Proceedings of the First Australian International Conference on Industrial Engineering and Operations Management, Sydney, Australia, December 20-21, 2022

Mapping of 4.0 Industry Revolution Enabling Technologies

Catarina de Andrade Lucizano[1], Adriano Gomes de Freitas[1,2,3,]
Alexandre Acácio de Andrade[1], Júlio Francisco Blumetti Facó [1]
[1] Postgraduate Program in Engineering and Management of Innovation
[2] Postgraduate Program in Energy
Federal University of ABC (UFABC)
Santo André, São Paulo, Brazil
catarina.lucizano@aluno.ufabc.edu.br; adriano.gomes@ufabc.edu.br; aacacio@ufabc.edu.br; julio.faco@ufabc.edu.br
[3] Lab for Simulation and Modelling of Particulate Systems (SIMPAS)
Monash University
Clayton, Melbourne, Australia
adriano.gomesdefreitas@monash.edu.au

Abstract

The manufacturing model developed in the third industrial revolution is going through a disruption process that will permanently change the way goods will be designed, manufactured and delivered to consumers. The fourth industrial revolution or Industry 4.0 rises from two main factors: (i) the demands of a rising portion of consumers who are highly connected, whose hyper customized and immediate consumption patterns tend to favor services despite products, and (ii) the breakthrough of digital technologies that permeate various segments of the modern society. For this new industrial paradigm, the purpose is to merge physical and virtual worlds, building environments where data and information will become the great assets of business models and human intervention in the manufacturing process will be even lesser than what's envisioned for the third industrial revolution. However, bringing this concept into reality is not trivial and there is a need for extensive planning of the physical, technological, and organizational transformations that will be needed to achieve its goals. In this work, two aspects of the manufacturing industry's digitalization process will be exploited: its technical requirements and the demanded strategic competencies. In the technical sphere, there is a range of technologies generally considered by the literature as the backbone of Industry 4.0. Through exploratory research, these technologies will be evaluated, and their characteristics analyzed to identify how they interact with one another and if there are dependencies among them, determining an implementation roadmap that is technically coherent. Within the strategic purview, the competencies enabled by these technologies will be associated with the competencies elected by the German Academy of Science and Engineering on its Industry 4.0 Maturity Index (SCHUH, GÜNTHER et al., 2020) as necessary to reach this new model's strategic goals. Once determining the technical and strategic interactions between the selected technologies, this work proposes a systemic roadmap for the implementation of Industry 4.0 enabling technologies that defines a path for the digitization process of the manufacturing industry.

Keywords
Advanced Manufacturing, Enabling Technologies, Fourth Industrial Revolution, Industrial Automation, Industry 4.0.

1. Introduction
The Fourth Industrial Revolution is a widely spread concept among different industries: manufacturing, services, construction, education, etc., and its development is related to the changes in consumer needs all over the world. Following its predecessors (First, Second, and Third Industrial Revolutions), the also known as Industry 4.0 rises as a response to today's consumption patterns, where industries must respond quickly to requests for highly customizable, environmentally friendly, and cost-effective products (KELLER et al., 2014; KHALID et al., 2017; RÜSSMANN, 2015). For the manufacturing industries, the challenge starts as early as during the product's idealization: how is it possible to constantly add compelling features to already well-established products? Furthermore, how to create means

of production flexible enough to be able to produce small scales of unlimited versions of personalized goods? There are also concerns about how cost-competitive nations can take advantage of this disruption to unsettle the ones that are historically production leaders (Daudt; Willcox, 2016; Cucinotta Et Al., 2009; Piccinini Et Al., 2015).

To tackle that demand and be able to expand, the common trend is to deploy digital technologies that will provide industries with more flexibility and agility. In fact, the three pillars upon which the Fourth Industrial Revolution rests are flexibility, competitiveness, and sustainability (KELLER et al., 2014). While the objective is fairly clear and there's a certain level of common sense when it comes to what are the relevant technologies to achieve the Industry 4.0 goals, the path to deploying them can be ambiguous and to effectively initiate the digitization process is not obvious. In fact, according to the German Federal Ministry of Education and Research, there's a need for fuller and more targeted information when it comes to how to implement Industry 4.0 principles (BACKES-GELLNER et al., 2013).

