UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL

ESCOLA DE ENGENHARIA

PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO

GUILHERME BRITTES BENITEZ

INNOVATION ECOSYSTEMS FOR INDUSTRY 4.0: A COLLABORATIVE PERSPECTIVE FOR THE PROVISION OF DIGITAL TECHNOLOGIES AND PLATFORMS

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Thesis submitted to the Post-Graduation Program in Production Engineering at the Federal University of Rio Grande do Sul as a partial requirement to obtain the title of Doctor of Engineering, in the area of concentration in Production Systems.

Advisor: Professor Alejandro Germán Frank, Ph.D.

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This Ph.D. thesis was considered adequate to obtain the title of Ph.D. in Engineering and approved in its final form by the Advisor and by the Examining Board designated by the Graduate Program in Production Engineering at the Federal University of Rio Grande do Sul .

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“There must be a beginning of any great matter, but the continuing unto the end until it be thoroughly finished yields the true glory”

-Sir Francis Drake (1540-1596)

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ABSTRACT

Industry 4.0 considers complex interrelated IoT-based technologies for the provision of digital solutions. This complexity demands a vast set of capabilities that are hard to be found in a single technology provider, especially in small and medium-sized enterprises (SMEs). Innovation ecosystems allow SMEs to integrate resources and cocreate Industry 4.0 solutions. This thesis investigates the role of collaboration for the development of technologies and solutions in the Industry 4.0 context. To this end, this thesis was organized into three papers, which objectives are: (i) to verify if collaboration through inbound Open Innovation activities with different actors in the supply chain positively moderates the relationship between Industry 4.0 technologies and their expected benefits; (ii) to identify how the characteristics of an innovation ecosystem focused on solutions for Industry 4.0 change at each evolutionary lifecycle stage using elements from social exchange theory; and (iii) to identify which technologies can be configured as platforms through boundary-spanning activities and how they operate collaboratively to develop solutions for Industry 4.0. As a result, this thesis proposes a model that explains the role of collaboration at different levels (supply chains, ecosystems, and platforms) for the development of solutions in the Industry 4.0 context. This research approach combines both qualitative (i.e., focus group, interviews, and case studies) and quantitative (i.e., survey research with multivariate data analysis) aspects. The main results obtained are: (i) we show how collaboration with different actors in the supply chain through Open Innovation strategy has both positive and negative impacts on three strategies associated with product development (cost reduction, focalization, and innovation); (ii) we define the main characteristics of innovation ecosystems focused on the provision of Industry 4.0 solutions, considering an evolutionary lifecycles perspective and a Social Exchange view (iii) we define which are the different technology platforms of the Industry 4.0 context at different operation levels using Boundary-Spanning view. As remarking conclusions, from an academic perspective, these results help to understand how collaboration for the development of new solutions in Industry 4.0 can be analyzed under different perspectives (Open Innovation, Social Exchange Theory, and Boundary-Spanning) and in different contexts of integration (supply chains, ecosystems, and platforms). From a practical perspective, the results help to enlighten a trending business topic by showing how the collaboration among technology providers for Industry 4.0 should be fostered and developed.

Keywords: Innovation ecosystems, Industry 4.0, collaboration, platforms, supply chain.

FIGURE LIST

TABLE LIST

SUMMARY

1 INTRODUCTION

Industry 4.0 – also called the ‘Fourth Industrial Revolution’ – represents a new industrial scenario where both production systems and business models are transformed by the advent of digital technologies (SCHUMACHER et al., 2016; WANG et al., 2016). Nowadays, due to the connectivity offered by the Industrial Internet of Things (IIoT), companies face a digital era in which equipment, devices, and products are interconnected to improve processes and develop new technologies (WEI et al., 2017; YIN et al., 2017). According to Rüßmann et al. (2015), Industry 4.0 comprises nine elements: internet of things, cybersecurity, cloud computing, horizontal and vertical integration systems, additive manufacturing, augmented and virtual reality, big data and business analytics, autonomous robots, and simulation. From an operational perspective, these elements reduce setup time, material handling, and processing time, among other aspects that help improve shop floor productivity (BRETTEL et al., 2014; JESCHKE et al., 2017). On the other hand, from the market perspective, these elements allow companies to offer new solutions to customers, such as services based on cloud computing and data analytics (YMASZEWSKA and GUNASEKARAN, 2017; ARDOLINO et al., 2017).

This new industrial age brings essential changes in competition rules, industrial structure, and customer demands (WEI et al., 2017; BARTODZIEJ, 2017). As a result, there is a need for a twofold digital innovation focus on both internal and external processes, products, and services. Managing these two sides simultaneously can be extremely complex for companies, especially for small and medium-sized enterprises (SMEs) (MOEUF et al., 2018). From the technology providers' perspective in the Industry 4.0 context, a single firm hardly has sufficient capabilities and knowledge to offer a complete set of solutions that meet customer needs (KAGERMANN et al., 2013; KIEL et al., 2016; SANDSTRÖM, 2016). From the technology adopters' perspective, companies demanding solutions most of the time do not have a sufficient understanding of their digital needs (KAGERMANN et al., 2013; KIEL et al., 2016). Therefore, there is a crescent need to collaborate with external actors to understand and meet these demands. This collaboration can arise from different scenarios, affecting the focal firm's processes and, consequently, its businesses. These scenarios can be configured in supply chains, innovation ecosystems, and even technological platforms (REYNOLDS and UYGUN, 2018; SANDSTRÖM, 2016).

In this regard, some developed countries have created strategic programs to shape ecosystems and business scenarios capable of performing digital transformations from Industry 4.0. Among these, it is worth mentioning the “Plattform Industrie 4.0” from Germany, the “Advanced Manufacturing Partnership” from the U.S., and the “Made in China 2025” from China (LIAO et al., 2017). These programs consider industrial development policies that focus on Digital Champions – companies that have taken digitization to the highest degree (GEISSBAUER et al., 2018) – working as central actors in ecosystems and scenarios that can contribute to the industry's digital transformation. For instance, in the Brazilian context, some national initiatives from different actors focusing on technology development already exist. For example, governmental agencies such as the Brazilian Industrial Development Agency (ABDI) concentrate their efforts on factories' “smartization”. Simultaneously, the Brazilian Industry 4.0 Chamber is centered on technology leverage and development through the use of technology demonstrators. These initiatives are mainly focused on Industry 4.0 technology development around the country.

In contrast, other private initiatives, such as the Local Alliance for Advanced Manufacturing 4.0 (ALMA 4.0), are focused on Industry 4.0 solutions development through firms' collaboration in ecosystems. Also, some factories, such as Renault from Paraná State, have been considered Industry 4.0 lighthouses, stimulating entrepreneurs over the country to develop their own 4.0 cases. In the case of universities, the University of São Paulo (USP) and University of Rio de Janeiro have Industry 4.0 demonstrators (e.g., InovaLab-Factory of the Future and the Laboratory of Artificial Intelligence - LabIA) simulating digital technologies applications for educational purposes. In general lines, there are several efforts both from government, industry, and academy to leverage Industry 4.0 over the country. However, these efforts have been empirical and pragmatic, and academic research is still necessary to clarify the effectiveness of the measures adopted by such programs and initiatives.

From an academic perspective, the international literature on Industry 4.0 still lacks studies that analyze these programs and initiatives' resulting impacts. Also, most studies are focused on the firm level and Industry 4.0 technology adopters' side. This opens an avenue for studies that look at the technology providers' side. From this view, it can be possible to discover how to leverage technology development at the national level. To do this, some approaches, as innovation ecosystems’ collaboration, can be promoted. There is little academic research that deals with how domestic industries can strategically integrate Industry 4.0 concepts and consider regional innovation actors' roles during the implementation stages. More recently, our research group developed a complementary study to this thesis related to the Industry 4.0 innovation ecosystem (KAHLE et al., 2020). The study explains how to develop smart products in innovation ecosystems in the Industry 4.0 context. However, when we search for research in other countries, the only high-impact documented studies that address aspects of innovation ecosystems focused on Industry 4.0 are those developed by Reynolds and Uygun (2018) in the United States and Rong et al. (2015) in China. Reynolds and Uygun (2018) work presents the dynamics of regional innovation actors for advanced manufacturing in the State of Massachusetts, in the U.S., and describes facilitating and harmful aspects for the ecosystem.

On the other hand, Rong and colleagues (2015) propose a framework to analyze ecosystems' main characteristics based on the Internet of Things. However, the actors structured an IoT-based ecosystem mainly centered on customer-manufacturing enterprise relationships, not exploring other actors' potential. Moreover, another limiting factor related to ecosystems is their ambiguous meaning in the literature (OH et al., 2016; SCARINGELLA et al., 2018). The term ‘ecosystem’ in companies’ context was first introduced by Moore (1993) in business literature as a ‘business ecosystem,’ explaining how enterprises can create an environment similar to an ecology ecosystem where they will have a competitive advantage. Moreover, while the theme evolved in literature, new nomenclatures such as innovation, entrepreneurial, and knowledge ecosystems emerged, resulting in a misunderstanding about the terms between scholars (SCARINGELLA et al., 2018). Oh et al. (2016) criticize that ‘innovation ecosystems’ became a popular term being portrayed in a wrongly way by academics. In general lines, according to Ritala and Almpanopoulou (2017), who answered Oh et al. (2016) critique, innovation ecosystems are environments that require interdependency among different actors to develop and create new knowledge and inventions (e.g., products and services) to market. Following this line, Scaringella et al. (2018), who classified different systems and ecosystems in their work, portray the innovation ecosystem as business ecosystems focused on innovation. In other words, the main difference in concepts is that while business ecosystems are focused on value capture for competitive advantage, innovation ecosystems have as main goal value creation (RITALA et al., 2013). Thus, this thesis focuses on innovation ecosystems term due to the Industry 4.0 concept's innovativeness potential, demanding new and disruptive technologies for innovation generation.

However, while innovation ecosystems are a way to collaborate and spread new technologies and solutions, companies may struggle to develop their business in such context. Firstly, it can be hard to gather partners for co-creation practices. Secondly, it can be challenging to convince third parties to invest efforts to reach new and uncertain markets. Lastly, the uncertainty of return on investment (ROI) and cultural and organizational aspects can hamper technology implementation and development in industries (KAHLE et al., 2020). Concerning these aspects, this work also considers firms' traditional environments such as supply chains and platforms as alternatives to create new technologies and solutions in the Industry 4.0 context. Regarding technology development in supply chains and platforms, Industry 4.0 literature also is scarce, lacking studies that show the development of technologies and solutions in these environments. Most studies related to supply chain and Industry 4.0 are about literature reviews seeking to understand the impacts of Industry 4.0 technologies (FREDERICO et al. 2019; BAG et al., 2018). While on platforms, studies in this field investigate the potential of data sharing on technological platforms based on IoT and cloud technologies, without showing details about collaborative development for technologies and solutions in Industry 4.0 (CUSUMANO et al., 2019; FAN et al ., 2019; FAHMIDEH et al., 2020). Overall, the literature lacks studies that analyze the complementarities of skills and capabilities among different actors through collaboration in the environments mentioned above to develop technologies and solutions in the Industry 4.0 context. Therefore, from a theoretical point of view, three research questions arise for the present thesis: *(i) How can collaboration with external actors in the supply chain be established to develop Industry 4.0 technologies? (ii) How can different ecosystem actors create synergies and collaborate to develop solutions for Industry 4.0? (iii) How can technological platforms be established and configured to develop solutions for Industry 4.0?*

The answers to the proposed research questions also imply the consideration of factors inherent to each country's reality. In particular, studying the minimum necessary conditions for the viability of Industry 4.0 within supply chains, innovation ecosystems, and platforms is fundamental for Brazil because of the practical implications. Recent studies point to significant differences between Industry 4.0 technologies implementation globally when compared to the Brazilian context, indicating the need for an urgent action plan to reduce these differences (CNI, 2016; PWC, 2016). Emerging economies like Brazil have a low degree of maturity in the industrial stages prior (e.g., traditional automation) to Industry 4.0 (GUAN et al., 2006; KRAWCZYŃSKI et al., 2016). Moreover, these countries are mainly composed of SMEs, which prioritize returns in a short time due to their financial limitations. SMEs in emerging economies like Brazil, usually do not have many resources, competences, and capabilities, being expert in one specific field (e.g., virtual commissioning) (KAHLE et al., 2020). Therefore, this thesis proposes to deepen these issues by expanding the current state of knowledge on collaborative practices for technology development in the Industry 4.0 context. Lastly, this thesis also offers practical solutions to companies by examining several industrial cases for managers and practitioners.

1.1 Theme and objectives

This thesis considers the intersection between the research fields of Technology Management, Innovation Management, and Operations Management. The theme of this research focuses on collaboration strategies for supply chains, ecosystems, and platforms to support the development of solutions in the Industry 4.0 context.

This thesis's general objective is to develop a model that explains the role of collaboration at different levels (supply chains, ecosystems, and platforms) for the development of technological solutions for Industry 4.0. This thesis also has a practical goal to serve as a reference for companies in developing countries like Brazil, which can evolve technologically and increase their competitiveness in the global scenario through a collaborative perspective. For this, it is necessary to achieve the following specific objectives:

a) To identify the potential of collaboration and the role of external actors of a supply chain for the development of technologies in the Industry 4.0 context;

b) To identify how ecosystems are established and evolve through collaborative practices for the development of technological solutions in the Industry 4.0 context;
c) To identify how platforms operate and collaborate to develop solutions and technologies in the Industry 4.0 context;
d) To integrate the findings from the aforementioned objectives in a model that explains the role of collaboration in the Industry 4.0 context.

1.2 Justification of the research problem

The theme of this thesis involves three environments (i) Supply chain networks, (ii) Ecosystem, and (iii) Industry 4.0 platforms; and four main research areas (i) Open Innovation, (ii) Social Exchange Theory, (iii) Industry 4.0 technologies, and (iv) Boundary-Spanning. Regarding the first area, investigating how Industry 4.0 affects supply chain relationships is essential to understand the role of technologies in this context. Studies that mention the impacts of Industry 4.0 technologies at the supply chain address collaboration as one of the essential elements for efficient Supply Chain Management (FREDERICO et al., 2019). In this sense, this thesis studies how collaboration within a supply chain network helps companies develop Industry 4.0 technologies. This leads to a collaborative approach called Open Innovation between supply chain partners. Open innovation is a strategy proposed by Chesbrough (2003) in which companies use flows of input and output of knowledge from different actors to promote internal and external innovation. This strategy emerges as an alternative within Industry 4.0, especially for small and medium-sized enterprises (SMEs) that do not have all the skills and capabilities to develop solutions in this context (MOUEF et al., 2018; MÜLLER et al., 2018). However, collaborating with supply chain partners can be a barrier for SMEs, which may not be able to integrate systems and resources to establish reciprocal relationships within their supply chains (PICCAROZZI et al., 2018).

As an alternative, SMEs can organize themselves in an ecosystem arrangement based on social interactions. James Moore proposed the concept of the ecosystem for business environments in 1993. The author proposed ecosystem theory using ecological ecosystems as an analogy to consider the survival and interdependence of the species in the environment (i.e., companies and other complementary actors) (MOORE, 1993, 1996). Thus, the author proposed the theory of business ecosystems where the evolution of these ecosystems can be described in four main evolutionary stages (birth, expansion, leadership, and self-renewal or death) from observing the behavior of species in biological ecosystems. Currently, this subject has reached a considerable degree of maturity in the business area, with its concept expanded to the area of innovation and digital platforms (ADNER 2006; GAWER and CUSUMANO, 2014; AUTIO and THOMAS, 2014). However, with the advent of Industry 4.0, dimensions such as cooperation, context, configuration, and platform leadership previously well-known in ecosystem theory must undergo significant changes (REYNOLDS and UYGUN, 2018; RONG et al., 2015). From this, the theory of social exchange (SET), explained by Blau (1964) and Emerson (1976) as a system of exchange of values between actors based on rewards, can understand these changes within the evolutionary stages of an ecosystem. Changes in the ecosystem can be analyzed from social interaction elements based on trust, commitment, reciprocity, and power to maintain relationships.

Thus, with the change in dimensions of innovation ecosystems due to Industry 4.0, the way actors collaborate may also change, especially for SMEs, as pointed out by Müller et al. (2018). Dallasega et al. (2018) and Ghobakhloo (2018) state that Industry 4.0 technologies (e.g., big data, cloud computing, 3D printer, collaborative robots, among others) require knowledge and capabilities that is hard for companies to have and manage independently, making cooperation with different actors a necessity. Studies such as Dalenogare et al. (2018) and Frank et al. (2019a) analyzed Industry 4.0 technologies' impacts on the expected results related to the development of products and operational processes. However, there is still a lack of studies in the literature about the potential of collaboration from different actors for technology development in Industry 4.0. For example, in SMEs context, they should adapt to Industry 4.0 to maintain competitiveness at national and international levels.

Finally, it is worth highlighting the fourth point, referring to platforms and boundary-spanning. According to Frank et al. (2019b), one of the trends in Industry 4.0 is related to platform-oriented business models. However, the literature still lacks studies to assist in developing business models for industrial platforms with a focus on the development and supply of digital solutions for Industry 4.0. The concept of platforms is frequently banalized in the literature, lacking a further explanation on how they are established and operated (GAWER and CUSUMANO, 2014). According to Sturgeon (2019), technologies can be configured into different platforms to collaborate to develop solutions in Industry 4.0. Some of our first findings in Benitez et al. (2020) complement this by saying that these technologies can connect with their surroundings by receiving other technologies as 'add-ons' to develop new products. Therefore, the theory of boundary-spanning can help explain how to measure the degree of connection that certain technology has with its surroundings. And as a consequence, how information is assimilated and transformed for the product development process within these platforms (ALDRICH and HERKER, 1977).

