of Industrial Engineering curricula.” (d) “seek greater internal and external integration, which makes it possible to take advantage of existing disciplines on artificial intelligence and other topics of industry 4.0.” (e) “the primary concern of the Industrial Engineering courses should be the diffusion of essential industrial technologies for most companies, much more than a set of advanced techniques and methods for the fewer high tech companies.” (f) “Industrial Engineering will need to undergo a revolution to adapt to the new production paradigms and environments. Digital transformation will require curriculum revision and additional competencies from professors. We will have more chances of success if an integrated work establishes a set of guidelines for the Industrial Engineering courses in the country.”

5. Conclusion

This article presents a survey of professors about teaching i4.0 technologies in undergraduate Industrial Engineering courses. In the respondents’ opinion, the i4.0 contents should be incorporated into the classes, although some more technical topics are necessary only at the introductory level.

The results also show that, despite the relevance, the maturity in teaching these contents, except for digital simulation and additive manufacturing, is in the early stages of adoption. In addition, respondents pointed to challenges for effective change, citing mainly the budget constraints of their institutions, most of them are public universities, as the biggest challenge to be overcome.

Concerning strategies, in addition to including these contents in mandatory disciplines and the creation of elective disciplines, the convenience of seeking greater integration between the departments is highlighted, facilitating the offer of subjects from different areas of engineering, and promoting multidisciplinary graduation.

Finally, the research points out some impacts, mainly on manufacturing, products and processes engineering, and supply chains, resulting from the ongoing digital transformation in companies and society.

This research has limitations inherent to the survey method, such as sample representativeness and quality of responses. We obtained a reasonable response rate (17.9%) and a Cronbach’s alpha coefficient of 0.84, thus showing adequate reliability for this type of research. Another limitation of the study is that it refers to the reality of Brazilian universities.

An extension of this work would be to replicate and compare the results of this survey with those of other countries at different stages of Industry 4.0 development. Another direction would be to carry out case studies in courses that have concluded or are reviewing their pedagogical projects, aiming to contemplate new contents and learning practices, to understand better how to conduct this process of transformation of Industrial Engineering education.

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Appendix

Survey – Industrial Engineering 4.0

Question 1 – This survey considers ten Industry 4.0 enabling technologies: (1) Big Data Analytics; (2) Augmented Reality; (3) Industrial Internet of Things; (4) Autonomous Robots; (5) Digital Simulation; (6) Horizontal and Vertical Integration of Systems; (7) Cloud Computing; (8) Cybersecurity; (9) Additive Manufacturing; (10) Artificial Intelligence. Would you have any inclusions or exclusions from this list? Which ones?

Question 2 – Assess the priority of inclusion (very high, high, medium, low, none, don't know) of the following i4.0 technologies in the undergraduate courses in Industrial Engineering at your institution: (1) Big Data Analytics; (2) Augmented Reality; (3) Industrial Internet of Things; (4) Autonomous Robots; (5) Digital Simulation; (6) Horizontal and Vertical Integration of Systems; (7) Cloud Computing; (8) Cybersecurity; (9) Additive Manufacturing; (10) Artificial Intelligence. Comments?

Question 3 – Rate the maturity (very high, high, medium, low, none, don't know) of teaching the following i4.0 technologies in the undergraduate courses in Industrial Engineering at your institution: (1) Big Data Analytics; (2) Augmented Reality; (3) Industrial Internet of Things; (4) Autonomous Robots; (5) Digital Simulation; (6) Horizontal and Vertical Integration of Systems; (7) Cloud Computing; (8) Cybersecurity; (9) Additive Manufacturing; (10) Artificial Intelligence. Comments?

Question 4 – Rate the difficulty (very high, high, medium, low, none, don't know) of inclusion of the following i4.0 technologies in the undergraduate courses in Industrial Engineering at your institution: (1) Big Data Analytics; (2) Augmented Reality; (3) Industrial Internet of Things; (4) Autonomous Robots; (5) Digital Simulation; (6) Horizontal and Vertical Integration of Systems; (7) Cloud Computing; (8) Cybersecurity; (9) Additive Manufacturing; (10) Artificial Intelligence. Comments?

Question 5 – Assess the difficulty of the following challenges (very high, high, medium, low, none, don't know) to include i4.0 technologies in the undergraduate courses in Industrial Engineering at your institution: (1) Teacher Training; (2) Resources for Laboratories; (3) Institutional Support; (4) Partnerships with Companies; (5) Others (specify). Comments?

Question 6 – Assess the adequacy of the following strategies (very high, high, medium, low, none, don't know) of inclusion of i4.0 technologies in the undergraduate courses in Industrial Engineering at your institution: (1) Include them in existing mandatory courses; (2) Create new mandatory courses, (3) Create new elective courses, (4) Use courses from other departments or colleges, (5) Include them in extracurricular activities, (6) Others (specify). Comments?

Question 7 – Rate the importance (very high, high, medium, low, none, don't know) of the teaching of i4.0 technologies in the undergraduate courses in Industrial Engineering at your institution. Comments?

Question 8 – Assess the impact of digital transformation (very high, high, medium, low, none, don't know) in the Industrial Engineering field: (1) Manufacturing, (2) Supply Chain, (3) Operations Research, (4) Quality Engineering, (5) Product Engineering, (6) Organizational Engineering, (7) Economics Engineering, (8) Human Factors Engineering, (9) Sustainability, (10) Engineering Education.

Question 9 – About the previous question, which new areas should be included in the Industrial Engineering field?

Question 10 – Please feel free to compliment your participation with any additional suggestions and comments about this research.

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