1.1 Objectives
This study's objective is to propose a systemic roadmap for the implementation of the Industry 4.0 enabling technologies, based on the comparison of the necessary and attainable capabilities by each technology at different levels of maturity.

2. Literature Review
The emergence of the Fourth Industrial Revolution is marked by a disruption from the dynamics of its three predecessors: instead of being first observed as it develops in an almost organic way, the Fourth Revolution was foreseen and planned by governments, universities, and private initiatives (Hermann et al., 2015).

In the face of growing international competition, several countries have launched structured programs for the development and application of new technologies in industrial environments. The first nation to publicly do it was Switzerland, in 2008 (Kagermann et al. 2013). However, the expression "Industry 4.0" was only publicly introduced in 2011 by Germany at the annual Hannover Fair. Due to its long history of being one of the most innovative countries, but also facing its greatest economic crisis since the WW2, Germany's Federal Ministry of Education and Research release in 2013 a document elaborated by the Industry 4.0 Working Group with recommendations for implementing the new strategic initiative and it became the cornerstone for following research and development of this new industrial paradigm (Backes Gellner et al., 2013 Lidong; Guanghui, 2016).

The Fourth Industrial Revolution principles for the manufacturing industry, or Industry 4.0 principles, are:

- Service orientation: the functionalities of the systems must be able to be offered as services.
- Interoperability: physical, virtual, and human systems must be able to communicate transparently.
- Virtualization: physical systems must be equipped with resources that allow their transcription to the virtual world.
- Decentralization: individual systems can make autonomous decisions, waiving the need for upper management commands
- Modularization: design of systems that allow rapid adaptation in the face of constantly changing requirements.
- Synchronicity: ability to collect, process and deliver information and actions in real time

Among the benefits promoted by Industry 4.0, the most often mentioned by manufacturing managers is the intensification of competitiveness. Changes in companies' strategies combined with the adoption of new technologies foster the need for new partnerships, in addition to improving local performance to meet customer demands. Thus, business opportunities flourish and increased competitiveness spreads throughout the production chain (Kiel et al. 2017).

However, there is a lack of deep understanding of how to start the so-called "digitalization process" and the precise knowledge of its steps is a determining factor as to whether an industry will fail or succeed in implementing it.'

3. Methods

In 2020, the German National Academy of Science and Engineering published the *Industrie 4.0 Maturity Index*, where a 6-stage maturity model is proposed considering capabilities displayed by companies individually (Schuh et al., 2020) and this index will be used in this work as a guide to collate the identified Industry 4.0 enabling technologies. However, the index itself does not explicitly link technologies to each level of maturity. Therefore, to achieve the main objective of this work, 4 interim steps will be pursued:

1. Identification of the technologies that are considered enabling for the Fourth Industrial Revolution.
    - On this step, bibliography research will be conducted to determine what are the technologies considered as enabling the Industry 4.0.
2. Mapping the technical dependencies among the elected technologies.
    - Once the enabling technologies have been selected, a detailed exploration of their definitions, characteristics, and usage will be conducted. A deeper understanding of how these technologies operate allows the identification of technical dependencies among them and makes it possible to establish an implementation sequence based on technical premises.
3. Maturity index analysis and identification of what are the competencies that the elected technologies aim to enable.
    - The Industry 4.0 Maturity Index proposed by the ACATECH will be used as the source that determines what are the non-technical competencies that a company needs to display to be engaged to the I4.0 principle in different levels of maturity.
    - Taking hold of the previous step outcome, the non-technical competencies fostered by the adoption of each enabling technology will be mapped and the technologies distributed at each maturity level that they may be more adherent to.
4. Proposal of an implementation roadmap that is technically coherent and complies with the desired maturity evolution.
    - On this step, the studies previously conducted will be overlapped to verify at what level the technical sequence and the maturity level distribution will converge.