As a concluding remark, it is evident the need to analyze alternatives for collaboration within Industry 4.0, such as (i) the potential of collaboration with external partners in supply chains; (ii) how companies can cooperate within innovation ecosystems to generate digital solutions; (iii) how technological platforms are established and operated to develop solutions and technologies; and (iv) understanding of the role of collaboration in these environments for the development of solutions in the context of Industry 4.0. By aligning these views, it will be possible to understand how collaboration aid the development of solutions and technologies in the Industry 4.0 context.

1.3 Research structure

Once the objectives of this work are defined, and the clarifications about the importance of this research are presented, it is necessary to establish the study design by which these objectives will be achieved, showing the proposed research method and design.

1.3.1 Research method

The inductive method clarifies where, after considering a sufficient number of cases, the researcher concludes a general truth (MARCONI and LAKATOS, 2010). The deductive method is the proposal and testing of hypotheses. The research carried out by this work follows a combined approach, using both qualitative and quantitative procedures (DALFOVO et al., 2008). Figure 1.1 presents the research methodology.

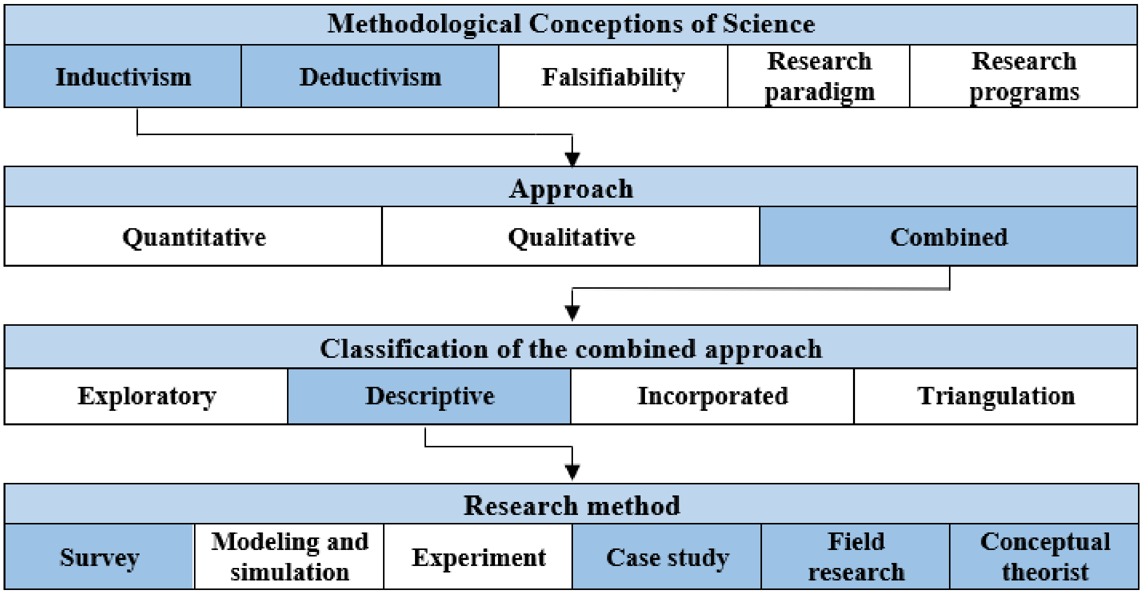

Figure 1.1 – Research methodology
Source: MARCONI and LAKATOS, 2010.

The classification of the approach is descriptive. According to Gil (2008), a descriptive research aims to describe the characteristics of a given population or phenomenon, or else, to establish relationships between variables. The approach is also classified as triangulation because it combines different sources and data collection methods (PATTON, 2002; DAVIDSON, 2005). The method is classified as a survey because the research was collected quantitatively from groups of individuals' characteristics and opinions (FOWLER JR, 2013). It is also classified as a case study for investigating contemporary phenomena within a real-life context when the boundary between the phenomenon and the context is not evident (YIN, 2001). Furthermore, the research is also classified as field research because it studies a group of people to highlight the interaction between them through observations (GIL, 2008). Finally, the study is from a conceptual, theoretical nature, as it mainly presents argumentative analyzes about research observations.

1.3.2 Research design

The development of the research and execution of its activities to achieve the proposed objectives occurs through three stages, presented in the article format. The articles represent the means to achieve the general objective of this thesis. The thesis structure is based on three articles; its research questions, goals, and methods are shown in Table 1.1.

Table 1.1 – Structure of the research stages

	Research question	Research goals	Theoretical lenses and environments	Method
Paper 1	What are the contributions of the different supply chain actors for the development of integrated Industry 4.0 solutions?	To verify if collaboration with different actors in the supply chain positively moderates the relationship between Industry 4.0 technologies and their expected benefits.	Supply chain Open Innovation (OI)	Exploratory quantitative research: Use of survey data. Use of EFA and multiple linear regression.
Paper 2	How can Industry 4.0 ecosystems consolidate and evolve, and how can value be cocreated through the joint development of Industry 4.0 solutions by the companies in the ecosystem?	To identify how an ecosystem's characteristics focused on solutions for Industry 4.0 change at each evolutionary lifecycle stage using elements from social exchange theory.	Innovation ecosystems Social Exchange Theory (SET)	Qualitative longitudinal research: Observations of survey results and case and field studies.
Paper 3	What are the Industry 4.0 technologies that can operate as platforms at different business levels? How these platforms disseminate and transform information for firms at the company, supply chain, and ecosystem levels?	To identify which technologies can be configured as platforms through boundary-spanning activities and how they operate collaboratively to develop solutions for Industry 4.0.	Platforms Boundary-Spanning (BS)	Descriptive qualitative research: Observations of results from multiple case studies.

Paper 1 – "*Industry 4.0 technologies provision: the moderating role of supply chain partners to support technology providers***"**, proposes that industries are undergoing a transformation process through the so-called Industry 4.0 era. As new technologies emerge, studies explore how these technologies can improve industrial performance (DALENOGARE et al., 2018; FRANK et al., 2019a). However, none of these studies sought to understand how certain strategic positions can help leverage industrial performance by implementing Industry 4.0 technologies. Therefore, in this article, we study how Open Innovation – a strategy is known to drive innovation - can improve the relationship between the adoption of Industry 4.0 technologies and strategies for product development through inbound activities (cost reduction, customer loyalty, and technology differentiation). Thus, we investigate the moderating effect of cooperation with four actors in the supply chain (suppliers, customers, R&D centers, and complementors) in the relationship between the technologies of Industry 4.0 and strategies for product development. The research is based on a survey carried out on

77 small and medium-sized enterprises (SMEs) in an industrial cluster from an electro-electronic sector composed of automation companies in southern Brazil. The results show that the Open Innovation strategy has both positive and negative effects on product development strategies for the development of Industry 4.0 technologies. In other words, differently from what most of the literature argues (CHESBROUGH, 2003; BRUNSWICKER and VAN DE VRANDE, 2014), in the context of Industry 4.0, cooperation is a strategy that is not always beneficial and, therefore, must be carefully planned. As a product of our analysis, we provide guidance on which actors can be the best cooperation options for the implementation of Industry 4.0 technologies in the supply chain.

Paper 2 – "*Industry 4.0 innovation ecosystems: An evolutionary perspective on value cocreation*", describes that Industry 4.0 is considered a new industrial stage in which several digital technologies converge and can be integrated to provide new business models (FRANK et al., 2019b; LERCH and GOTSCH, 2015). These solutions tend to be more complex, requiring technology providers with multidisciplinary capabilities from different knowledge fields. Small and medium-sized enterprises (SMEs) generally do not have all of these necessary capabilities (MOEUF et al., 2018; MÜLLER et al., 2018). One way to overcome this difficulty would be to participate in innovation ecosystems where complementarities are sought. However, as the concept of Industry 4.0 is still emerging, there is a lack of understanding of the conditions required to create an appropriate ecosystem to provide Industry 4.0 solutions (REYNOLDS and UYGUN, 2018). The purpose of this article is to understand these conditions in the context of SMEs, considering the different evolutionary stages from an innovation ecosystem using the theoretical lens of social exchange theory. The social exchange theory considers elements such as commitment, reciprocity, trust, and power in order to acquire rewards through the exchange of values (ALDRICH and HERKER, 1977). Thus, the literature on ecosystems was first analyzed, based on Moore's studies (1993, 1996) on the lifecycle stages of business ecosystems and the 6C framework proposed by Rong et al. (2015) for IoT ecosystems to build innovation ecosystems for Industry 4.0. Then, we conducted a qualitative method approach to collect empirical evidence for understanding the elements of this structure: we conducted a survey with 87 SMEs that started the creation of an ecosystem focused on Industry 4.0 solutions. We also followed a testbed project of one of the most prominent Industry 4.0 ecosystems in Brazil since its generation. In addition, we conducted semi-structured interviews with other complementary actors, such as universities, manufacturing companies (buyers), and government agencies to understand their role in this new ecosystem. As a result, our structure shows the evolutionary cycle of an innovation ecosystem focused on providing solutions for Industry 4.0 based on exchanges of social interaction between the actors.

Paper 3 – “*Industry 4.0 platforms: a typology using a boundary-spanning perspective*”, draws attention to the study and evaluation of platforms in the context of Industry 4.0 (STURGEON, 2019). Industry 4.0 platforms have technical standards such as connectivity, integration, and interoperability, enabling the connection of different technologies as “add-ons” (BENITEZ et al., 2020). However, these platforms behave differently depending on the technology that controls their operation, impacting the business differently. In this sense, the literature lacks studies that allow identifying which technologies act as platforms receiving other technologies (add-ons) to work organically and provide innovative solutions for Industry 4.0. Thus, this article's objective is to investigate which technologies in Industry 4.0 operate as platforms and what levels of business (firm, supply chain, and ecosystems) they can reach. For this, four levels of platforms based on the literature have been proposed (Operational, Digital, Higher-level, and Business). The theory of boundary-spanning was used to analyze these platform levels, which allows an understanding of how these platform levels obtain and disseminate information (ALDRICH and HERKER, 1977) to assist in the company's innovation process, supply chain, and ecosystem levels. The study adopts multiple case studies, analyzing seven companies related to one platform level. As a result, we show dissemination and transformation of knowledge growth in these different platform configurations, as well as the main benefits of each technology as a platform.

1.4 Limitations

For the development of the research, the following study limitations are proposed. First, the use and adaptation of a specific configuration for IoT (Internet of Things) ecosystems based on the previous work of Rong et. (2015). Rong et al. (2015) proposed a framework for large companies' ecosystems, focusing more on the relationship with customers. The framework needed to be adapted for SMEs and relationships with other actors and customers to provide Industry 4.0 solutions. Large companies were not considered in the study, which would present different results due to their higher economic power and more qualified labor than SMEs.

Secondly, only the electronics sector was chosen in Papers 1 and 2 as the unit of analysis, with other industrial sectors being disregarded. The reason is mainly that this sector is considered one of the largest developers of solutions for Industry 4.0 due to the vast experience of companies in industrial automation in the country (FRANK et al., 2019a; KAHLE et al., 2020). However, several sectors (e.g., automotive and chemicals) with high economic and technological power could contribute to the development of ecosystems for Industry 4.0 in the country.

Third, the subjectivism from a qualitative analysis in Papers 2 and 3 can be a boundary condition for results generalization. Further empirical investigation with statistical methods in a broader scope (several industrial sectors) is required to give a general conclusion about our insights. Therefore, the study is limited to understanding the forms of collaboration and contribution to the structuring of a business model for supply chain, ecosystems, and platforms oriented to Industry 4.0. A broader scope should also include the analysis and influence of government initiatives such as technology demonstrators focused on collaborative strategies for developing solutions in Industry 4.0.

1.5 Thesis structure

This thesis is organized into five main chapters. In this first chapter, the work's context and objectives were presented, justifying the importance of this research from an academic and practical point of view. This chapter also presented the study method, structure, and limitations. The next sections, from two to four, give the proposed articles, according to the architecture shown in Table 1.1. The fifth chapter presents the final considerations of the present doctoral thesis, discusses the results, and presents a conceptual collaboration model consolidated from the findings and future research opportunities.

References

ADNER, R. Match your innovation strategy to your innovation ecosystem. **Harvard business review**, v. 84, n. 4, p. 98, 2006.

ALDRICH, H.; HERKER, D. Boundary spanning roles and organization structure. **Academy of management review**, v. 2, n. 2, p. 217-230, 1977.

ARDOLINO, M.; RAPACCINI, M.; SACCANI, N.; GAIARDELLI, P.; CRESPI, G.; RUGGERI, C. The role of digital technologies for the service transformation of industrial companies. **International Journal of Production Research**, p. 1-17, 2017.

AUTIO, E.; THOMAS, L. Innovation Ecosystems: Implications for Innovation Management, em: Dodgson, M., Gann, D.M., Phillips, N. (Eds.), The Oxford Handbook of Innovation Management. **Oxford University Press**, p. 204–228, 2014.

BAG, S.; TELUKDARIE, A.; PRETORIUS, J.H.C.; GUPTA, S. Industry 4.0 and supply chain sustainability: framework and future research directions. **Benchmarking: An International Journal**, 2018.

BARTODZIEJ C.J. The concept Industry 4.0. **Springer Gabler, Wiesbaden**, 2017.

BENITEZ, G.B.; AYALA, N.F.; FRANK, A.G. Industry 4.0 innovation ecosystems: An evolutionary perspective on value cocreation. **International Journal of Production Economics**, 2020.

BLAU, P.M. Exchange and Power in Social Life. John Wiley & Sons, NY, 1964.

BRETTEL, M.; FRIEDERICHSEN, N.; KELLER, M. How virtualization, decentralization and network building change the manufacturing landscape: An industry 4.0 perspective. **International journal of mechanical, industrial science and engineering**, v. 8, n. 1, p. 37–44, 2014.

BRUNSWICKER, S.; VAN DE VRANDE, V. Exploring open innovation in small and medium-sized enterprises, in: Chesbrough, H., Vanhaverbeke, W., West, J. (Eds.), New Frontiers in Open Innovation. **Oup Oxford**, p. 135–156, 2014.

CASTELLACCI, F. Technological paradigms, regimes and trajectories: Manufacturing and service industries in a new taxonomy of sectoral patterns of innovation. **Research Policy**, v.37, 978–994, 2008.

CHESBROUGH, H. Open innovation: The new imperative for creating and profiting from technology. **Harvard Business Press**. 2003.

CNI. **Industry 4.0: a new challenge for Brazilian industry**. Confederação Nacional da Indústria (CNI). Industrial Report, 2016. Retrieved from: http://www.portaldaindustria.com.br/publicacoes/2016/8/challenges-industry-40-brazil/

DALENOGARE, L.S.; BENITEZ, G.B.; AYALA; N.F., FRANK, A.G. The expected contribution of Industry 4.0 technologies for industrial performance. **International Journal of Production Economics**, 204, 383–394, 2018.

DALFOVO, M. S.; LANA, R. A.; SILVEIRA, A. Métodos quantitativos e qualitativos: um resgate teórico. **Revista Interdisciplinar Científica Aplicada**, v. 2, n. 3, p. 1-13, 2008.

DALLASEGA, P.; RAUCH, E.; LINDER, C. Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. **Computers in industry**, v. 99, p. 205-225, 2018.

DAVIDSON, E. J. Evaluation methodology basics. **Thousand Oaks: Sage**, 2005.

DOSI, G. Technological paradigms and technological trajectories. **Research Policy**, 11, 147–162, 1982.

EMERSON, R.M.. Social exchange theory. **Annual Review of Sociology**, v. 2, p. 335–362, 1976.

FAHMIDEH, M.; ZOWGHI, D. An exploration of IoT platform development. **Information Systems**, v. 87, p. 101409, 2020.

FOWLER JR, F. J. Survey research methods. **Sage publications**, 2013.

FRANK, A.; DALENOGARE, L.; AYALA, N. Industry 4.0 technologies: implementation patterns in manufacturing companies **International Journal of Production Economics**, p. 210, 15–26, 2019a.

FRANK, A.; MENDES, G.; AYALA, N.; GHEZZI, A. Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective. **Technological forecasting and social change**, 2019b.

FREDERICO, G.F.; GARZA-REYES, J.A.; ANOSIKE, A.; KUMAR, V. Supply Chain 4.0: concepts, maturity and research agenda. **Supply Chain Management: An International Journal**, 2019.

GAWER, A.; CUSUMANO, M. A. Industry Platforms and Ecosystem Innovation. **Journal of Product Innovation Management**, 31(3), 417–433, 2014.

GEISSBAUER, R.; LUBBEN, E.; SCHRAUF, S.; PILLSBURY, S. **Digital champions. How industry leaders build integrated operations ecosystems to deliver end-to-end customer solutions. Pricewaterhouse Coopers**, 2018.

GHOBAKHLOO, M. The future of manufacturing industry: A strategic roadmap toward Industry 4.0. **Journal of Manufacturing Technology Management**, v. 29, n. 6, p. 910-936, 2018.

GIL, A.C. Methods and techniques of social research. 6. ed. **Editora Atlas SA**, 2008.

GUAN, J.C.; MOK, C.K.; YAM, R.C.M.; CHIN, K.S.; PUN, K.F. Technology transfer and innovation performance: Evidence from Chinese firms. **Technological Forecasting and Social Change**, v.73, 666–678, 2006.

JESCHKE, S.; BRECHER, C.; SONG, H.; RAWAT, D.B. (Editores). **Industrial Internet of Things**: Cyber Manufacturing Systems. **Springer International Publishing**, p. 3–19, 2017.

KAGERMANN, H.; WAHLSTER, W.; HELBIG, J. **Industrie 4.0: Recommendations for implementing the strategic initiative**. National Academy of Science and Engineering (ACATECH), 82p, 2013.

KAHLE, J.H.; MARCON, É.; GHEZZI, A.; FRANK, A.G. Smart Products value creation in SMEs innovation ecosystems. **Technological Forecasting and Social Change**, v. 156, p. 120024, 2020.

KIEL, D.; ARNOLD, C.; COLLISI, M.; VOIGT, K.-I. The Impact of the Industrial Internet of Things on Established Business Models. **Proceedings of the 25th international association for management of technology (IAMOT) conference**, p. 673–695, 2016.

KRAWCZYŃSKI, M.; CZYŻEWSKI, P.; BOCIAN, K. Reindustrialization: A Challenge to the Economy in the First Quarter of the Twenty-First Century. **Foundations of Management,** 8, 2016.

LASI, H.; FETTKE, P.; KEMPER, H.G.; FELD, T.; HOFFMANN, M. Industry 4.0. **Business & Information Systems Engineering**, 6(4), 239-242, 2014.

LERCH, C.; GOTSCH, M. Digitalized product-service systems in manufacturing firms: A case study analysis. **Research-Technology Management**, v. 58, n. 5, p. 45-52, 2015.

LIAO, Y.; DESCHAMPS, F.; LOURES, E.D.F.R.; RAMOS, L. F. P. Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. **International Journal of Production Research**, v. 55, n. 12, p. 3609–3629, 18 jun. 2017.

MARCONI, M.D.A.; LAKATOS, E.M. Fundamentos de metodologia científica. **Atlas**, 2010.

MOEUF, A.; PELLERIN, R.; LAMOURI, S.; TAMAYO-GIRALDO, S.; BARBARAY, R. The industrial management of SMEs in the era of Industry 4.0. **International Journal of Production Research**, v. 56, n. 3, p. 1118-1136, 2018.

MOORE, J. F. Predators and prey: a new ecology of competition. **Harvard business review**, v. 71, n. 3, p. 75-86, 1993.

MOORE, J. F. The death of competition: leadership and strategy in the age of business ecosystems. **New York: HarperBusiness**, 1996.

MÜLLER, J.M.M.; BULIGA, O.; VOIGT, K.-I. Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. **Technological Forecasting and Social Change**, 132, 2–17, 2018.

OH, D.-S.; PHILLIPS, F.; PARK, S.; LEE, E. Innovation ecosystems: A critical examination. **Technovation**, v. 54, p. 1-6, 2016.

PATTON, M. Q. Qualitative research and evaluation methods. 3.ed. **Thousand Oaks: Sage**, 2002.

PICCAROZZI, M.; AQUILANI, B.; GATTI, C. Industry 4.0 in management studies: A systematic literature review. **Sustainability**, v. 10, n. 10, p. 3821, 2018.

PORTER, M.E.; HEPPELMANN, J.E. How smart, connected products are transforming competition. **Harvard**

Business Review, v. 92, n. 11, p. 64-88, 2014.

PWC. **Industry 4.0: Building the digital enterprise**. – Pricewaterhouse Cooper – PWCs, Business Report, 2016.

RITALA, P.; AGOURIDAS, V.; ASSIMAKOPOULOS, D.; GIES, O. Value creation and capture mechanisms in innovation ecosystems: a comparative case study. **International Journal of Technology Management**, v. 63, n. 3-4, p. 244-267, 2013.

RITALA, P.; ALMPANOPOULOU, A. In defense of 'eco'in innovation ecosystem. **Technovation**, v. 60, p. 39-42, 2017.

RÜßMANN, M.; Lorenz, M.; Gerbert, P.; Waldner, M.; Justus, J.; Engel, P.; Harnisch, M. **Industry 4.0: The future of productivity and growth in manufacturing industries**. Boston Consulting Group, 9, 2015.

REYNOLDS, E.B.; UYGUN, Y. Strengthening advanced manufacturing innovation ecosystems: The case of Massachusetts. **Technological Forecasting and Social Change**, v. 136, p. 178-191, 2018.

RONG, K.; HU, G.; LIN, Y.; SHI, Y.; GUO, L. Understanding business ecosystem using a 6C framework in Internet-of-Things-based sectors. **International Journal of Production Economics**, v.159, 41–55, 2015.

SANDSTRÖM, C. G. The non-disruptive emergence of an ecosystem for 3D Printing - Insights from the hearing aid industry's transition 1989-2008. **Technological Forecasting and Social Change**, v.102, 160–168, 2016.

SCARINGELLA, L.; RADZIWON, A. Innovation, entrepreneurial, knowledge, and business ecosystems: Old wine in new bottles?. **Technological Forecasting and Social Change**, v. 136, p. 59-87, 2018.

SCHUMACHER, A.; EROL, S.; SIHN, W. A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. **Procedia CIRP**, 52, 161–166, 2016.

STURGEON, T.J. Upgrading strategies for the digital economy. **Global Strategy Journal**, 2019.

WANG, S.; WAN, J.; LI, D.; ZHANG, C. Implementing Smart Factory of Industrie 4.0: An Outlook. **International Journal of Distributed Sensor Networks**, v.12, 3159805, 2016.

WEI, Z.; SONG, X.; WANG, D. Manufacturing flexibility, business model design, and firm performance. **International Journal of Production Economics**, v.193, 87-97, 2017.

YIN, R. K. Estudo de caso: planejamento e métodos. 2ª Ed. Porto Alegre. **Editora: Bookman**. 2001

YIN, Y.; STECKE, K. E.; LI, D. The evolution of production systems from Industry 2.0 through Industry 4.0. **International Journal of Production Research**, 7543(Novembro), 1–14, 2017.

2 PAPER 1 – Industry 4.0 technology provision: the moderating role of supply chain partners to support technology providers

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Abstract

Purpose: The provision of Industry 4.0 solutions demands a vast range of technology domains. To provide these solutions, Small and Medium-sized Enterprises (SMEs) may need the support of different supply chain actors through an inbound open innovation strategy. We study the contribution of four types of supply chain actors for inbound open innovation: suppliers, competitors with complementary technologies, R&D centers, and customers. We analyze how these four actors moderate the effect of integrated Industry 4.0 solutions on three main competitive strategies: cost, focalization, and differentiation.
Methodology: We conducted a survey on 77 SMEs from the automation sector, using OLS regression with moderating effects. We considered the integration of 15 technologies and 7 classic automation activities in the provision of Industry 4.0 solutions. We also studied three competitive outputs – technology cost reduction (cost), customer loyalty (focalization), and technology innovation (differentiation) –, as well as four supply chain actors (moderators).
Findings: Expanding the provision of Industry 4.0 technologies increases customer loyalty and technology innovation. Collaboration with competitors (complementary technologies) leverage these results and reduce technology costs. Integration between customers and R&D centers elevates costs but R&D centers can foster long-run innovation.
Originality/value: This study is the first to empirically investigate inbound open innovation in the supply chain for technology development in the context of Industry 4.0. We discuss how these actors contribute to four inbound open innovation activities: (i) technology scouting; (ii) horizontal technology collaboration; (iii) vertical technology collaboration; and (iv) technology sourcing.

Keywords: Industry 4.0; supply chain; inbound open innovation; technology providers; SMEs; collaboration.

2.1 Introduction

Industry 4.0 considers the use of the Internet of Things (IoT) and the integration of several emerging technologies to create and provide Cyber-Physical Systems (CPS) (Dalenogare et al., 2018; Frank et al., 2019a). Combining these emerging technologies allows for the provision of 'integrated Industry 4.0 solutions', i.e., interconnected technologies that execute a complete operation for a customer's Industry 4.0 requirements (Benitez et al., 2020). Examples of integrated solutions are the manufacturing lines for reconfigurable production and mass customization – which can integrate sensors, flexible machines, real-time production scheduling systems, collaborative robots, etc. – and integrated manufacturing systems that allow vertical integration between manufacturing and corporate information systems (Dalenogare et al., 2018). Industry 4.0 principles demand such integrative solutions rather than single technologies in the manufacturing process (Frank et al., 2019). These solutions are complex by nature since they demand the mastering of several technologies and capabilities, including hardware, software, and digital technologies such as big data and artificial intelligence (Kahle et al., 2020).

In this context, 'technology providers' are challenged to deal with such complexity. They have expertise in IT, automation, software and/or hardware, but it is hard for them to independently manage a whole wide range of technologies (Dalenogare et al., 2018; Kahle et al., 2020). Such a challenge is even bigger for small and medium-sized enterprises (SMEs) that usually offer some technology subsystems but are not able to provide the complete solution (Müller et al., 2018; Dallasega et al., 2018). Therefore, many technology providers follow a collaborative strategy based on value co-creation through alliances, cooperation, and joint ventures with different actors in the supply chain, following an Open Innovation (OI) approach (Benitez et al., 2020; Kahle et al., 2020). In such a case, defining with whom to collaborate becomes an issue for companies to tackle (Enkel et al., 2009). While some studies suggest that 'the more actors, the merrier' in the OI approach (Laursen and Salter, 2006; Schneider, 2018), others have warned about the potential negative impact of OI strategies depending on the actors and contexts of collaboration (Enkel et al., 2009; Love et al., 2011). As our literature review (Appendix A) shows, this aspect is still a gap in the Industry 4.0 context since most studies have focused on understanding the supply chain digitization process instead of the forms of collaboration to develop digitized solutions. The potential forms of collaboration for the provision of integrated Industry 4.0 solutions and the resulting benefits are unclear, which brings up the following research question: *what are the contributions of the different supply chain actors for the provision of integrated Industry 4.0 solutions?*

We analyze the contribution of each supply chain actor in the provision of integrated Industry 4.0 solutions to achieve a greater competitive advantage. We consider 15 Industry 4.0 technologies and analyze how their provision through integrated solutions helps achieve three different competitive advantage dimensions: a) technology cost reduction, b) increased customer loyalty, and c) differentiation through technology innovation. We examine how four types of supply chain actors – suppliers of technological components, competitors that develop complementary technologies, R&D centers, and technology adopters – moderate this relationship. We test these relationships through a survey with 77 technology providers from the automation industry. We demonstrate an OI approach with technology complementors for Industry 4.0 technology solutions with positive impact on the three competitive advantage dimensions. On the other hand, cooperation with R&D centers and customers for technology provision elevates costs but creates other direct benefits in terms of customer loyalty and technology innovation regardless of the Industry 4.0 solution provided. Our findings empirically demonstrate the relevance of creating a supply chain network of SMEs to provide integrative Industry 4.0 solutions and drive the appropriate selection of supply chain partners.

2.2 Open innovation for the provision of Industry 4.0 technologies

Chesbrough and coauthors have proposed open innovation (OI) as an innovation strategy that considers "*the use of purposive inflows and outflows of knowledge to accelerate internal innovation and to expand the markets for external use of innovation, respectively'* (Chesbrough et al., 2006: 1). The concept has been broadly applied in the management literature as a modern approach to boost company innovation and technological development through the sharing of resources with external partners (Frank et al., 2021). We focus our study on inbound OI, which refers to the practice of exploring and integrating external knowledge and resources for technology development and technology exploitation (Chesbrough, 2003). We choose this approach because while outbound OI considers the inside-out flow (i.e., when technology is sold to the market), inbound OI, on the other hand, focuses on inflows of knowledge and resources for development purposes internal to the central company analyzed in the supply chain (Chesbrough et al., 2006).

Inbound OI considers four collaboration activities as paramount for technological innovation: (i) *technology scouting*; (ii) *horizontal technology collaboration*; (iii) *vertical technology collaboration*; and (iv) *technology sourcing* (Chesbrough et al., 2006; Van De Vrande et al., 2009; Parida et al., 2012). *Technology scouting* refers to the identification, observation, and information acquisition about the development of emerging and trending technologies for the decision on whether to acquire them (Van Wyk, 1997). *Horizontal technology collaboration* represents the collaboration with partners that are not part of the value chain of a traditional supply chain (e.g., competitors and R&D centers) (Parida et al., 2012). *Vertical technology collaboration* considers collaborative actions with customers and suppliers (Barratt, 2004). Lastly, *technology sourcing* represents an inbound activity of buying or using external technology through intellectual property agreements (Van De Vrande et al., 2009). The breadth of the adopted OI strategy through collaboration with different external partners helps to increase the level of these four inbound OI activities in the central firm (Frank et al., 2021). External partners can play different roles, some of them promoting access to relevant information and others as an outsource of technological innovation in the companies' network (Kahle et al., 2020).

Since Industry 4.0 demands complex and integrated technological solutions, which are difficult to achieve by single companies, inbound OI can be a strategy to leverage these companies' technological innovation. Benitez et al. (2020) have previously argued that Industry 4.0 should be built around platforms requiring the integration of different technologies from external partners into single solutions, which is exactly what the inbound OI concept proposes. However, as evidenced in our literature review (Appendix A), few studies in the intersection between Industry 4.0 and supply chain literature have addressed interfirm collaboration for technology provision. Most studies about Industry 4.0 and the supply chain have focused on digital supply chains and the utilization of Industry 4.0 technologies to improve information exchange between different actors. Few studies have considered the relevance of creating Industry 4.0 ecosystems as a means to increase technological innovation (Benitez et al., 2020; Kahle et al., 2020; Reynolds and Uygun, 2018; Rong et al., 2015), or the relevant role of external partners for the creation of new business models in this context (Welking et al., 2020; Schneider, 2018). Although these studies have advanced the discussion about the need for a general external network to cope with Industry 4.0 technology provision, they evidence a research gap regarding the investigation of *specific* roles different external partners can play in this context. Thus, we believe that the use of inbound OI as a middle-range theory (Stank et al., 2017) to understand collaboration mechanisms in this context can provide a new perspective on Industry 4.0 and supply chain state of the art, as proposed below in our Hypotheses development.

2.3 Hypotheses development

This section first provides the hypotheses about the direct effects of Industry 4.0 technology provision on competitive performance. Then, in the second subsection, we explore the moderating effects of supply chain partners using the inbound OI perspective.

2.3.1. Technology provision in the Industry 4.0 context

Several studies have proposed technologies that can be comprised in the Industry 4.0 concept (e.g., Bartodziej, 2016; Dalenogare et al., 2018; Frank et al., 2019a). Some works have considered that Industry 4.0 only encompasses disruptive technologies, mainly those based on the Internet of Things (IoT) and big data analytics (Almada-Lobo, 2016; Yin et al., 2018), while others have included classic advanced manufacturing technologies like robotics and automated machines (Frank et al., 2019a; Osterrieder et al., 2019). In this study, we follow Frank et al. (2019a) to select the technologies comprised under the Industry 4.0 concept, as summarized in Table 2.1.

The technologies listed in Table 2.1 must work in synergy to achieve the so-called ‘smart’ stage (Frank et al., 2019a). Combining such technologies into integrated Industry 4.0 solutions is the key competitive advantage proposed by Industry 4.0 (Reischauer, 2018). Such an integration demands complementarity between different knowledge domains, including information technology, digital technology, operational technology, hardware, and automation systems. Thus, we expect that technology providers offering more integrative Industry 4.0 solutions, i.e., technological solutions that contain a wide set of interconnected technologies under the Industry 4.0 concept, will be more competitive in the industrial market.

Table 2.1 – Technologies associated with Industry 4.0

Technologies	**Definition**
Sensors, actuators, and transductors	Sensors are equipment characterized by their ability to collect data about a process. Actuators receive information from the sensors and transductors to perform actions. Transductors are devices that convert one form of energy into another (Frank et al., 2019a; Dalenogare et al., 2018).
Supervisory Control and Data Acquisition (SCADA)	Systems for monitoring shop floor operations through real-time data collection (Jeschke et al., 2017).
Big data analytics	Correlation of great quantities of data for predictive analytics applications, data mining, statistical analysis, and others (Gilchrist, 2016).
Manufacturing Execution Systems (MES)	Systems that work in real time enable the control of multiple elements of the production process (Almada-Lobo, 2016; Jeschke et al., 2017).
Machine-to-machine communication (M2M)	Technologies allow systems and equipment to communicate with other devices, either to exchange or provide data (Gilchrist, 2016).
Process traceability	The use of IT to track product movements and monitor processes at the shop-floor level implies applying digital devices (e.g., RFID, QR code, to mention but a few) in product life-cycle management (Bartodziej, 2016; Tao et al., 2018).
Virtual commissioning	Debug real data of equipment in a virtual environment, simulating the automation equipment virtually, validating its operation in the production line (Jeschke et al., 2017; da Costa et al., 2019).
Digital manufacturing	Use of data management systems with data management technologies and simulation technologies for manufacturing optimization before starting production, supporting the ramp-up phases (Rüßmann et al., 2015).
Augmented and virtual reality	Real-scene integration with computer-generated information. Integration between the real and the virtual worlds (Frank et al., 2019a; Rüßmann et al., 2015).
Additive manufacturing	Versatile manufacturing machines for flexible manufacturing systems (FMS), transforming digital 3D models into physical products (Garrett, 2014; Weller et al., 2015).
Machine vision	Detection of object positioning by image processing systems for quality control (Tao et al., 2018).
Industrial robots (Industrial automation)	Processes automated by internal robotic mechanisms, without human intervention (Gilchrist, 2016; Tao et al., 2018).
Collaborative robots (Man-machine)	Robot systems with sensors and processors, enabling direct cooperation with human operators (Bartodziej, 2016; Gilchrist, 2016).
Energy efficiency monitoring system	Sensors, meters, and other tools that identify the level of energy consumption in equipment (Gilchrist, 2016; Kagermann et al., 2013).
Energy efficiency improving system	Real-time analysis and evaluation of energy consumption enabling decision-making based on process capabilities (Jeschke et al., 2017; Kagermann et al., 2013).