3.1 Identification of the Industry 4.0 enabling technologies.

There are no official international norms or standards established as to which technologies are considered enablers for Industry 4.0. However, there is a certain level of agreement between academic works (BORTOLINI; GALIZIA; MORA, 2018; CHEAH; LEONG, 2019; NAKAYAMA, 2017; SATURNO et al., 2018) and other studies regarding this topic, such as those published by Capgemini, McKinsey and Boston Consulting Group (BECHTOLD et al., 2014; MCKINSEY, 2015; RÜSSMANN, 2015).

Table 1 displays the technologies cited by authors whose work specifically address the indication of Industry 4.0 enabling technologies. It also shows the frequency with which each technology is addressed by different authors. In total, 16 different technologies were proposed, four of which were only addressed once: IoS, cognitive computing, RFID, and Smart ERPs; and one cited twice: Mobile Devices. These, as they represent less than 30% of the frequency of approach by the studied authors, were excluded from the present analysis. Thus, the technologies here considered as enabling for the Fourth Industrial Revolution are:

- Industrial Internet of Things (IIoT).
- Cyber Physical Systems (CPS).
- Digital simulations.
- Cyber security.
- Additive manufacturing.
- Collaborative robots.
- Big Data Analytics.
- Augmented reality.
- Horizontal and Vertical Systems Integration (HVSI)

- Cloud computing.
- Smart Sensors.

Table 1. Industry 4.0 enabling technologies

Industry 4.0 enabling technologies	**Authors**						
	Bortolini *et al*., 2018	Cheah *et al*., 2019	Nakayama, 2017	Saturno *et al*., 2018	Capgemini, 2014	McKinsey, 2015	BCG, 2015
IoT	X	X	X	X		X	X
IoS			X				
Smart ERP			X				
Big Data	X	X		X	X	X	X
Additive Manufacturing	X	X		X	X	X	X
Cloud Computing	X	X		X	X	X	X
Cyber Security	X	X		X			X
Collaborative Robots		X		X	X	X	X
Augmented Reality	X	X				X	X
Digital Simulations	X	X					X
Cognitive Computing				X			
Mobile Devices				X	X		
RFID				X			
Cyber-physical Systems	X				X	X	X
Smart Sensors	X			X	X	X	
Horizontal and Vertical Systems Integration	X	X					X

3.2 Industry 4.0 Maturity Index Analysis

The maturity assessment on how a company is complying with the Fourth Industrial Revolution premises results in its classification at one of the six different levels proposed by the German National Academy of Science and Engineering. This indicator is based on the available infrastructures and technologies in addition to the analysis of their corporate strategies and processes. It can provide an outlook on the status and on what should be pursued by the company to achieve higher levels of maturity if that's an objective.

As shown on Figure 1, each maturity level represents a capability to be conquered by the company as it moves towards full adherence to Industry 4.0: Visibility, Transparency, Predictive Capability and Adaptability. However, the document does not link specific technologies to each level, except for the Transparency level, which the document associates to Big Data.

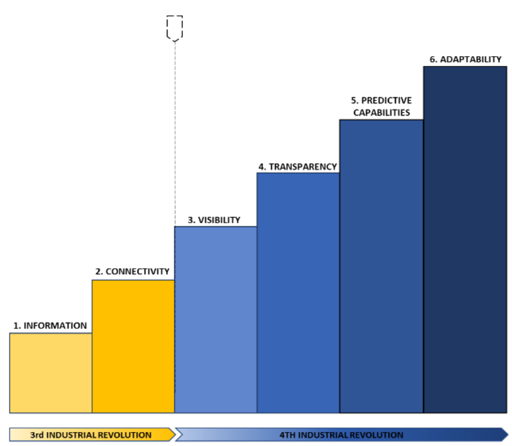

Figure 1. I4.0 Maturity Index

- Visibility: at this level, the adoption of devices capable of capturing and providing in real time the status of each of the company's processes stands out, guaranteeing the visibility of these processes. The security of the data is also an important concern.
- Transparency: the outcome of the massive amount of data previously collected after being treated, grouped and contextualized.
- Predictive Capability: here, the company should be able to apply tools to predict deviations in the process before they occur.
- Adaptability: the process is robust enough to operate autonomously. It is possible that adaptations to sudden events, be they operational failures, production scope changes, etc., occur as quickly as possible, preferably in real time.

4. Results and Discussions

4.1 Correlations between enabling technologies of Industry 4.0 and Maturity Levels.

After the Industry 4.0 enabling technologies were reviewed, it was noted that they do have technical correlations to each other, whether direct or given through other technologies. These links were mapped and the ones that are characterized as direct technical dependent – that is, when one technology requires another to fully function – were established. Ultimately, it was possible to group the technologies to have an overview of these relationships as shown in Figure 2.

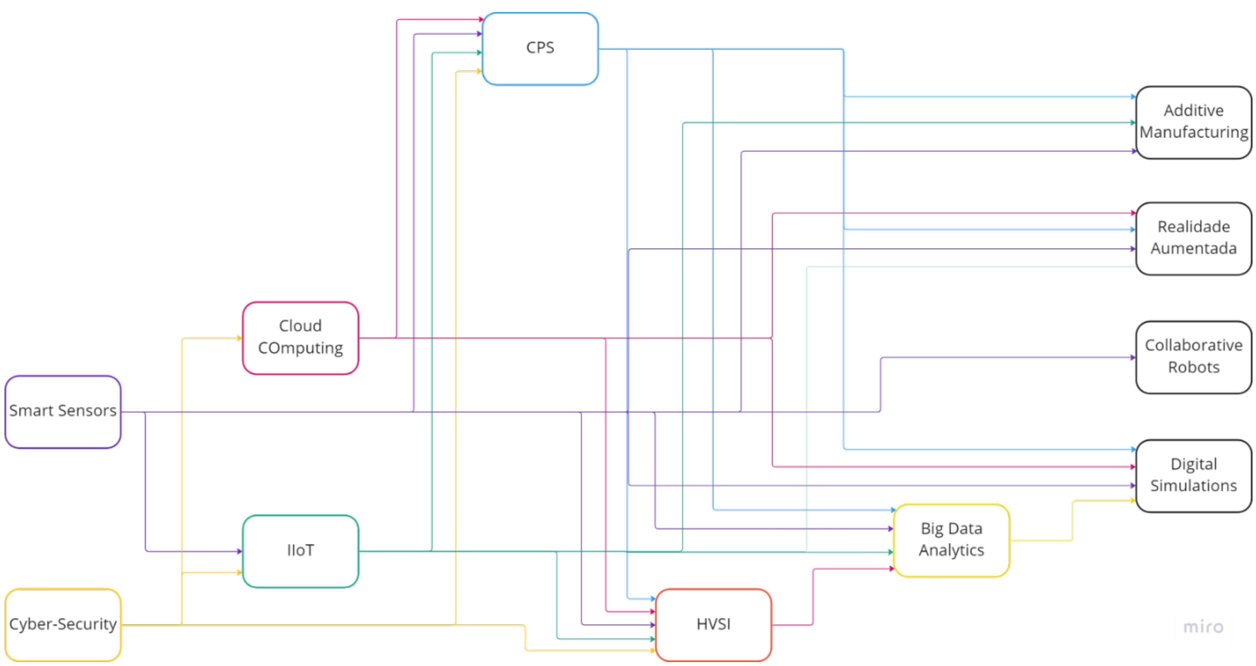

Figure 2. Technical correlations between the enabling technologies

Once the redundancies are removed, it's possible to re-align the technologies, as shown on Figure 3 and obtain a more accurate perception of what the implementation order would be, based only on technical aspects.