We summarize the competitive performance of technology providers in three main competitive metrics that companies may pursue. These three metrics are based on Porter's (1980) competitive advantage strategies: *cost reduction* in technology development, *focalization* on specific customers to create loyalty, and *product differentiation* through innovation. As Kahle et al., (2020) exposed, the cost of developing smart solutions is a barrier that should be reduced to render them more attractive to customers. The implementation costs of Industry 4.0 solutions increase when different technologies are not integrated. For instance, M2M is not allowed when equipment uses different communication protocols, and extra investment for software development and equipment update is required to solve the problem (Bartodziej, 2016). By integrating different technologies and providing a more comprehensive solution for Industry 4.0 needs, technology providers can reduce these costs while accessing a larger segment of customers, thus increasing their sales and achieving marginal cost reduction, demanding a broader integration of technologies and standardized solutions (Dalenogare et al., 2018; Frank, et al., 2019a). Another strategy is the integration and combination of Industry 4.0 technologies to serve a specific customer (focalization). As stated by Wang et al. (2017) and Weking et al. (2020), the integration of Industry 4.0 technologies in modules can allow a shift from mass production toward mass customization or even mass ‘individualization’ or ‘personalization’ to meet customer requirements more efficiently and effectively through the provision of individually distinct solutions with a positive user experience.

Ghobakhloo (2018) also relates the combination of industrial robots and additive manufacturing capabilities to the transition from mass customization to mass personalization, allowing for the combination of standardized parts with customized ones. Naturally, technology providers that can manage several of these capabilities will be of paramount importance to support technology adopters, enhancing these customers' loyalty through the provision of more comprehensive Industry 4.0 solutions (Frank, et al., 2019b). Additionally, the more a company can master different technologies and offer them through integrated solutions, the more innovative these solutions may be (Müller et al., 2018). For instance, the combination of equipment with sensors and actuators, SCADA, process traceability, digital manufacturing, and virtual commissioning, among others, would allow technology providers to innovate in their solutions to offer an entire cyber-physical system to their customers

(Dalenogare et al., 2018). Therefore, we synthesize these relationships between Industry 4.0 technology integration and the competitive advantage outputs in the following hypotheses:

> *H1. The offer of more integrated Industry 4.0 solutions is positively associated with a) a reduction in technology costs (H1a); b) an increase in customer loyalty (H1b), and c) an increase in technology innovation (H1c).*

2.3.2. Supply chain collaboration for Industry 4.0 technology provision

Following Barratt (2004), we investigate the role of four supply chain partners: suppliers and customers – usually involved in traditional supply chain collaboration – and competitors with complementary technologies, namely complementors and R&D centers – which are more common in supply networks and ecosystems where relationships between actors are not exclusively linear. These four different external partners can play specific roles in creating an inbound OI strategy for the provision of integrated Industry 4.0 solutions.

The first type of supply chain actor is represented by the suppliers [SUPPLIERS]. These are companies that supply components of the technology developed (Yin et al., 2018). Suppliers can play two major roles in the inbound OI strategy for integrated Industry 4.0 solutions, contributing to *vertical technology collaboration* and *technology sourcing*. The general literature on the supply chain has argued that suppliers can be involved in the co-design of a buyer’s solution development (Ayala et al., 2020). In this sense, suppliers can act as an external source of knowledge on product capabilities that are not well developed internally by the central company (Ayala et al., 2017). Thus, they can help to understand how to integrate technology components into enhanced solutions. For instance, hardware telecommunication suppliers can help a flexible manufacturing lines provider to embed IoT solutions to increase the connectivity of its equipment (Hozdić, 2015). Suppliers can also act as an outsource of technologies (*technology sourcing*) to be integrated into the wider final solution for Industry 4.0 applications (Frederico et al., 2019). This is the case of add-on technologies, as sensor kits can be acquired from technology suppliers and plugged into a wider solution like a machine vision system for quality control (Dos Santos et al., 2020). Both vertical collaboration and technology sourcing with suppliers can help to increase competitiveness. Technology sourcing can help to reduce development costs that will be incorporated by the supplier (Parida et al., 2012), to expand the innovation capacity of the company in the Industry 4.0 context (Benitez et al., 2020), and to better align with customers' expectations to achieve an increase in loyalty (Ayala et al., 2019). Thus, we propose the following hypothesis:

> *H2. An inbound OI strategy based on collaboration with component suppliers positively moderates the impact of integrated Industry 4.0 solutions on a) technology cost reduction (H2a); b) customer loyalty enhancement (H2b), and c) technology innovation (H2c).*

R&D Centers [R&D_CNT] are the second type of actor considered in our supply chain structure. These centers are traditionally levers of innovation in supply chain networks (Albors-Garrigós et al., 2014). They are strategic partners for technology providers in Industry 4.0 initiatives because they can support radical innovation by affording high-risk projects in partnership with private companies and with the support of government funds (Ahn et al., 2020), potentially reducing the final cost of technologies. For example, in some countries, R&D centers have led testbed projects for Industry 4.0 initiatives, which can later be disseminated in the industry if the project is successful (Reischauer, 2018; Tu et al., 2018a, 2018b). Consequently, they contribute especially for *horizontal technology collaboration* in the inbound OI strategy since they can afford higher risks in the innovation process than the buyer (Ahn et al., 2020; Reischauer, 2018). Bentiez et al. (2020) have reported that these centers share resources with SMEs to help such companies reduce costs in the offering of Industry 4.0 solutions. For instance, these centers can provide advanced simulation services that may be too expensive for small technology providers to include in the Industry 4.0 solution (Benitez et al., 2020). This can allow assessing a customer's solution before implementing it, resulting in fewer technology costs for the provider, as well as higher customer satisfaction and innovation. R&D centers can also support *technology scouting* because they are mostly focused on the initial stages of the Technology Readiness Levels (TRL) and consequently test future solutions that providers can incorporate in their solutions (Phaal et al., 2011); this is an important source to advance technology innovation. In some specific cases, R&D centers can also act as highly qualified *technology sourcing*, developing specific technologies for a buyer based on innovation contracts. This is frequently the case in collaboration policies between universities and the private sector to foster technology transfer, integrating innovation from high-skilled centers with market requirements resulting from the private sector's knowledge of market demands (Reynolds and Uygun, 2018). Therefore, we propose the following hypotheses:

> *H3. An inbound OI strategy based on collaboration with R&D centers positively moderates the impact of integrated Industry 4.0 solutions on a) technology cost reduction (H3a); b) customer loyalty enhancement (H3b), and c) technology innovation (H3c).*

The third actor in the supply chain is represented by technology adopters, i.e., the customers [CUSTOMERS] of the Industry 4.0 solutions. Customer involvement has an important contribution to *technology scouting* in the inbound OI strategy because it allows to better understand their needs and future technology requirements (Wang et al., 2015). This is especially important in providing integrated Industry 4.0 solutions, which tend to be highly customized according to the manufacturing needs (Dalenogare et al., 2018). Moreover, Industry 4.0 technology provision considers the use of customer data collected by smart connected technologies (Frank et al., 2019b). Data access and collection can also be important to improve the provision of Industry 4.0 solutions because it allows for the identification of customer preferences (*technology scouting*) and organization of the product development process based on such preferences and needs. For instance, through the provision of smart connected robots in the manufacturing process and customer collaboration in allowing the company to collect and use the generated data, the company can learn about other needs like process optimization services, system integration needs for improved process synchronization, etc. (Nakayama et al., 2020). *Technology scouting* through customer involvement can help in many ways: it can increase innovation capabilities by promoting a better understanding of market needs, it can help to speak the 'customer's language' and consequently increase loyalty, and it may lead to technology cost reduction by solving mismatches between technology provision and customer demands. Thus, we propose:

> *H4. An inbound OI strategy based on collaboration with technology adopters (customers) positively moderates the impact of integrated Industry 4.0 solutions on a) technology cost reduction (H4a); b) customer loyalty enhancement (H4b), and c) technology innovation (H4c).*

The last supply chain actor considered in our analysis comprises competitors that develop complementary technologies. We named these companies 'complementors'

[COMPLEMENTORS] because, while they compete with technology providers in some products, they also provide independent technologies or have knowledge and capabilities that could be combined in the same solution to reach better integration in Industry 4.0 solutions (Benitez et al., 2020). Complementors have been acknowledged as important actors in successful supply chain networks (Lejeune and Yakova, 2005; Noonan and Wallace, 2003). They play an important role in both *horizontal technology collaboration* and *technology sourcing* of the inbound OI strategy. The literature has highlighted the relevance of collaboration between competitors to tackle the challenges of Industry 4.0 through the creation of regional ecosystems (Reynolds and Uygun, 2018; Rong et al., 2015). Instead of embracing the whole Industry 4.0 solution provision, different complementors can focus on their main skills and cooperate for the interoperability of their technologies as add-ons to a single platform. This is the effort reported by Benitez et al. (2020) in a regional ecosystem for Industry 4.0 provision. As shown in their example, companies can cocreate value by working in joint development projects (*horizontal collaboration*) or can be coordinated by a supply chain orchestrator providing technologies that will be "connected" to a larger solution. Although the relevance of this inbound OI approach with complementors was well documented in this study, its contribution to competitiveness was not assessed. In this sense, we expect that such an inbound OI approach will reduce costs, because companies will focus on the division of labor and on gaining scale by dividing resources with other complementors (Kahle et al., 2020). The ability to integrate different technologies into customized solutions can also increase the level of customization of the solution provision, which is an important factor for customer loyalty (Frank et al., 2019b) and to increase technology innovation (Dos Santos et al., 2020). Therefore:

> *H5. An inbound OI strategy based on collaboration with technology complementors (competitors) positively moderates the impact of integrated Industry 4.0 solutions on a) technology cost reduction (H5a); b) customer loyalty enhancement (H5b), and c) technology innovation (H5c).*

The model shown in Figure 2.1 summarizes all our proposed hypotheses for both direct effects and moderating effects. We consider the direct effect of integrated Industry 4.0 solutions [SOLUTION 4.0] developed by technology providers on three performance metrics: cost reduction, customer loyalty, and technology innovation. SOLUTION 4.0 is composed of Industry 4.0 technologies and classic automation technologies[1] due to their high level of correlation and the need to have these technologies integrated to reach the levels of Industry 4.0. We also add the positive moderating effects of the four supply chain actors considered in our hypotheses' development based on an inbound OI strategy of the technology providers.

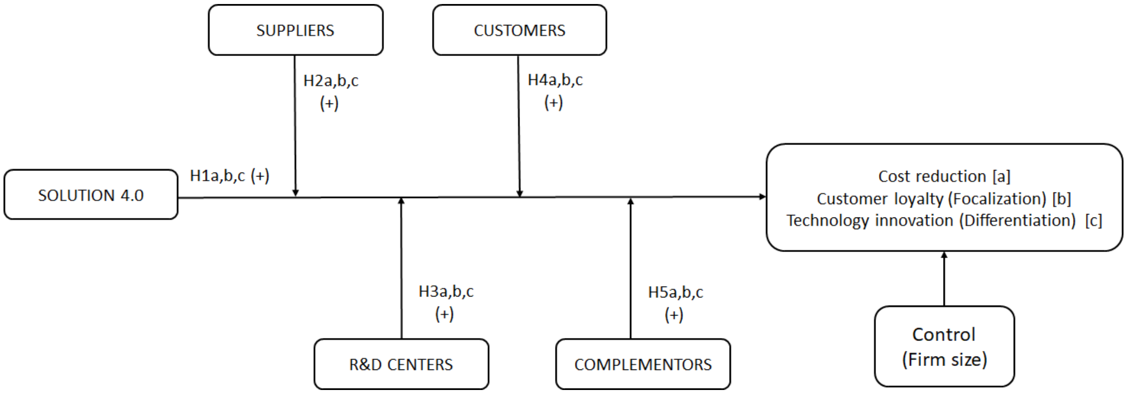

Figure 2.1 – Theoretical model

2.4 Research method

For the empirical quantitative study, we followed Fowler's (2013, p.3) structure for the survey research method based on three main stages: sampling, questionnaire design, and data analysis. We explain each of these stages in detail below.

2.4.1. Sampling

We performed a cross-sectional survey into the electro-electronic industry in Brazil. Our sample was obtained from a business association representing automation companies (a sub-sector of this larger industry) located in Southern Brazil. The electro-electronic sector was chosen because this sector is key to increasing the competitiveness of several other Brazilian industries since it develops and provides most technologies associated with Industry 4.0 (Benitez et al., 2020). Our choice of location was based on the high level of industrial development in southern and southeastern Brazil as compared to other regions of the country (Frank et al., 2019a). Nowadays, this cluster of companies comprises SMEs with several

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[1] See more details in Section 2.4.2.3. – Construct definition.

different and complementary domains, including IT, automation, software, and hardware, combined to provide smart automation for Industry 4.0 demands.

The initial sample comprised 120 SMEs affiliated with the business association. The targeted respondents were top executives such as technology and product development managers or others with similar roles and technical background. After the initial survey, we made phone calls to follow up with companies that had answered the questionnaire incompletely. We obtained 87 answers, amongst which 77 provided complete information about their research model variables (i.e., a response rate of 64.2%). Such a high response rate was obtained thanks to the support of the business association, which sent personal e-mails to the companies' representatives and promoted the research project in industry workshops. In this final sample, following the classification of the Brazilian Institute of Geography and Statistics (IBGE, 2015), 74% is composed of micro and small firms (up to 99 employees), while 26% represents medium-sized firms (100 to 500 employees). The overall respondent profile includes managers or directors with comprehensive knowledge on Industry 4.0 technologies. Table 2.2 details the sample composition and the profile of the respondents.

Table 2.2 – Characteristics of the firms considered in the sample

Category	Description	(%)	Category	Description	(%)
Industrial sectors served by the solutions of the cluster	Electro-electronic	51%	Company size	Small (<100 employees)	74%
	Metal products	39%		Medium (100-500 employees)	26%
	Food and beverage	26%	Respondent's profile	Managers or directors	82%
	Software and technology	22%		Supervisors	8%
	Energy	22%		Analysts	6%
	Steelworks	16%		Other	4%
	Pulp and paper	14%			
	Pharmaceutical	12%			
	Agriculture	12%			
	Tobacco	12%			
	Transport	12%			
	Leather and related products	10%			
	Petrochemical	10%			
	Chemicals	10%			
	Furniture	9%			
	Biotechnology	1%			
	Other	31%			

2.4.2. Questionnaire design

2.4.2.1. Definition of measures

Our study used four groups of items from the questionnaire (Appendix B). First, *Classic automation activities*: a list of 7 activities related to the design, installation, and programming of mechanical, pneumatical, and electrical components, all adapted from CNI (2016) and PWC (2016). Although they are not essentially Industry 4.0 technologies, we considered providing these technological activities because they are the basis for Industry 4.0 provision (Dalenogare et al., 2018). This classification followed previous studies by Kagermann et al. (2013), Schumacher et al. (2016), and Mittal et al. (2018), which suggest maturity models for Industry 4.0 implementation. Following the suggestions in these works, companies should have a minimum of automation and technical knowledge from the third industrial revolution to begin their path towards Industry 4.0 maturity stages. Therefore, Industry 4.0 solutions should be accomplished through other classic automation activities. Second, a list of 15 *Industry 4.0-related technologies* was defined based on Frank et al. (2019a). As mentioned above, we followed this study because it was also developed in the Brazilian context for manufacturing companies adopting Industry 4.0 technologies, i.e., the potential customer of the technology providers' solutions. Both lists of classic automation activities and Industry 4.0-related technologies were validated by a group of automation and Industry 4.0 experts formed by three professionals from one of the most important Technology Research Institutes in Brazil, two representatives from the business association, and one operational director from an automation firm affiliated to the association. Third, for (iii) *Collaboration with* s*upply chain actors*: we considered the level of collaboration technology providers have with the four supply chain actors for technology development purposes. The list of collaboration types was adapted from the Brazilian Survey of Innovation (IBGE, 2016), a well-known industrial survey in the national business context (Frank et al., 2016). For (iv) *Companies' performance metrics*: a list of three outcomes (technology cost reduction, customer loyalty, and technology innovation) companies have achieved with the provision of Industry 4.0 technologies. These performance metrics were based on Porter's (1980) three main competitive advantages: cost reduction, focalization, and differentiation. A 5-point Likert scale was used to capture each of these categories. The list of 15 Industry 4.0 technologies was measured as the level of the offering of each of them, ranging from "1 – *very low or no* *presence in the company's portfolio*", to "*5 – highly developed in the company's portfolio*". The Likert scale used to assess levels of collaboration ranged from "*1 – irrelevant"* to *"5 – extremely relevant*". Finally, the performance metrics were assessed in terms of the level of benefits that each company obtains from providing Industry 4.0 solutions, ranging from "*1 – very low or no results*" to "*5 – excellent results*". Additionally, we included a dummy control variable related to the size of the firms under analysis considering the size of the technology portfolio. Consequently, the level of integration between different technologies could be significantly different when we compare small to medium-sized companies. Table 2.3 summarizes the list of questionnaire items used for the independent, dependent and moderating variables.

Table 2.3 – Technologies, cooperating actors and benefits for companies' performance in NPD considered in the research model

Industry 4.0 technologies (independent variables)*	**Classic automation (independent variables) ***	**Supply chain network**	**Performance metrics**
Sensors, actuators and transductors	PLCs (Programmable Logic Controllers) programming and installation	Customers	Cost reduction
Supervisory Control and Data Acquisition (SCADA)	CNC (Computer Numeric Control) programming and installation	Suppliers	Customer loyalty
Big Data analytics	Design and manufacture of mechanical systems	Complementors	Technology innovation
Manufacturing Execution Systems (MES)	Design and installation of pneumatic systems	R&D centers	
Machine-to-machine communication (M2M)	Design and installation of power drive systems (servomotors)		
Process traceability	Electrical assembling		
Virtual commissioning	Mechanical assembling		
Digital manufacturing			
Augmented and virtual reality			
Additive manufacturing			
Machine vision			
Industrial robots (Industrial automation)			
Collaborative robots (Man-machine)			
Energy efficiency monitoring system			
Energy efficiency improving system			

*All these variables subsequently originated a single variable, described in Section 2.4.2.3.

2.4.2.2. Method bias

Before obtaining the final variables shown in Table 2.3, we conducted a pretest of the questionnaire with three Industry 4.0 experts from one of the most important Technology Research Institutes in Brazil. This institute is strongly engaged in technological innovation for Industry 4.0, developing projects with the private sector. We also reviewed the questionnaire with two business representatives and one of the companies affiliated to the association. These procedures aimed at improving scale items and eliminating potential ambiguities in the instrument (Podsakoff et al., 2012).

We also used some strategies recommended by Podsakoff et al. (2012) to reduce method bias. In this sense, as recommended by Guide and Ketokivi (2015), we addressed common method bias at the research design phase (*ex ante*) rather than only checking it after the facts (*ex post*). Firstly, we sought to increase respondents' motivation to provide accurate answers through the offer of a final benchmark feedback report based on their answers (Podsakoff et al., 2012). The 77 companies from the association were able to learn about their positions regarding the items assessed as compared to the average for the sector. This report also contained strategic guidelines for the business association, aiming to make the research more valuable for these companies. Secondly, we separated our questionnaire items to eliminate proximity effects (Podsakoff et al., 2012). Another strategy used at this point was to include other topics in this questionnaire between the dependent and independent variables, including barriers to the implementation of Industry 4.0 and external funds the companies can access to develop Industry 4.0 solutions. This renders it more difficult for respondents to relate dependent and independent variables while answering (Podsakoff et al., 2012). Thirdly, although we used a five-point Likert scale in all measures, we varied their meaning for each group of variables since this also reduces method bias (Podsakoff et al., 2012). Finally, although we used all these procedures, the strongest way to reduce method bias is to use multiple sources to obtain the measures, which was not possible in our study because of our restricted access to company informants (Podsakoff et al., 2012). In this case, there is no way to determine what ratio of item variance is trait variance (Guide and Ketokivi, 2015). Therefore, we cannot affirm that method bias is not present, but we took all possible measures to minimize it.

2.4.2.3. Construct definition

We used the four supply chain actors (CUSTOMERS, SUPPLIERS, COMPLEMENTORS, and RD_CNT) as described in Table 2.3. On the other hand, the set of Industry 4.0 technologies and classic automation technologies described in Table 2.3 were combined in a single variable [SOLUTION 4.0] representing the level of integration of these technologies in the companies' solution. This was conducted in two steps, as follows.

Industry 4.0 technology variables (Table 2.3) were synthesized in the main constructs using Exploratory Factor Analysis (EFA). This technique aims at reducing the dimensionality of a dataset, increasing interpretability while reducing information loss. This technique provides benefits in enhancing the analysis, removing correlated features, and reducing overfitting of variables (Wold et al., 1987). This technique has been used for many practices, tools, or technologies with potential latent constructs not predefined by the researchers (e.g., Frank et al., 2016; Dalenogare et al., 2018; Marodin et al., 2019). Our study's primary interest is evaluating the features of each group of variables rather than the variables individually. We used two criteria to assess the adequacy of our data to the EFA technique: the Kaiser-Meyer-Olkin (KMO) test, as a measure of sampling adequacy, and Bartlett's sphericity test (Hair et al., 2009). The KMO test result was 0.796 (the generally recommended threshold value is 0.5), and Bartlett's sphericity test showed significance levels lower than 1% (p-value <0.01, while the threshold reference is usually 0.05). Therefore, both tests were considered very satisfactory for our sample size (Hair et al., 2009). Then, we performed an EFA for this set of technologies, as shown in Table 2.4. We used a Varimax orthogonal rotation to obtain the EFA's final factor solutions (Hair et al., 2009). Our optimized solution was obtained after following an iterative process in which the number of factors was selected based on the eigenvalues generated. This criterion establishes that the eigenvalues should be higher than 1.0 (latent root criterion). In addition, we followed another criterion, which is the percentage of variance that the reduced variables can explain. According to this criterion, the ideal number of main factors should exceed the percentage of the variance of 70% (Hair et al., 2009). The results of our EFA showed the existence of four main factors that explain 71.26% of the variance (Table 2.4), indicating that these factors account for most of the variance in the variables. As shown in Table 2.4, these four groups were named based on the main characteristics that the grouped technologies allow to achieve in the manufacturing process: Digitization [DIGITAL], Process control [PROCESS], Flexibilization [FLEX], and Energy efficiency [ENERGY].

Table 2.4 – Rotated factor-loading matrix from the EFA procedure

	Factor loadings				
Industry 4.0 technologies	**Digitization [DIGITAL]**	**Process control [PROCESS]**	**Flexibi-lization [FLEX]**	**Energy efficiency [ENERGY]**	**Commu-nalities**
Sensors, actuators and transductors	0.304	**0.518**	0.161	0.448	0.587
Supervisory Ctrl & Data Acquis. (SCADA)	**0.705**	0.377	-0.047	0.271	0.716
Big data analytics	**0.686**	0.367	0.003	0.271	0.678
Manufacturing Execution System (MES)	0.499	**0.549**	0.132	0.228	0.620
Machine-to-machine communic. (M2M)	0.344	**0.655**	0.226	0.288	0.682
Process traceability	**0.527**	0.509	0.272	0.003	0.612
Virtual commissioning	**0.795**	0.105	0.138	0.276	0.739
Digital manufacturing	**0.721**	0.146	0.367	0.045	0.678
Augmented and virtual reality	**0.665**	-0.092	0.442	0.198	0.684
Additive manufacturing	0.049	0.232	**0.685**	0.052	0.528
Machine vision	-0.007	**0.793**	0.348	0.083	0.757
Industrial robots (Industrial automation)	0.180	0.274	**0.789**	0.190	0.766
Collaborative robots (Man-machine)	0.329	0.139	**0.746**	0.355	0.809
Energy efficiency monitoring system	0.238	0.218	0.185	**0.875**	0.904
Energy efficiency improving system	0.232	0.134	0.223	**0.898**	0.928
Eigenvalue	7.108	1.378	1.145	1.059	
% of variance explained (cumulative)	23.69%	39.81%	55.63%	71.26%	
Cronbach's alpha	0.864	0.808	0.796	0.948	

Besides the four factors obtained from the EFA (Table 2.4), we also considered an additional set of technology-related activities described in Table 2.3 as ‘Classic automation’. We did not include these activities in the EFA analysis since it is generally agreed that they do not essentially constitute Industry 4.0 technologies or activities, being sometimes considered ‘3.0’ rather than ‘4.0’ (Dalenogare et al., 2018). However, they are fundamental activities for the provision of Industry 4.0 technologies (Kagermann et al., 2013; PWC, 2016). Therefore, they constituted an additional construct for the development of integrated Industry 4.0 solutions. We calculated the means of each of the constructs obtained from the EFA (Table 2.4) and the Classic Automation [AUTO] set of activities (Table 2.3). Then, we integrated the five different constructs into an integrative index. Integrative indexes are commonly used for benchmarking purposes in different fields since they allow obtaining single indicators from a comparison between the considered units of analysis (Saary, 2008). We performed this procedure due to the high level of correlation between Industry 4.0 technologies and classic automation technologies for industrial performance, as suggested in the literature (Dalenogare et al., 2018; Frank et al., 2019a). Therefore, the integrative index of the overall

Industry 4.0 technologies constructs and [AUTO] construct was calculated as a vector sum of the five axes (each representing one construct), as represented in Equation 1:

$$SOLUTION\_4.0_{k} =$$

$$\sqrt{\overline{(X}_{DIGITAL_{k}})^{2} + \overline{(X}_{PROCESS_{k}})^{2} + (\bar{X}_{FLEX_{k}})^{2} + \overline{(X}_{ENERGY_{k}})^{2} + \overline{(X}_{AUTO_{k}})^{2}} \qquad (1)$$

In Equation 1, SOLUTION 4.0 represents the level of provision of the five types of Industry 4.0 technologies (DIGITAL, PROCESS, FLEX, ENERGY, and AUTOMATION) in a technology provider k solution offering. Each of the quadratic means in Equation 1 corresponds to one of the five types of Industry 4.0 constructs. Thus, the square root of the five axes results in SOLUTION 4.0, representing an integrative vector index serving as an efficient shorthand to represent the general structure of the constructs. Table 2.5 presents the correlation matrix of the final set of variables used in our analysis. Additionally, this table presents some descriptive statistics, such as mean and standard deviation as well as the skewness and kurtosis of the data.

Table 2.5 – Correlation matrix and analysis of descriptive statistics

		MEAN	S.D.	Skewness	Kurtosis	1	2	3	4	5	6	7	8	9
1	Firm_size (control)	0.233	0.426	1.283	-0.363	-								
2	SOLUTION 4.0	5.697	1.843	0.253	-0.480	0.023	-							
3	CUSTOMERS	4.220	1.033	-1.413	1.453	-0.208	0.384**	-						
4	SUPPLIERS	3.324	1.018	-0.159	-0.367	-0.117	0.155	0.393**	-					
5	COMPLEMENTORS	3.090	1.028	0.038	-0.475	0.161	0.054	0.426**	0.311**	-				
6	R&D_CNT	3.064	1.127	-0.187	-0.661	0.105	-0.112	0.100	0.371**	0.426**	-			
7	Cost reduction	3.545	1.179	-0.499	-0.578	0.057	0.111	0.072	0.167	0.164	0.150	-		
8	Customer loyalty	3.844	1.032	-0.761	0.054	-0.154	0.352**	0.338**	0.160	0.026	-0.047	0.400**	-	
9	Technology innovation	4.051	0.965	-0.989	0.912	-0.061	0.359**	0.290*	0.315**	0.206	0.225*	0.386**	0.646**	-

**p < 0.01; *p < 0.05.

2.4.2.4. Reliability, validity, and generalizability

We used inter-item analysis to check digital, process, flexibility and energy scales for internal consistency reliability (Nunnally and Bernstein, 1994). More specifically, we used Cronbach's alpha, which was calculated for each scale, as Flynn et al. (1990) recommended. According to traditional literature in psychometrics (e.g., Nunally and Bernstein, 1994) and specialized literature in Operations Management (e.g., Flynn et al., 1990; Van de Ven and Ferry, 1978), the minimum generally accepted Alpha is 0.70. The coefficients for Cronbach's alpha are reported in Table 2.4; they are above the aforementioned threshold. Table 2.5 also brings a correlation matrix for the scales described above.

Additionally, we also assessed the concept of validity in our research. Validity is generally a measurement of two things. First, if the item or scale is truly measuring what it intends to measure. Second, if it measures something else, in our research, we used three types of validity to assess the accuracy of our instrument: (i) face validity, (ii) content validity, and (iii) construct validity (Nunnally and Bernstein, 1994). Before we started the data collection process, we evaluated the face and content validity of our scale items. Both face validity and content validity cannot be determined statistically, but only by experts and references to the literature (Flynn et al., 1990). Hence, we had meetings with academics and practitioners who participated in a pretest survey. Literature in our research was also an important resource to evaluate the validity of our constructs. Chin et al. (2008) refer to this as a 'semantic differential scale'. This method consists of evaluating the meaning suggested by a word, concept, or thing, referred to as *connotative meaning* (Albaum et al., 1977), and it is particularly useful for research involving technology acceptance and adoption (Chin et al., 2008). Since we did not assess psychometrical measurements but rather technologies, the semantic differential scale can be used straightforwardly. Therefore, the two assessment steps involving the literature and expert knowledge were useful in checking the validity of our constructs. Furthermore, we used construct validity to measure whether a scale is an appropriate operational definition of an abstract variable or a construct. In this paper, the latent variables [DIGITAL], [PROCESS], [FLEX] and [ENERGY] are our constructs, that is, they were not directly observed but rather measured through individual observable variables. The latter variables compose the set of 15 Industry 4.0 technologies. We used factor analysis to establish construct validity. Factor analysis helps identify dimensions and suggest items for deletion, as well as places where they should be added (Schwab, 1980). As shown in Table 2.4, the EFA with orthogonal rotation successfully loaded all Industry 4.0 technologies into our constructs. The factor loadings are all above the threshold of 0.5, following specialized literature in multivariate analysis (e.g., Rencher, 2003). In terms of external validity, our results were presented in two final workshops, one with the companies and representatives from the electro-electronic industry, and another with the regional chapter of the Brazilian Association of Machinery and Equipment Builders (ABIMAQ) in Southern Brazil, which is the main customer of the surveyed companies. Moreover, companies from different industrial sectors were present in the ABIMAQ workshop, including the ones that participated in our study. The workshop with ABIMAQ companies allowed us to obtain an external comparison. As the companies also have access to international providers worldwide, that allowed us to compare our results with global trends. Therefore, these workshops were useful to validate the coherence of our results considering an external perspective of the customers.

Finally, regarding generalizability, while this research focuses on a single industrial sector in one country, its insights are valuable and can be generalized to some extent. Firstly, although we only investigated the electro-electronic industrial sector, this was not an arbitrary choice. As explained earlier, the sector was strategically selected because it generally adopts technology to a greater extent than other sectors (de Sousa Jabbour et al., 2011). Furthermore, this sector has a strong link with other industrial activities, which can serve as a proxy for technology adoption in other sectors (de Oliveira Gavira and Quadros, 2011; Gandhi et al., 2016). Secondly, our sample comprises companies in Southern Brazil. Although this can be a limitation to the extent of our findings, we argue for the representativeness of our sample selection. The industrial scenario in Brazil is geographically divided by industrial activity, and the country's technology sector is located mainly in the southern region (Monclaro Mury, 2016). In short, our sample choice was strategic, and it is in line with our research question. Therefore, we believe that our findings are generalizable to other scenarios, including technology clusters sharing similarities with the one described in our research. Clusters comprising companies that adopt Industry 4.0 technologies may benefit from our findings. Ultimately, we took some measures to render results more generalizable. For instance, we decided to obtain a response rate above 20% because studies published in the operations management literature with response rates as low as 10% to 20% have proven to be unreliable (Flynn et al., 1990). Our response rate was 64.2%, mitigating the potential skepticism of researchers in social sciences.

2.4.3. Data analysis

To test our hypotheses, we used ordinary least square (OLS) regression, which was calculated in IBM SPSS® version 20. To test the moderation effects of the four supply chain actors on the relationship between SOLUTION 4.0 and the three performance metrics – cost reduction, customer loyalty, and technology innovation – (H2 to H5), we standardized the independent and moderating variables using a mean-centering (Z-score) and multiplied the moderator by each independent variable, creating a multiplicative score for the interaction effect. Our final model contains five independent variables, four interaction effects, three dependent variables, and one control variable. We tested to confirm the assumptions of normality, linearity, and homoscedasticity for all independent and dependent variables. As reported in Table 2.5, skewness and kurtosis values indicate that the variables are normally distributed as they all present values between the thresholds of -2.58 and 2.58 for both tests (Hair et al., 2009). Furthermore, we have carried out the Jarque Bera (jb) test for normality of residuals (Thadewald and Büning, 2007), which is particularly recommended for studies with small samples. The results of this test support the null hypothesis, indicating that our residuals follow a normal distribution (p = 0.2204). We also plotted graphics of partial regressions to examine homoscedasticity and collinearity. We evaluated collinearity through the relationship between independent and dependent variables, and we examined homoscedasticity visually from the standardized residue plots. Both requirements were met. Besides, literature has pointed to multicollinearity as a potential problem in regression models using multiple independent variables (Hair et al., 2009). In the presence of multicollinearity, regression estimates are unstable and have high standard errors. In this sense, we also tested our multicollinearity model through the Variance Inflator Factor (VIF). Our results indicate a low VIF for all the variables (≤10) (Hair et al., 2009).

2.5 Results

The final regression results with direct and moderating effects are reported in Table 2.6. Unstandardized coefficients are reported in Table 2.6 since the scales were standardized before the analysis (i.e., unstandardized coefficients represent a standardized effect) (Goldsby et al., 2013). As shown in Table 2.6, the three final models were statistically significant. The regression model for our first dependent variable 'Cost reduction' explains 11.3% of the variance (F = 1.921, p = 0.058). The second regression model 'Customer loyalty' explains 12.6% of the variance (F = 2.097, p = 0.037). The third model 'Technology innovation' explains 17.6% of the variance (F = 2.667, p = 0.008).

Table 2.6 – Results of the regression analysis with moderating effects

	Cost reduction	**Customer loyalty**	**Technology innovation**
Firm_size (control)	-0.182	-0.309	-0.262
SOLUTION 4.0	0.190	**0.281****	**0.346*****
SUPPLIERS	0.014	0.01	0.116
R&D_CNT	0.115	0.071	**0.280****
CUSTOMERS	-0.170	**0.273***	0.100
COMPLEMENTORS	-0.058	-0.208	-0.072
SUPPLIERS x SOLUTION 4.0	0.166	0.036	0.063
R&D_CNT x SOLUTION 4.0	**-0.266***	-0.156	-0.178
CUSTOMERS x SOLUTION 4.0	**-0.513*****	-0.144	-0.110
COMPLEMENTORS x SOLUTION 4.0	**0.360****	**0.286****	**0.282****
F-value	1.921*	2.097**	2.667***
R²	0.225	0.241	0.288
Adjusted R²	0.108	0.126	0.180

Notes: n=77 SMEs.[1]Unstandardized regression coefficients are reported; * p<0.1.; **p<0.05; ***p<0.01.

Organizing these results by each hypothesis: first, hypothesis H1 was positively confirmed for SOLUTION 4.0 increasing customer loyalty (H1b: β = 0.281, p = 0.029) and increasing technology innovation (H1c: β = 0.346, p = 0.006). Nevertheless, no significance was found for the relationship with technology costs (H1a). Second, for hypothesis H2, no significance was found for any relationship of SUPPLIERS moderating the association of the offer of integrated Industry 4.0 solutions with a reduction in technology costs (H2a), an increase in customer loyalty (H2b), or an increase in technology innovation (H2c).

Surprisingly, regarding the third hypothesis, it was possible to observe that collaboration with R&D centers negatively moderates the association of the offer of integrated Industry 4.0 solutions with a reduction in technology costs (H3a: β = -0.266 p = 0.061), while no significant moderation was observed for customer loyalty (H3b) and technology innovation (H3c). Similar results were found for the test of hypothesis H4, with the collaboration with technology adopters [CUSTOMERS] negatively moderating the association of the offer of integrated Industry 4.0 solutions with a reduction in technology costs (H4a: β = -0.513, p = 0.003), with no significant results in increasing customer loyalty (H4b) or technology innovation (H4c).