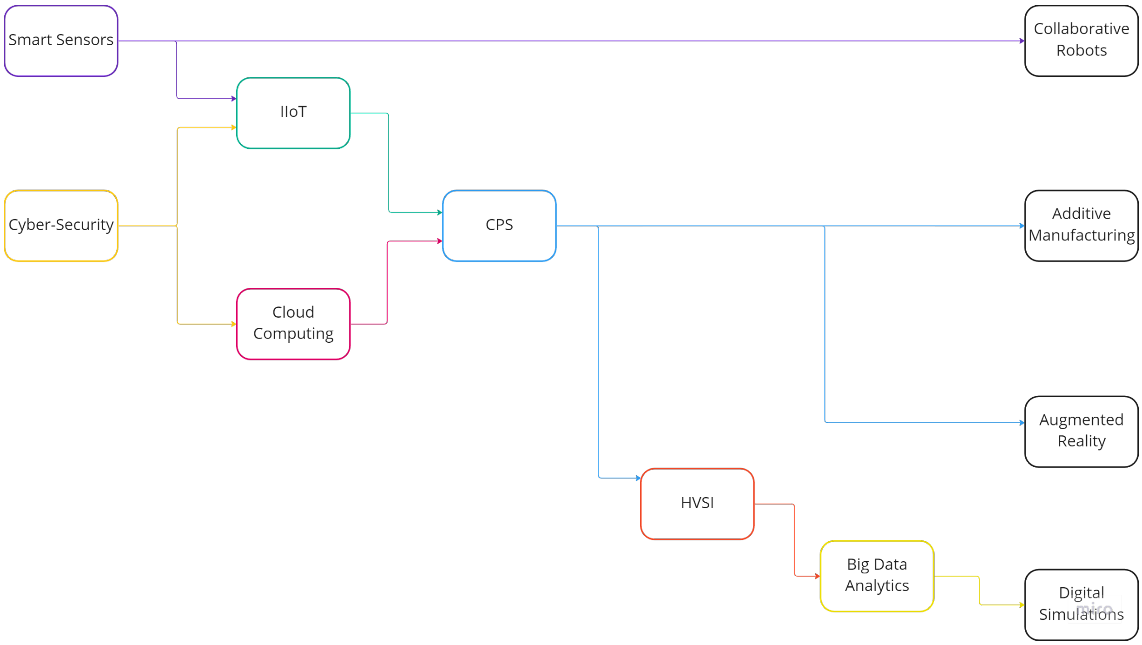

Figure 3. Simplified technical correlations between the enabling technologies

Although it already displays some level of ordination, it is not possible to take the technology sequence displayed in Figure 3 as conclusive because it does not take into consideration the non-technical capabilities discussed previously. The maturity index is composed of both technical and non-technical aspects; therefore, it is necessary to correlate the capabilities leveraged by the technologies individually to the capabilities required by each maturity level.

Table 2 displays the correlation between the competencies for each maturity level and the technologies that enable them, based on the previous exploration of its characteristics. Only the maturity levels concerning the Fourth Industrial Revolution were listed.

Table 2. Correlation between the competencies for each I4.0 maturity level.

Maturity Level	Competencies	**Enabling Technologies**
1. Visibility	Capturing and providing real time data	Smart Sensors IIoT Cyber Security
2. Transparency	Full vision of the data, after it's been contextualized	Big Data Vertical and Horizontal Systems Integration Cloud Computing Cyver physical Systems.
3. Predictive Capability	Predict deviations in the process before they occur.	Digital Simulations Augmented Reality
4. Adaptability	Adaptations should occur as quickly as possible	Additive Manufacture Collaborative Robots

Once each enabling technology is associated with the maturity level, it's possible to establish a systemic roadmap that takes into consideration both technical and non-technical aspects of what is expected from the Fourth Industrial Automation concept.

Figure 4 displays the result of this study. The model is proposed in levels for two fundamental reasons. The first concerns helping the planning process, so that there is a clear objective: to achieve the competence proposed by the level; as well as the technical path to be adopted to achieve this objective: the sequence of technologies. In this format, the establishment of resources and metrics is favored. The second reason is to highlight the need to assess the impact that the implementation of these technologies has generated, if not individually, in the general context of the level. This assessment is an important decision-making tool, as it will indicate whether the performance of the implemented technologies is positive and whether the competencies from a strategic point of view have been achieved, thus indicating whether the company is prepared to advance to higher levels.