Finally, regarding hypothesis H5, it was possible to corroborate that collaboration with COMPLEMENTORS positively moderates the association of the offer of integrated Industry 4.0 solutions with a reduction in technology costs (H5a: β = 0.360, p = 0.015), an increase in customer loyalty (H5b: β = 0.286, p = 0.049), and an increase in technology innovation (H5c: β = 0.282, p = 0.045).

Figure 2.2 presents the slopes for the significant interaction effects (H3a, H4a, and H5a,b,c). We represent the three metrics, 'cost reduction', 'customer loyalty', and 'technology innovation' against SOLUTION 4.0 for two different collaboration levels (low and high) with the supply chain actors. Figure 2.2 (b), (d), and (e) shows that the more intensive the collaboration with a complementor, the higher the benefits obtained from having an integrated portfolio of Industry 4.0 technologies. However, the slopes of these three quadrants in Figure 2.2 are positive for both high and low collaboration levels, although results are better with a high level of collaboration. The opposite happens when customers and R&D centers collaborate in technology development to obtain more integrated Industry 4.0 solutions (Figure 2.2 a and c): in such cases, technology costs increase instead of decreasing. The slopes help to visualize the substantial increase in technology costs when these two actors are involved.

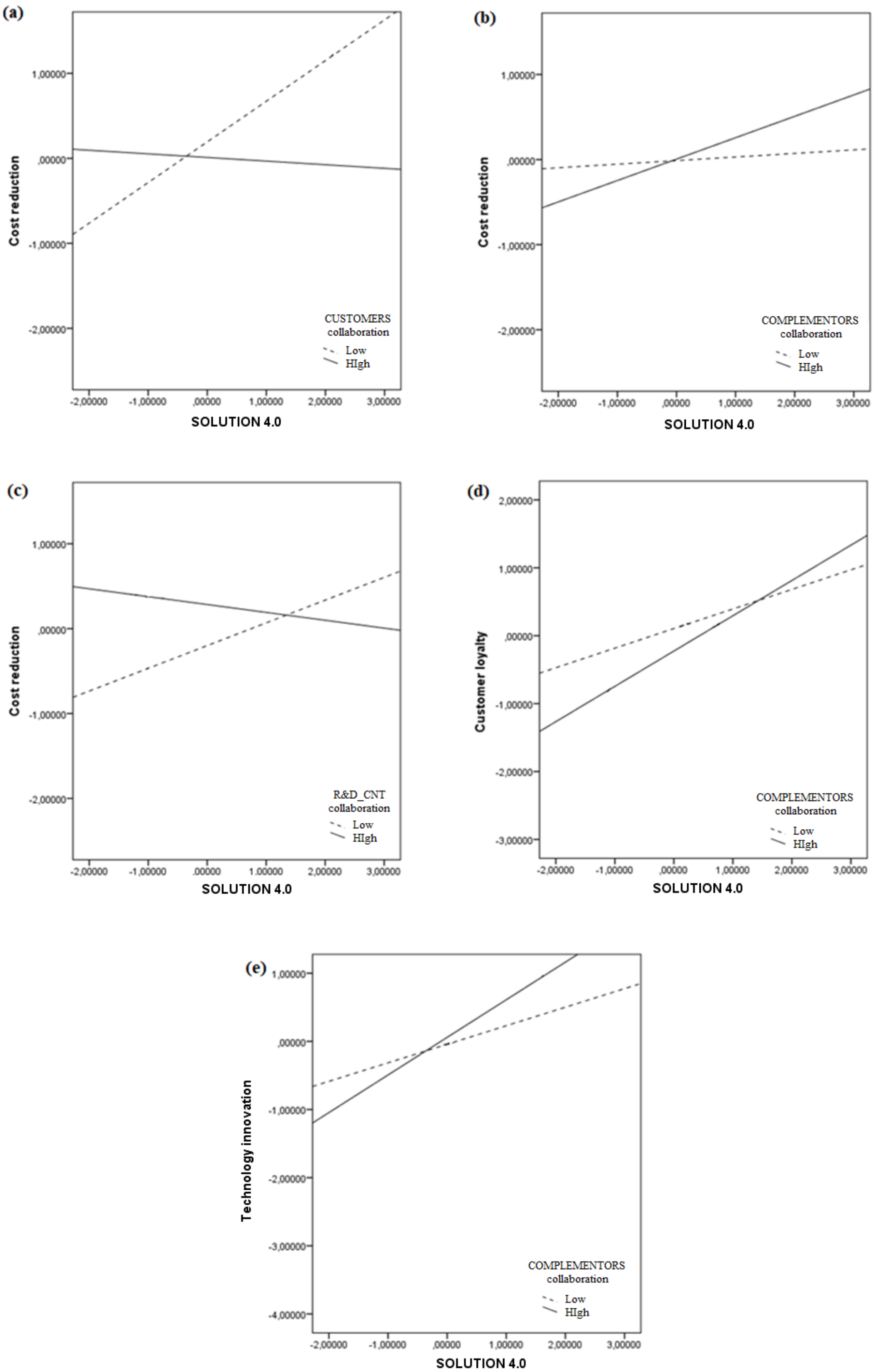

Figure 2.2 – Slopes for the moderating roles: (a) CUSTOMERS on SOLUTION 4.0 vs cost reduction; (b) COMPLEMENTORS on SOLUTION 4.0 vs cost reduction; (c) R&D_CNT on SOLUTION 4.0 vs cost reduction; (d) COMPLEMENTORS on SOLUTION 4.0 vs customer loyalty; and (e) COMPLEMENTORS on SOLUTION 4.0 vs technology innovation

2.6 Discussion

Our results evidence that the provision of integrated Industry 4.0 solutions creates competitive advantage sources, and an inbound OI strategy through the involvement of supply chain partners can contribute in different manners to leverage competitive advantage. This is represented in our conceptual framework in Figure 2.3, which summarizes our theoretical findings discussed below.

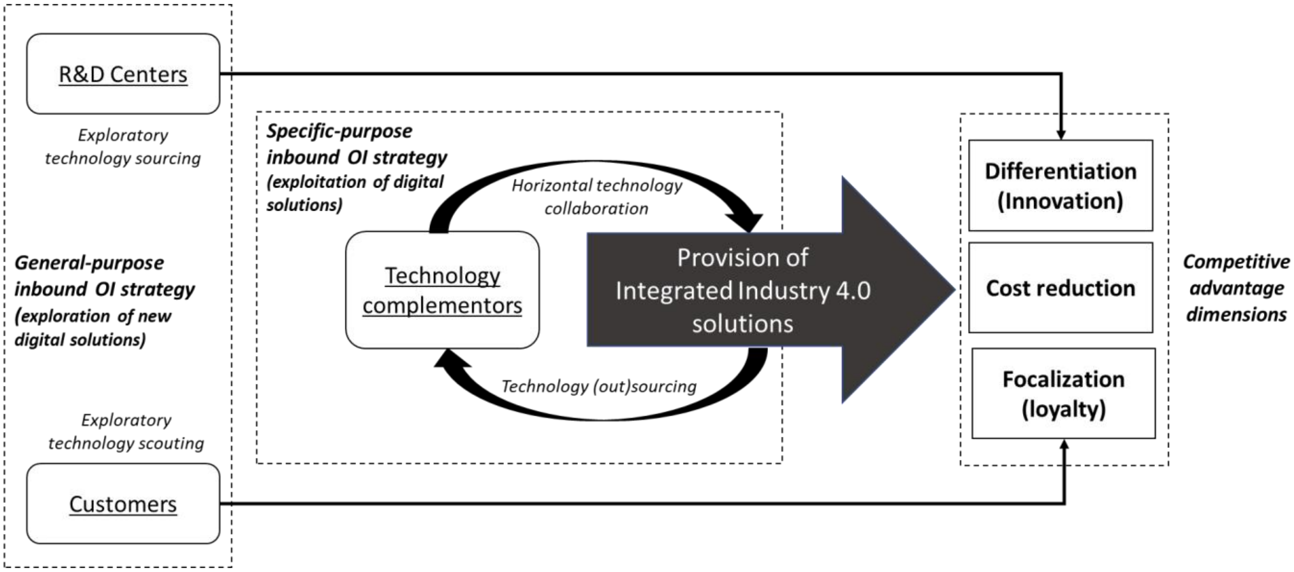

Figure 2.3 – Conceptual framework summarizing the findings – the role of supply chain actors in the inbound open innovation strategy in the Industry 4.0 context

As our results show, companies that rely on technology complementors of the supply chain network to provide Industry 4.0 solutions are more likely to enhance their competitive advantage in all three dimensions (cost, differentiation, and focalization). This is represented in Figure 2.3 through a specific-purpose inbound OI strategy, aiming to exploit digital solutions by combining technologies with those from complementors to obtain integrated Industry 4.0 solutions. Such arrangements can be achieved by means of two inbound OI activities (Figure 2.3); *horizontal technology collaboration* (i.e., codesign of the solution), and *technology sourcing* (i.e., outsourcing parts of the technology development). Therefore, we consider that the exploitation of digital solutions is the specific purpose of this inbound OI activity with complementors since technology scouting is not the main activity in this form of collaboration (Parida et al., 2012; Hossain and Kauranen, 2016). Moreover, as component suppliers did not show a significant effect in our model, whereas technology complementors showed a central role in the inbound OI approach, we can support the view that linear supply chain management is less effective in the provision of Industry

4.0 solutions and that dynamic relationships may be more suitable in this context, as previously argued by Rong et al. (2015). Recent studies have suggested that the creation of an ecosystem of horizontal relations with technology complementors would be more suitable in this context due to this dynamicity (Benitez et al., 2020; Kahle et al., 2020), and we go a step further by showing that this arrangement will have a positive contribution to the three competitive advantage dimensions (H5a, H5b, and H5c). Moreover, some authors have highlighted that key companies can become central industry platforms connecting other complementors and, consequently, orchestrating the ecosystem (Cusumano and Gawer, 2002; Gawer and Cusumano, 2014). Recent findings reported by Benitez et al. (2020) and Kahle et al. (2020) have shown that coordinating this integration is an important activity for the supply chain network, and we add that integration can be based on two inbound OI activities: *horizontal collaboration* and *technology sourcing*, as shown in our framework in Figure 2.3.

On the other hand, R&D centers and Customers did not show positive moderating effects on solution provision and on the competitive advantage of this relationship. Our results showed that collaborating with these two actors will negatively impact Industry 4.0 solution provision in terms of cost reduction. Such a collaboration demands more time to build trust and negotiate the expected outcomes (Ayala et al., 2020), elevating the technological cost of solution development, as suggested by our results. On the other hand, as shown in our findings and summarized in our final theoretical framework (Figure 2.3), the involvement of both R&D centers and Customers has a direct effect on differentiation through innovation and loyalty, respectively. Therefore, we represent this in our framework in Figure 2.3 as a ‘general-purpose inbound OI strategy’ focused on the exploration of new digital solutions (radical innovation). Instead of using such actors to expand the provision of integrated Industry 4.0 solutions, companies should focus on creating long-term competitive advantage through innovative solutions and deeper customer relationships (Weking et al., 2020). Our framework shows that R&D centers help to create exploratory technology sourcing.

SMEs usually invest expecting short and medium-term benefits, while partnerships with R&D centers in technology development are generally established in the long run (Reynolds and Uygun, 2018). R&D centers typically develop technologies for Technological Readiness Level (TRL) (Mankins, 2009) 1 to 6 (i.e., up to technology demonstration and before system development), while technology providers are more focused on TRL 7 to 9, which comprise technologies that are ready to be applied by the customers. Focusing on R&D centers should be regarded as a sort of technology sourcing for cutting-edge solutions, which may not have immediate outcomes in the provision of Industry 4.0 solutions, but rather in the long term. Likewise, collaboration with customers can help explore technology scouting to prospect future trends in technology applications (Wang et al., 2015). This complements the collaboration with R&D centers. While a company can invest in such centers to learn about future, cutting-edge technologies, collaboration with customers can focus on new customers' expectations and needs that future digital technologies can fulfill. Consequently, *technology sourcing* and *scouting* are inbound OI activities useful at the very early stages of technology development. Both are not directly focused on the provision of Industry 4.0 solutions but on building differentiation and loyalty in the long term.

2.7 Conclusions

Unlike closed innovation, the OI strategy takes into account the best partners in the supply chain to meet challenges (Bravo et al., 2016). Being inbound OI the most suitable alternative to tackle the challenge of offering integrated Industry 4.0 solutions, our study sheds light on the contribution of each of the main supply chain actors – Suppliers, Complementors, R&D centers, and Customers – in the relationship between the offering of these solutions and technology cost reduction, customer loyalty and technology innovation as sources of competitive advantage. In this sense, the main contribution of or study is showing which roles these actors can play in Industry 4.0 provision and the mechanisms of inbound activities that support the inbound OI approach in this context. We provide empirical evidence of the moderating role of these partners and build a theoretical framework that connects to the middle-range theory on inbound OI in this relationship, which has implications for theory and practice.

2.7.1. Implications for theory

We empirically demonstrate that the integration of Industry 4.0 technologies is a key factor for the competitive advantage of technology providers and that technology complementors can support the provision of such Industry 4.0 technologies integrated into market solutions. We also showed the effects of other supply chain actors in these relationships. First, we chose inbound OI as a theoretical lens to explain the mechanisms behind the investigated relationships. Second, we showed that technology complementors have a specific-purpose inbound OI strategy to exploit digital solutions by providing more integrative Industry 4.0 solutions. Lastly, we explained that this advantage is created by horizontal technology collaboration (codesign) and technology sourcing (outsourcing). In this sense, our results support the view of ecosystems or supply chain networks rather than linear supply chain relationships for technology provision in the complex Industry 4.0 domain. We also showed that R&D centers and Customers play a general-purpose inbound OI role by supporting the exploration of technology sourcing (e.g., basic research) and technology scouting (technology forecast based on future customer needs) for long-term exploratory purposes, helping to foster innovation and customer loyalty, respectively. We also showed the limits of collaboration and potential negative effects that some of these partners can have on the technology integration and provision activity. We compiled this in a theoretical framework that summarizes the inbound OI mechanisms providing a new theoretical perspective on Industry 4.0 and supply chain for technology provision. Thus, our findings complement extant literature that is mostly focused on the adoption of Industry 4.0 technologies, neglecting the technology-provision side (e.g., Osterrieder et al., 2019; Oztemel and Gursev, 2020). We argue that technology providers are an essential actor to unlock the full potential of Industry 4.0, supporting the transition of technology adopters from a disconnected utilization of technologies towards integrated solutions, as required by Industry 4.0 (Benitez et al., 2020).

2.7.2. Implications for practice

Managers can get several takeaways from our study. First, SMEs should seek to expand their range of Industry 4.0 technologies and pursue their integration into advanced solutions, which will help them increase customer loyalty and technology innovation. Second, aware that this may be hard for SMEs, our study demonstrates that the best way to achieve this is by collaborating with other SMEs from the same sector that possesses complementary technologies and capabilities. Thus, technology providers should work in supply chain networks for Industry 4.0 provision. This will also help them reduce technology costs besides addressing customer loyalty and technology innovation needs. Third, although Industry 4.0 solutions require customer involvement in the business-to-business market, SMEs should be judicious in the means of involving them. A highly customized solution achieved through intensive collaboration with customers will damage the cost reduction capacity of such companies. Thus, based on our findings, we recommend that managers pursue complementarity and modularity of Industry 4.0 solutions so that they can be configured based on different needs without requiring too many potentially costly changes. Lastly, our results show that technology providers should collaborate with R&D centers, but not with the intention of reducing technology costs through outsourcing (in fact, this would negatively impact costs reduction due to the risky and costly projects that these centers develop with companies). They should rather pursue such a collaboration as a strategy for knowledge acquisition for future technology innovation in the Industry 4.0 trend.

2.7.3. Limitations and future research

This research has some limitations that offer opportunities for future research. Firstly, our work considers a sample from a specific industrial cluster, with its unique characteristics. The industrial cluster of technology providers is composed of SMEs. If we considered a scenario with larger companies, with more resources available, the results might differ. Thus, future studies should also expand the testing of our hypotheses to larger companies in the global Industry 4.0 market. Moreover, our survey was conducted in an emerging country. This context can bear a strong influence on the way companies collaborate, especially when pursuing technology cost reductions while several components are imported and, therefore, much more expensive. Besides, our scope of analysis was limited to supply chain actors, while other tangential actors – such as government, university, and society –, which may be important for a sustainable Industry 4.0 development, were not included. Hence, future studies could consider this wider perspective to analyze how other actors can support the development and provision of Industry 4.0 solutions.

References

Addo-Tenkorang, R. and Helo, P.T. (2016), “Big data applications in operations/supply-chain management: A literature review”, *Computers and Industrial Engineering*, Vol. 101, pp. 528–543.

Ahn, J.M., Lee, W. and Mortara, L. (2020), “Do government R&D subsidies stimulate collaboration initiatives in private firms?”, *Technological Forecasting and Social Change*, Vol. 151, in press.

Albaum, G., Best, R., & Hawkins, D. (1977). The measurement properties of semantic scale data. *Journal of the Market Research Society*.

Albors-Garrigós, J., Rincon-Diaz, C.A. and Igartua-Lopez, J.I. (2014), “Research technology organisations as leaders of R&D collaboration with SMEs: role, barriers and facilitators”, *Technology Analysis and Strategic Management*, Vol. 26 No. 1, pp. 37–53.

Almada-Lobo, F. (2016), “The Industry 4.0 revolution and the future of Manufacturing Execution Systems (MES)”, *Journal of Innovation Management*, Vol. 3 No. 4, pp. 16–21.