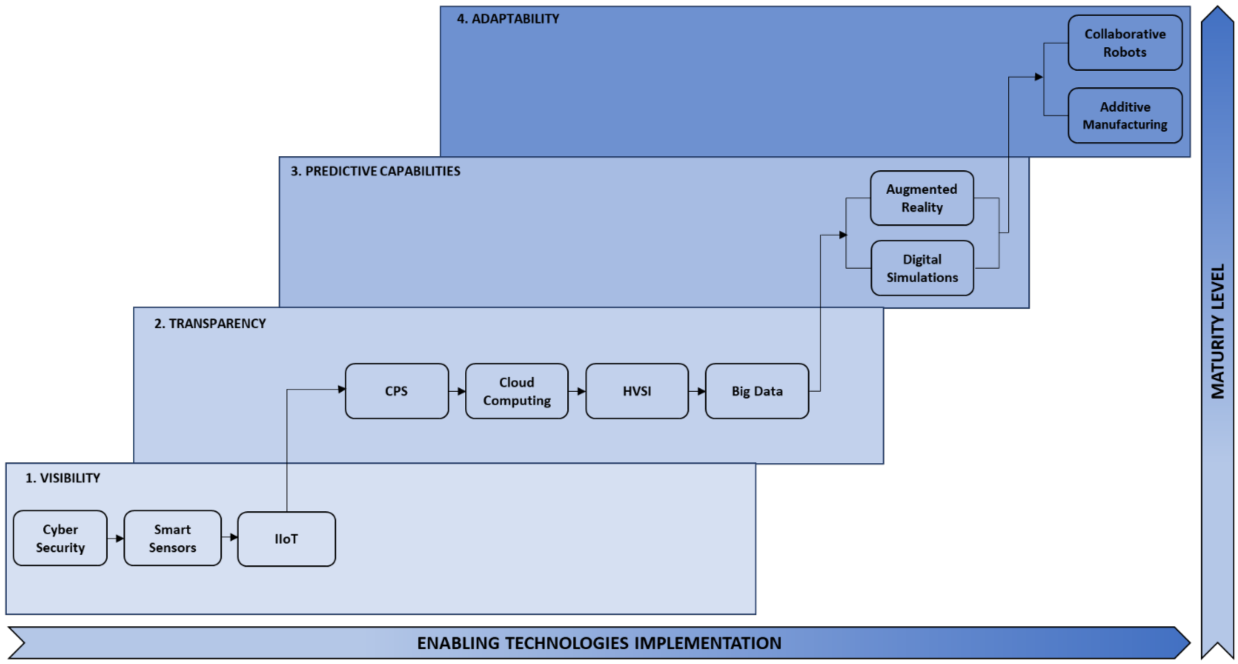

Figure 4. Simplified technical correlations between the enabling technologies

5 Conclusion

This work aimed to investigate the relationship between the technologies associated with Industry 4.0 and the strategic competencies that an industry in compliance with it must display. A set of eleven technologies was identified, among the ones appointed by authors both in the academic and corporate spheres and were considered as the enablers of this new model. It was also observed that most of these technologies have technical interdependencies, which naturally imposes a logical order of implementation. As for the strategic competencies, the ACATECH model of industry maturity assessment was used as a basis for relating the functionalities provided by each technology to the competencies expected in each of the maturity levels. The study accomplishes its objective of establishing a systemic roadmap for the implementation of the Industry 4.0 enabling technologies, however, there are considerations that should be made about its context. The model considers that the industry at issue should be at the highest level of maturity regarding the Third Industrial Revolution, no technical requirements were established prior to the first level of maturity for the Fourth Industrial Revolution. Also, the model's adherence should be tested on a concrete case to confirm whether the theoretical inferences made are applicable.

References

Backes-gellner, uschi et al. *Research, innovation and technological performance in germany* (report 2013). Ssrn electronic journal, p. 160, 2013.

Bechtold, jochen et al. *Industry 4.0 - the capgemini consulting view*. Capgemnini consulting, p. 31, 2014.

Bortolini, marco; galizia, francesco gabriele; mora, cristina. Reconfigurable manufacturing systems: literature review and research trend. *Journal of manufacturing systems*, v. 49, n. October, p. 93–106, 2018. Available in: <https://doi.org/10.1016/j.jmsy.2018.09.005>.

Cheah, sin-moh; leong, helene. *Relevance of cdio to industry 4.0-proposal for 2 new standards*. 2019, [s.l: s.n.], 2019. Available in: www.aethon.com.

Cucinotta, tommaso et al. A real-time service-oriented architecture for industrial automation. *Ieee transactions on industrial informatics*, v. 5, n. 3, p. 1–11, 2009.

Daudt, gabriel marino; willcox, luiz daniel. *Reflexões críticas a partir das experiências dos estados unidos e da alemanha em manufatura avançada.* Bndes setorial, n. 44, p. 5–45, 2016. Available in: <https://web.bndes.gov.br/bib/jspui/handle/1408/9936>.

Facó, j. F. B., & de andrade, a. A. (2017). *Vale a pena investir?: finanças e inovação em uma análise interdisciplinar*. Simplissimo livros ltda.

Freitas, adriano gomes de., *mensuração de inovações em mpes: um estudo exploratório com ênfase nos processos em manufaturas na região sul de são paulo*. Santo andré: matsunaga, 2019, v.1. P.184. Doi: 10.13140/rg.2.2.33941.83681/1.

Freitas, adriano gomes de; pinto, alexandre caramelo; facó, júlio francisco blumetti; andrade, alexandre acácio de; faria, vinicius tasca; heidrich, felipe; medição do grau de inovação com ênfase na dimensão processo para pequenas indústrias da região sul de são paulo, p. 848-856 . In: 11º congresso brasileiro de inovação e gestão de desenvolvimento do produto. São paulo: blucher, 2017. Issn 2318-6968, doi 10.5151/cbgdp2017-089.

Freitas, adriano gomes. (2018). Mensuração de inovações em mpes: um estudo exploratório com ênfase nos processos em manufaturas na região sul de são paulo. Dissertação de mestrado em engenharia de gestão da inovação. Universidade federal do abc. Doi: 10.13140/rg.2.2.33941.83681. Https://bdtd.ibict.br/vufind/record/ufbc_a0ee2d94733f5f7015654f904d088e06

Freitas, a. G., muritiba, p., muritiba, s., lima, y. O., riascos, l. A. M., (2018). Measurement of innovations in sme: exploratory study with emphasis on manufacturing processes in the south of são paulo. In: *enegep 2018 - encontro nacional de engenharia de produção*. Doi: 10.14488/enegep2018_ti_st_265_520_36054.

Freitas, a. G., de andrade, a. A., faco, j. F. B., & gasi, f. (2022). Perspectives of innovation in small companies in brazil. *International journal of advanced engineering research and science*, 9, 2. Doi:10.22161/ijaers.92.6.

Freitas, a., riascos, l., andrade, a., faco, j., & gallotta, b. (2021). Innovation in small & medium enterprises in são paulo. *International conference on industrial engineering and operations management*. Issn: 21698767, isbn: 978-179236125-8.

Freitas, adriano gomes de; rodrigues-silva, jefferson. Steam na educação física do ensino fundamental. *Revista brasileira de educação básica*, belo horizonte – online, vol. 6, número 25, junho – dezembro, 2022, issn 2526-1126. Disponível em: < http://pensaraeducacao.com.br/rbeducacaobasica/wp-content/uploads/sites/5/2022/12/steam-na-educacao-fisica-do-ensino-fundamental.pdf>.

Lidong, wang; guanghui, wang. Big data in cyber-physical systems, *digital manufacturing and industry 4.0. International journal of engineering and manufacturing*, v. 6, n. 4, p. 1–8, 2016.