Aryal, A., Liao, Y., Nattuthurai, P., & Li, B. (2018). “The emerging big data analytics and IoT in supply chain management: a systematic review”, Supply Chain Management: *An International Journal*, Vol. 25 No. 2, pp. 141–156.

Ayala, N.F., Gerstlberger, W. and Frank, A.G. (2019), “Managing servitization in product companies: the moderating role of service suppliers”, *International Journal of Operations & Production Management*, Vol. 39 No. 1, pp. 43–74.

Ayala, N. F., Le Dain, M. A., Merminod, V., Gzara, L., Enrique, D. V. and Frank, A. G. (2020), "The contribution of IT-leveraging capability for collaborative product development with suppliers", *The Journal of Strategic Information Systems*, Vol. 29 No. 3, 101633.

Ayala, N.F., Paslauski, C.A., Ghezzi, A. and Frank, A.G. (2017), "Knowledge sharing dynamics in service suppliers' involvement for servitization of manufacturing companies", *International Journal of Production Economics*, Vol. 193, pp. 538–553.

Bag, S., Telukdarie, A., Pretorius, J.H.C. and Gupta, S. (2018), "Industry 4.0 and supply chain sustainability: framework and future research directions", *Benchmarking: An International Journal*.

Barata, J., Rupino Da Cunha, P. and Stal, J. (2018), "Mobile supply chain management in the Industry 4.0 era: An annotated bibliography and guide for future research", *Journal of Enterprise Information Management*, Vol. 31 No. 1, pp. 173–192.

Barratt, M. (2004), "Understanding the meaning of collaboration in the supply chain", *Supply Chain Management: An International Journal*, Vol. 9 No. 1, pp. 30–42.

Bartodziej, C.J. (2016), *The Concept Industry 4.0: An Empirical Analysis of Technologies and Applications in Production Logistics*, Springer.

Ben-Daya, M., Hassini, E. and Bahroun, Z. (2019), "Internet of things and supply chain management: a literature review", *International Journal of Production Research*, Vol. 57 No. 15–16, pp. 4719–4742.

Benitez, G.B., Ayala, N.F. and Frank, A.G. (2020), "Industry 4.0 innovation ecosystems: an evolutionary perspective on value cocreation", *International Journal of Production Economics*, Vol. 228, in press.

Birkel, H. S., & Hartmann, E. (2019), "Impact of IoT challenges and risks for SCM", *Supply Chain Management: An International Journal*, Vol. 24 No. 1, pp. 39–61.

Bravo, M.I.R., Ruiz Moreno, A. and Llorens-Montes, F.J. (2016), "Supply network-enabled innovations. An analysis based on dependence and complementarity of capabilities", *Supply Chain Management: An International Journal*, Vol. 21 No. 5, pp. 642–660.

Büyüközkan, G. and Göçer, F. (2018), "Digital Supply Chain: Literature review and a proposed framework for future research", *Computers in Industry*, Vol. 97, pp. 157–177.

Chauhan, C. and Singh, A. (2019), "A review of Industry 4.0 in supply chain management studies", *Journal of Manufacturing Technology Management*, in press.

Chehbi-Gamoura, S., Derrouiche, R., Damand, D. and Barth, M. (2020), "Insights from big Data Analytics in supply chain management: an all-inclusive literature review using the SCOR model", *Production Planning and Control*, Vol. 31 No. 5, pp. 355–382.

Chesbrough, H. (2003), *Open Innovation: The New Imperative for Creating and Profiting from Technology*, Harvard Business Press.

Chesbrough, H., Vanhaverbeke, W. and West, J. (Eds.). (2006), *Open innovation: Researching a new paradigm*, Oxford University Press on Demand.

Chin, W. W., Johnson, N. and Schwarz, A. (2008). A fast form approach to measuring technology acceptance and other constructs. *MIS Quarterly*, 687-703.

CNI - Confederação Nacional da Indústria. (2016), *Industry 4.0: A New Challenge for Brazilian Industry*, available at:

http://www.portaldaindustria.com.br/publicacoes/2016/8/challenges-industry-40-brazil/.

Cusumano, M. and Gawer, A. (2002), “The elements of platform leadership”, *MIT Sloan Management Review*, Vol. 43 No. 3, pp. 51-58.

da Costa, M.B., Dos Santos, L.M.A.L., Schaefer, J.L., Baierle, I.C. and Nara, E.O.B. (2019), "Industry 4.0 technologies basic network identification", Scientometrics, Vol. 121 No. 2, pp. 977-994.

da Silva, V.L., Kovaleski, J.L. and Pagani, R.N. (2019), “Technology transfer in the supply chain oriented to industry 4.0: a literature review”, *Technology Analysis and Strategic Management*, Vol. 31 No. 5, pp. 546–562.

Dalenogare, L.S., Benitez, G.B., Ayala, N.F. and Frank, A.G. (2018), “The expected contribution of Industry 4.0 technologies for industrial performance”, *International Journal of Production Economics*, Vol. 204, pp. 383–394.

Dallasega, P., Rauch, E. and Linder, C. (2018), “Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review”, *Computers in Industry*, Vol. 99, pp. 205–225.

Dos Santos, L.M.A.L., da Costa, M.B., Kothe, J.V., Benitez, G.B., Schaefer, J.L., Baierle, I.C. and Nara, E.O.B. (2020), "Industry 4.0 collaborative networks for industrial performance", *Journal of Manufacturing Technology Management*, ahead-of-print.

Enkel, E., Gassmann, O. and Chesbrough, H. (2009), “Open R&D and open innovation: exploring the phenomenon”, *R&D Management*, Vol. 39 No. 4, pp. 311–316.

Flynn, B. B., Sakakibara, S., Schroeder, R. G., Bates, K. A., & Flynn, E. J. (1990). Empirical research methods in operations management. *Journal of operations management*, *9*(2), 250-284.

Fowler Jr, F. J. (2013), *Survey research methods*, Sage publications.

Frank, A.G., Cortimiglia, M.N., Ribeiro, J.L.D. and Oliveira, L.S. de. (2016), “The effect of innovation activities on innovation outputs in the Brazilian industry: Market-orientation vs. technology-acquisition strategies”, *Research Policy*, Vol. 45 No. 3, pp. 577–592.

Frank, A.G., Dalenogare, L.S. and Ayala, N.F. (2019a), “Industry 4.0 technologies: implementation patterns in manufacturing companies”, *International Journal of Production Economics*, Vol. 210, pp. 15–26.

Frank, A.G., Benitez, G.B., Ferreira Lima, M.J.R and Bernardi, J.A.B. (2021), “Effects of Open Innovation breadth on industrial innovation input-output relationships”, *European Journal of Innovation Management*, in press.

Frank, A.G., Mendes, G.H.S., Ayala, N.F. and Ghezzi, A. (2019b), “Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective”, *Technological Forecasting and Social Change*, North-Holland, Vol. 141, pp. 341–351.

Frederico, G.F., Garza-Reyes, J.A., Anosike, A. and Kumar, V. (2019), “Supply Chain 4.0: concepts, maturity and research agenda”, *Supply Chain Management: An International Journal*, in press.

Garrett, B. (2014), “3D Printing: New Economic Paradigms and Strategic Shifts”, *Global Policy*, Vol. 5 No. 1, pp. 70–75.

Gawer, A. and Cusumano, M.A. (2014), “Industry Platforms and Ecosystem Innovation”, *Journal of Product Innovation Management*, Vol. 31 No. 3, pp. 417–433.

Ghobakhloo, M. (2018), “The future of manufacturing industry: a strategic roadmap toward Industry 4.0”, *Journal of Manufacturing Technology Management*, Vol. 29 No. 6, pp. 910–936.

Gilchrist, A. (2016), *Industry 4.0: The Industrial Internet of Things*, Apress, Berkeley.

Goldsby, T.J., Michael Knemeyer, A., Miller, J.W. and Wallenburg, C.M. (2013), “Measurement and moderation: Finding the boundary conditions in logistics and supply chain research”, *Journal of Business Logistics*, Vol. 34 No. 2, pp. 109–116.

Guide, V.D.R. and Ketokivi, M. (2015), “Notes from the Editors: Redefining some methodological criteria for the journal”, *Journal of Operations Management*, Vol. 37 No. 1, pp. v–viii.

Hair, J.F., Black, W.C., Babin, B.J. and Anderson, R.E. (2009), *Multivariate Data Analysis: A Global Perspective*, Upper Saddle River: Prentice Hall.

Hossain, M. and Kauranen, I. (2016), “Open innovation in SMEs: a systematic literature review”, *Journal of Strategy and management*, Vol. No. 1, pp. 58-73.

Hozdić, E. (2015), “Smart factory for industry 4.0: A review”, *International Journal of Modern Manufacturing Technologies*, Vol. 7 No. 1, pp. 28-35.

IBGE - Instituto Brasileiro de Geografia e Estatística. (2015), “Demografia das Empresas | IBGE”, available at: https://www.ibge.gov.br/estatisticas/economicas/industria/9068-demografia-das-empresas.html?=&t=o-que-e.

IBGE - Instituto Brasileiro de Geografia e Estatística. (2016), *Pesquisa Industrial de Inovação Tecnológica (PINTEC, 2014 Report).*

Jeschke, S., Brecher, C., Meisen, T., Özdemir, D. and Eschert, T. (2017), *Industrial Internet of Things and Cyber Manufacturing Systems*, Springer.

Kagermann, H., Wahlster, W. and Helbig, J. (2013), *Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0, Final Report of the Industrie 4.0 Working Group. Forschungsunion*.

Kahle, J.H., Marcon, É., Ghezzi, A. and Frank, A.G. (2020), “Smart Products value creation in SMEs innovation ecosystems”, *Technological Forecasting and Social Change*, Vol. 156, in press.

Laursen, K. and Salter, A. (2006), “Open for innovation: the role of openness in explaining innovation performance among U.K. manufacturing firms”, *Strategic Management Journal*, Vol. 27 No. 2, pp. 131–150.

Lejeune, M.A. and Yakova, N. (2005), “On characterizing the 4 C’s in supply chain management”, *Journal of Operations Management*, Vol. 23 No. 1, pp. 81–100.

Liboni, L.B., Cezarino, L.O., Jabbour, C.J.C., Oliveira, B.G. and Stefanelli, N.O. (2019), “Smart industry and the pathways to HRM 4.0: implications for SCM”, *Supply Chain Management: An International Journal*, Vol. 24 No. 1, pp. 124–146.

Love, J. H., Roper, S. and Bryson, J. R. (2011), "Openness, knowledge, innovation and growth in UK business services", *Research Policy*, Vol. 40 No. 10, pp. 1438-1452.

Manavalan, E. and Jayakrishna, K. (2019), “A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements”, *Computers and Industrial Engineering*, Vol. 127, pp. 925–953.

Mankins, J.C. (2009), “Technology readiness assessments: A retrospective”, *Acta Astronautica*, Vol. 65 No. 9–10, pp. 1216–1223.

Marodin, G.A., Frank, A.G., Tortorella, G.L. and Fetterman, D.C. (2019), “Lean production and operational performance in the Brazilian automotive supply chain”, *Total Quality Management & Business Excellence*, Vol. 30 No. 3-4, pp. 370-385.

Mittal, S., Khan, M.A., Romero, D. and Wuest, T. (2018), “A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs)”, *Journal of Manufacturing Systems*, Vol. 49, pp. 194–214.

Müller, J.M., Buliga, O. and Voigt, K.-I. (2018), “Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0”, *Technological Forecasting and Social Change*, Vol. 132, pp. 2–17.

Nakayama, R. S., de Mesquita Spínola, M. and Silva, J. R. (2020), “Towards I4. 0: a comprehensive analysis of evolution from I3.0”, *Computers & Industrial Engineering*, 106453.

Nguyen, T., ZHOU, L., Spiegler, V., Ieromonachou, P. and Lin, Y. (2018), “Big data analytics in supply chain management: A state-of-the-art literature review”, *Computers and Operations Research*, Vol. 98, pp. 254–264.

Noonan, J. and Wallace, M. (2003), “Complementers: Fellow travellers in contract manufacture”, *Supply Chain Management: An International Journal*, Vol. 8 No. 1, pp. 26–31.

Novais, L., Maqueira, J.M. and Ortiz-Bas, Á. (2019), “A systematic literature review of cloud computing use in supply chain integration”, *Computers and Industrial Engineering*, Vol. 129, pp. 296–314.

Nunnally, J. C., & Bernstein, I. H. (1994). Psychometric theory 3rd edn. New York [etc].: *McGraw-Hill.*

Obal, M. and Lancioni, R.A. (2013), “Maximizing buyer-supplier relationships in the Digital Era: Concept and research agenda”, *Industrial Marketing Management*, Vol. 42 No. 6, pp. 851-854.

Osterrieder, P., Budde, L. and Friedli, T. (2019), “The smart factory as a key construct of industry 4.0: A systematic literature review”, *International Journal of Production Economics*, in press.

Oztemel, E. and Gursev, S. (2020), “Literature review of Industry 4.0 and related technologies”, *Journal of Intelligent Manufacturing*, Vol. 31 No. 1, pp. 127-182.

Parida, V., Westerberg, M. and Frishammar, J. (2012), “Inbound open innovation activities in high-tech SMEs: the impact on innovation performance”, *Journal of small business management*, Vol. 50 No. 2, pp. 283-309.

Phaal, R., O'Sullivan, E., Routley, M., Ford, S. and Probert, D. (2011), “A framework for mapping industrial emergence”, *Technological Forecasting and Social Change*, Vol. 78 No. 2, pp. 217-230.

Podsakoff, P.M., MacKenzie, S.B. and Podsakoff, N.P. (2012), “Sources of method bias in social science research and recommendations on how to control it.”, *Annual Review of Psychology*, Vol. 63, pp. 539–569.

Porter, M.E. (1980), *Competitive Strategy: Techniques for Analyzing Industries and Competitors*, New York: Free Press.

PWC - PricewaterhouseCoopers, Geissbauer, R., Vedso, J. and Schrauf, S. (2016), *Indústria 4.0: Digitização Como Vantagem Competitiva No Brasil*, Pricewaterhouse Coopers Brasil Ltda., available at: https://www.pwc.com.br/pt/publicacoes/servicos/assets/consultoria-negocios/2016/pwc-industry-4-survey-16.pdf.

Reischauer, G. (2018), “Industry 4.0 as policy-driven discourse to institutionalize innovation systems in manufacturing”, *Technological Forecasting and Social Change*, North-Holland, Vol. 132, pp. 26–33.

Rencher, A. C. (2003), *Methods of multivariate analysis, 2nd edn* New York. NY: John Wiley & Sons.

Reynolds, E.B. and Uygun, Y. (2018), “Strengthening advanced manufacturing innovation ecosystems: The case of Massachusetts”, *Technological Forecasting and Social Change*, Vol. 136, pp. 178–191.

Roh, J., Hong, P., & Min, H. (2014), "Implementation of a responsive supply chain strategy in global complexity: The case of manufacturing firms", *International Journal of Production Economics*, Vol. 147 No. PART B, pp. 198–210.

Rong, K., Hu, G., Lin, Y., Shi, Y. and Guo, L. (2015), "Understanding business ecosystem using a 6C framework in Internet-of-Things-based sectors", *International Journal of Production Economics*, Vol. 159, pp. 41–55.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P. and Harnisch, M. (2015), *Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries*, *Boston Consulting Group*, available at: http://www.inovasyon.org/pdf/bcg.perspectives_Industry.4.0_2015.pdf.

Saary, M.J. (2008), "Radar plots: a useful way for presenting multivariate health care data", *Journal of clinical epidemiology*, Vol. 61 No. 4, pp. 311-317.

Stank, T. P., Pellathy, D. A., In, J., Mollenkopf, D. A. and Bell, J. E. (2017), "New frontiers in logistics research: theorizing at the middle range", *Journal of Business Logistics*, Vol. 38 No. 1, pp. 6-17.

Schneider, P. (2018), "Managerial challenges of Industry 4.0: an empirically backed research agenda for a nascent field", *Review of Managerial Science*, Vol. 12 No. 3, pp. 803–848.

Schwab, D. P. (1980). Construct validity in organizational behavior. *Res Organ Behav, 2*, 3-43.

Schniederjans, D.G., Curado, C. and Khalajhedayati, M. (2020), "Supply chain digitisation trends: An integration of knowledge management", *International Journal of Production Economics*, Vol. 220.

Schumacher, A., Erol, S. and Sihn, W. (2016), "A maturity model for assessing industry 4.0 readiness and maturity of manufacturing enterprises", *Procedia CIRP*, Vol. 52, pp. 161–166.

Tao, F., Qi, Q., Liu, A. and Kusiak, A. (2018), "Data-driven smart manufacturing", *Journal of Manufacturing Systems*, Vol. 48, pp. 157–169.

Thadewald, T. and Büning, H. (2007), "Jarque–Bera test and its competitors for testing normality–a power comparison", *Journal of applied statistics*, Vol. 34 No. 1, pp. 87-105.

Tu, M., Lim, M.K. and Yang, M.F. (2018a), "IoT-based production logistics and supply chain system – part 1 modeling IoT-based manufacturing IoT supply chain", *Industrial Management and Data Systems*, Vol. 118 No. 1, pp. 65–95.

Tu, M., Lim, M.K. and Yang, M.F. (2018b), "IoT-based production logistics and supply chain system – part 2 IoT-based cyber-physical system: A framework and evaluation", *Industrial Management and Data Systems*, Vol. 118 No. 1, pp. 96–125.

Van de Vrande, V., De Jong, J. P., Vanhaverbeke, W. and De Rochemont, M. (2009), "Open innovation in SMEs: Trends, motives and management challenges", *Technovation*, Vol. 29 No. 6-7, pp. 423-437.

Van Wyk, R. J. (1997), "Strategic technology scanning", *Technological Forecasting and Social Change*, Vol. 55 No. 1, pp. 21-38.