Kagermann, henning. Wolfgang, wahlster. Johannes, helbig. Germany - *industrie 4.0. Final report of the industrie 4.0* wg, n. April, p. 82, 2013.

Keller, michael et al. How virtualization, decentralization and network building change the manufacturing landscape: an industry 4.0 perspective. *International journal of mechanical, aerospace, industrial, mechatronic and manufacturing engineering*, v. 8, n. 1, p. 37–44, 2014.

Khalid, a et al. Implementing safety and security concepts for human-robot collaboration in the context of industry 4 . 0 towards implementing safety and security concepts for human-robot- collaboration in the context of industry 4 . 0. International matador *conference on advanced manufacturing*, n. July, p. 1–7, 2017.

Kiel, daniel; müller, julian m; arnold, christian. Sustainable industrial value creation: benefits and challenges of industry 4.0 [rewarded with ispim best student paper award] integration of industry 4.0 within the entire value chain view project sustainable smart industry-industry 4.0 as a future model. June, p. 0–21, 2017.

Saturno, m. Et al. Proposal of an automation solutions architecture for industry 4.0. *Destech transactions on engineering and technology research*, n. Icpr, 2018.

Schuh, günther et al. Industrie 4.0 maturity index. Managing the digital transformation of companies. Web, v. 1, n. 5765, p. 46, 2020. Available in: <www.acatech.de/publikationen.>.

Silva-filho, j. C., freitas, a. G., freitas, r. S. G. Corporate compliance approach to discrimination-free workplace. In: proceedings of the *1st australian ieom conference in sydney. International conference on industrial engineering and operations management*. 2022, issn: 2169-8767 (u.s. library of congress). Http://ieomsociety.org/australia/proceedings/.

Rüssmann, michael; et al. Industry 4.0: future of productivity and growth in manufacturing.available in:<https://www.bcg.com/ptbr/publications/2015/engineered_products_project_business_industry_4_future_productivity_growth_manufacturing_industries.aspx>.

Nakayama, r u y somei. *Oportunidades de atuação na cadeia de fornecimento de sistemas de automação para indústria 4.0 no brasil*. 2017. 240 f. São paulo federal university , 2017.

Piccinini, everlin et al. Transforming industrial business: the impact of digital transformation on automotive organizations. 2015 *international conference on information systems: exploring the information frontier,* icis 2015, n. September, 2015.

Mckinsey. *Industry 4.0 how to navigate digitization of the manufacturing sector.* Mckinsey digital, n. 1, p. 62, 2015.

Biographies

Catarina de Andrade Lucizano received her M.Sc. in Engineering and Management of Innovation from the Federal University of ABC in 2021 and a B.Sc. in Automation and Robotics engineering in 2020, from the same university. She is currently an IT manager and is pursuing her Ph.D. in Electrical Engineering.

Adriano Gomes de Freitas is a visiting Ph.D. scholar at Laboratory for Simulation and Modelling of Particulate Systems (SIMPAS) at Monash University, Australia. He also was an Erasmus+ exchange Ph.D. at the Department of Mechanical and Energy Systems Engineering at University of Bradford, United Kingdom. He holds a Ph.D. in Energy from Federal University of ABC, Brazil. M.Sc. in Engineering and Management of Innovation and a B.Sc. in Management Engineering and a B.Sc and Technology from the same university. ORCID: https://orcid.org/0000-0002-2770-9154

Alexandre Acácio de Andrade graduated in B.Sc. Electrical Engineering with emphasis in Energy and Automation (1997), M.Sc. in Electrical Engineering (Automation) (2001) and Ph.D. (2007) in Electrical Engineering (Automation) all from the Polytechnic School of the University of São Paulo. Professor at the Federal University of ABC.

Júlio Francisco Blumetti Facó is a PhD with visual disability and professor. Graduated in Engineering (1999), postgraduate in Marketing (2002), Master's in business administration (2006) and Ph.D. in Business Administration. Professor at the Federal University of ABC.