Wang, C. H., Chang, C. H. and Shen, G. C. (2015), "The effect of inbound open innovation on firm performance: Evidence from high-tech industry", *Technological Forecasting and Social Change*, Vol. 99, pp. 222-230.

Wang, Y., Ma, H.S., Yang, J.H. and Wang, K.S. (2017), "Industry 4.0: a way from mass customization to mass personalization production", *Advances in Manufacturing*, Shanghai University, Vol. 5 No. 4, pp. 311–320.

Weking, J., Stöcker, M., Kowalkiewicz, M., Böhm, M. and Krcmar, H. (2020), "Leveraging industry 4.0 – A business model pattern framework", *International Journal of Production Economics*, in press.

Weller, C., Kleer, R. and Piller, F.T. (2015), "Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited", *International Journal of Production Economics*, Vol. 164, pp. 43–56.

Winkelhaus, S. and Grosse, E.H. (2020), "Logistics 4.0: a systematic review towards a new logistics system", *International Journal of Production Research*, Vol. 58 No. 1, pp. 18–43.

Wold, S., Esbensen, K. and Geladi, P. (1987), "Principal component analysis" *Chemometrics and intelligent laboratory systems*, Vol. 2 No. 1-3, pp. 37-52.

Yin, Y., Stecke, K.E. and Li, D. (2018), "The evolution of production systems from Industry 2.0 through Industry 4.0", *International Journal of Production Research*, Vol. 56 No. 1–2, pp. 848–861.

Zhong, R. Y., Newman, S. T., Huang, G. Q. and Lan, S. (2016), "Big Data for supply chain management in the service and manufacturing sectors: Challenges, opportunities, and future perspectives", *Computers & Industrial Engineering*, Vol. 101, pp. 572-591.

Appendix A – Literature review on Supply Chain and Industry 4.0

Literature research was carried out to identify the state of the art of the relationship between Supply Chain and Industry 4.0. Since the literature on these broad topics is vast, we first focused our analysis on articles that had already conducted literature reviews. To do so, we searched the Web of Science, Science Direct, Scopus, and Emerald databases only for InCites Journal Citation Reports (JCR) high-quality journals. We searched by using the following topics: "supply chain" AND "literature review" AND Industry 4.0 related terms ("Industry 4.0", "smart manufacturing", "advanced manufacturing" OR "digitization"). As search filters, we imposed the following: (i) Publication years: 2011-2020 (the term Industry 4.0 was introduced in 2011); (ii) Publication type: Articles; and (iii) Subject areas: all (any research field approaching the terms). We obtained 17 literature review articles addressing the relationship between Industry 4.0 and the supply chain (Table A-1). We performed a second literature review, specifically on technology development in this context. Following the same database criteria, we searched the following topics: "supply chain" AND "technology development" AND "open innovation" AND "Industry 4.0" OR "advanced manufacturing" OR "smart manufacturing" OR "digitization". As search filters, we imposed the following: (i) publication years: 2011-2020; (ii) publication type: articles; and (iii) subject areas: all. As a result, we found six articles related to the topic, as presented in Table A-2.

Table A-1 – Literature review articles on Industry 4.0 and Supply Chain

Author	Study focus	Key findings	Research gaps identified
Addo-Tenkorang and Helo (2016)	A literature review to investigate big data and its applications in operations and SCM	Big data 4V's (variety, velocity, volume, and veracity) expanded to 5V's (value-adding) when acting in SCM	How do RFID's application in IoT and its impact on the efficient management of big data applications in operations/SC management happen?
Zhong et al. (2016)	A literature review of big data applications in the service and manufacturing sectors for SCM	The paper discusses challenges, opportunities, and future perspectives on SCM by analyzing six aspects concerning big data: data collection methods; data transmission; data storage; processing technologies; decision-making models; and interpretation and applications	The study is limited to the discussion of big data features and applications on SCM, lacking a better explanation of technology integration for SCM in the Industry 4.0
Aryal et al. (2018)	A literature review to understand the implementation of big data analytics and IoT in SCM	Identifies how big data and IoT studies in SCM evolved in the 2010-2013 and 2014-2017 periods. Big data evolved from customer satisfaction and services to analytics and data management, while IoT moved from general supply chain and business information management to a more specific context, including supply chain design, model, and performance	Lack of studies showing a comprehensive understanding of the relationship between SCM and disruptive technologies
Barata et al. (2018)	A literature review to identify avenues for future research in mobile supply chain management (mSCM) in the Industry 4.0 context	Identifies indoor and outdoor use of technologies in mSCM Identifies managerial aspects in mSCM lifecycle: adoption, coordination, integration, and dissemination of technologies	Need for methods to guide the application of mobile technologies in mSCM Lack of mSCM cases
Bag et al. (2018)	A literature review to identify Industry 4.0 enablers of supply chain sustainability	Identifies 13 key enablers of Industry 4.0 playing an important role in driving supply chain sustainability	Collaboration with customers and suppliers through these 13 key enablers requires further investigation
Büyüközkan and Göçer (2018)	A literature review about the state of the art of existing Digital Supply Chains (DSC)	The framework proposes three main steps focused on digitalization, technology implementation, and SCM for DSC	Lack of development frameworks that guide DSC adoption Lack of tools and technologies that address supply chain problems in a DSC environment

Author	Study focus	Key findings	Research gaps identified
Nguyen et al. (2018)	A literature review about the application of Big Data Analytics (BDA) in SCM	A general overview of five main areas in which BDA have been applied in SCM: Procurement, Manufacturing, Logistics/transportation, Warehousing, and Demand management	1 - How various stakeholders contribute to adding the value of big data (BD) in the supply chain (SC)? 2 - What is the dynamic impact of new business models on SC performance through emerging technologies such as BD? 3 - What are the tipping points that transfer a conventional business model to a BD-driven business model?
Ben-Daya et al. (2019)	A literature review about the role of IoT and its impact on SCM	Shows that most studies have focused on conceptualizing the impact of IoT with limited analytical models and empirical studies on the delivery supply chain process in food and manufacturing supply chains	1 - Lack of solid frameworks that provide guidance for IoT adoption in a supply chain 2 - Lack of models that address supply chain problems in an IoT environment 3 - How to implement IoT technologies in SCM from both technological and managerial perspectives?
Chauhan and Singh (2019)	A literature review to assess how Industry 4.0 is considered in the context of SCM	Identifies key topics related to logistics and manufacturing regarding the conceptualization, implementation, digitalization, performance measurement, drivers and barriers of Industry 4.0 in SCM	1 - How to measure digital supply chain performance? 2 - Lack of models to assess economic viability 3 - How to assess quality management in the digital supply chain?
Birkel and Hartmann (2019)	A literature review to provide a comprehensive overview of the challenges and risks of the IoT in SCM	The framework shows that to adopt IoT systems for SCM, technological, organizational, and network-related issues should be considered to have an impact on environmental, economic, social, and political aspects inside supply chains	1 - How to develop trust for IoT projects regarding end customers, business partners, or organizations? 2 - How to assess the main risks and challenges for technology implementation in supply chains? 3 - How to offer solutions in the Industry 4.0 context?
Novais et al. (2019)	A literature review to analyze the current state of research into Cloud Computing (CC) and Supply Chain Integration (SCI)	CC can advance the development of the supply chain through effective supply chain flow integration, providing support to other forms of integration (process, technology, and partner)	1 - How to integrate manufacturing, logistics, design, financial and marketing processes, and activities through CC? 2 - How to use CC for technology and system integration, i.e., how to use CC to integrate other internal technologies? 3 - How to manage and foster collaboration between SC partners through the use of CC?

Author	Study focus	Key findings	Research gaps identified
Frederico et al. (2019)	A literature review that conceptualizes Industry 4.0 in the supply chain context	The authors present two frameworks, (i) a conceptual one, with four constructs: managerial and capability supporters, technology levers, processes performance requirements, and strategic outcomes related to Industry 4.0; and (ii) a framework using these four constructs at four maturity levels: initial, intermediate, advanced and cutting-edge	Several research questions related to the four constructs presented in the conceptual framework (e.g., what are the impacts of disruptive technologies of Supply Chain 4.0 on collaboration and transparency along the supply chain?)
Manavalan and Jayakrishna (2019)	A literature review to explore the potential opportunities available in IoT embedded sustainable supply chain for Industry 4.0 transformation	The framework presents five important perspectives of supply chain management, namely Business, Technology, Sustainable Development, Collaboration, and Management Strategy in the Industry 4.0 context	How can IoT and Industry 4.0 technologies be implemented in sustainable supply chains to achieve better results in these contexts?
Winkelhaus and Grosse (2019)	A literature review about logistics practices in the Industry 4.0 context	The framework presents six key aspects in Logistics 4.0: technology, external changes, human factors, tasks, domains, and objectives from Industry 4.0	1 - What are the influences of external environments in SCM? 2 - How to adopt Industry 4.0 technologies for Logistics 4.0? 3 - Need for investigation of emerging organizational structures within Logistics 4.0 systems
Schniederjans et al. (2020)	A literature review to leverage knowledge management in supply chain digitization	The framework highlights the supply chain digital optimization contribution to organizational digital performance and benefits through knowledge management	1 - How Industry 4.0 technologies may address large-scale problems and facilitate supply chain performance through knowledge management capabilities? 2 - How knowledge management fosters a greater understanding of the industry, technology, and management roles in supply chain digitization?
Oztemel and Gursev (2020)	A literature review to define the concept of Industry 4.0	As a key result, the paper defines Industry 4.0 in six design principles, namely interoperability, virtualization, local, real-time talent, service orientation, and modularity, providing rich discussions on each principle and giving examples of project implementation	The paper does not focus on SCM. It only presents studies that mentioned the relationship between SCM and Industry 4.0, lacking a clear focus on this matter
Chehbi-Gamoura et al. (2020)	A literature review that addresses BDA (Big Data Analytics) methods in SCM	All BDA applications (e.g., EFA, QDA, EDA) for SCM were revised, and the authors highlight the need for collaboration among stakeholders in the task of extracting business data through BDA	How can collaboration between supply chain partners and stakeholders extract valuable data using BDA techniques for better results in SCM?

Table A-2 – Literature review about Open Innovation for technology development in Industry 4.0 and Supply Chain

Author	Study focus	Key findings	Research gaps identified
Roh et al. (2014)	A regression analysis to identify the key variables relevant to the implementation of a successful responsive supply chain through advanced manufacturing technologies	A key result of this paper is showing that the effective implementation of a responsive supply chain strategy involves the integration of collaboration with suppliers and advanced manufacturing technologies	Collaboration is not measured for technology development inside the supply chain. It also does not measure collaboration with customers, competitors, and other organizations.
Schneider (2018)	A systematic literature review on the managerial challenges of Industry 4.0 and a survey.	18 managerial challenges of Industry 4.0 falling into six interrelated clusters: (1) strategy and analysis, (2) planning and implementation, (3) cooperation and networks, (4) business models, (5) human resources and (6) change and leadership.	In the context of Industry 4.0, the importance of cooperation and networks is particularly emphasized. However, managers lack knowledge about suitable cooperation partners and providers.
Mittal et al. (2018)	A literature review about Smart Manufacturing (SM) and Industry 4.0 maturity models	As a major result, a “level 0″ specifically designed to reflect the ‘real - base level’ for SMEs is proposed in the roadmap. Collaboration in SMEs supply chain and open innovation culture are discussed by analyzing the lack of flexibility of SMEs in adopting cutting-edge technologies to support partnerships	Extant models have not provided any suggestions on how to pursue a healthy collaboration network for SME’s technology development

Author	Study focus	Key findings	Research gaps identified
da Silva et al. (2019)	A literature review about technology transfer in the Industry 4.0 context inside supply chains	A framework illustrating the main Industry 4.0 technologies and barriers for the technology transfer process in the supply chain	How technology transfer occurs in supply chain relationships (supplier - manufacturing enterprise and manufacturing enterprise - customer)?
Weking et al. (2020)	Investigates Business models patterns in the Industry 4.0 context	Three super-patterns are identified: integration, servitization, and expertization, with Open Innovation being part of the integration super-pattern. The Open Innovation approach is discussed as an integrator of the supply chain, focusing on the role of customer participation in the product development process	Open Innovation and collaboration are poorly discussed in this paper, showing only the need for customer integration in the supply chain for technology development, not explaining how to perform it.
Benitez et al. (2020)	Investigates how innovation ecosystems in the Industry 4.0 context can consolidate and evolve using the social exchange theory (SET), and how value is cocreated for technology and product development within them	The authors explain that, in the birth stage, companies are oriented toward a linear supply chain model in which each Industry 4.0 technology was seen as a unit to be exchanged with other companies for technology development. Then, they propose two frameworks, one explaining the shifts in SET elements during the evolutionary lifecycle stages, and another about the governance structure in each lifecycle stage, showing the shifts from supply chain to ecosystem approaches	Although the paper covers collaboration through open innovation approaches for technology development, it focuses mainly on ecosystems. Moreover, only competitors and research organizations have a strong analysis. lacking a deeper understanding of customers and suppliers for supply chain collaboration.

Appendix B – Questionnaire applied for the research

Industry 4.0 questionnaire

1) Company____
2) Contact/E-mail____
3) Nº of employees______________________________________
4) Occupation ____
5) Industrial sectors attended by your company:

Agriculture	( )	Petrochemical	( )
Biotechnology	( )	Pharmaceutical	( )
Chemicals	( )	Pulp and paper	( )
Electro-electronic	( )	Software and technology	( )
Energy	( )	Steelworks	( )
Food and beverage	( )	Tobacco	( )
Furniture	( )	Transport	( )
Leather and related products	( )	Other	( )
Metal products	( )		

6) Regarding the technologies related to classic automation and Industry 4.0, answer about your company:
Offering level (from 1 to 5): *1 - Very low or no presence in the company's portfolio / 5 - Highly developed in the company's portfolio*

Classic automation activities	
PLCs (Programmable Logic Controllers) programming and installation	( )
CNC (Computer Numeric Control) programming and installation	( )
Designing and manufacturing of mechanical systems	( )
Design and installation of pneumatic systems	( )
Design and installation of power drive systems (servomotors)	( )
Electrical assembling	( )
Mechanical assembling	( )

Industry 4.0	
Sensors, actuators, and transductors	( )
Supervisory Control and Data Acquisition (SCADA)	( )
Big data analytics	( )
Manufacturing Execution Systems (MES)	( )
Machine-to-machine communication (M2M)	( )
Process traceability	( )
Virtual commissioning	( )
Digital manufacturing	( )
Augmented and virtual reality	( )
Additive manufacturing	( )
Machine vision	( )
Industrial robots (Industrial automation)	( )
Collaborative robots (Man-machine)	( )
Energy efficiency monitoring system	( )
Energy efficiency improving system	( )

7) Please indicate how relevant each of the following supply chain actors is for your company to collaborate with in the development of Industry 4.0 offers:
Level of relevance (from 1 to 5): 1 - Irrelevant / 5 - Extremely relevant

Customers	( )
Suppliers	( )
Competitors with complementary technologies	( )
R&D centers	( )

8) Regarding companies' performance metrics (benefits) associated with Industry 4.0:
Level of expected results (from 1 to 5)
1 – Very low or no results *5 – Excellent results*

Cost reduction	( )
Customer loyalty	( )
Technology innovation	( )

3 PAPER 2 – Industry 4.0 innovation ecosystems: An evolutionary perspective on value cocreation

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Abstract

Industry 4.0 considers complex interrelated IoT-based technologies for the provision of digital solutions. Such a complexity demands a vast set of capabilities that are hard to be found in a single technology provider, especially for small and medium-sized enterprises (SMEs). Innovation ecosystems allow SMEs to integrate resources and cocreate Industry 4.0 solutions. We aim to understand how such ecosystems can consolidate and evolve, and how value is cocreated within them. We adopt a social exchange perspective to consider the relationships in the ecosystem across six structural dimensions and three lifecycle stages. We analyze eleven years of an ecosystem's evolution using a technology mapping of 87 companies, 37 interviews with stakeholders, and a 2.5-year follow-up of a testbed project conducted by 8 companies. Our final framework shows that the ecosystem's mission shifted from accessing innovation funds to Industry 4.0 solution cocreation and, then, to smart business solutions cocreation. As trust and commitment grew, the power structure shifted from the centrality of business association toward a mechanism of neutral coordination of complex projects involving the university and business associations and, lastly, to a platform-driven ecosystem structure, where key technologies emerged as drivers of relationships among the companies and value cocreation. We also show the changes of reciprocity between actors, as well as in value exchange and expected rewards from the social exchange. Managers can learn how to establish technology development strategies in Industry 4.0 ecosystems, while policymakers can learn how to organize the evolution of such ecosystems.

Keywords: Industry 4.0; innovation ecosystem; technology providers; SMEs.

3.1 Introduction

Industry 4.0 has been proposed as a new industrial maturity stage based on the connectivity provided by the industrial Internet of Things (IoT) and the use of several digital technologies such as cloud computing, big data and artificial intelligence (Dalenogare et al., 2018; Frank et al., 2019a, 2019b). These technologies allow the connection of objects such as products and equipment to form the so-called Cyber-Physical Systems (CPS) (Lu, 2017; Wang et al., 2015) and to enable new technology applications such as additive manufacturing, adaptive robotics, and flexible machines (Dalenogare et al., 2018; Frank et al., 2019a, 2019b).

Before the advent of Industry 4.0, technology providers had mostly worked in a dyadic relationship for the development of their solutions in the supply chain (Marodin et al., 2017, 2018), while technology implementation was based on the exchange of units (Lusch and Vargo, 2014). This means that each actor contributed with specific technology modules to the supply chain, which were developed independently from other technology parts and based mainly on transaction as a mechanism of exchange (Yin et al., 2018; Schiele et al., 2012). However, Industry 4.0 solutions consider a complex system of interconnected digital technologies, information systems and processing technologies that demands high interdependency of competences and technological complementarity (Dalenogare et al., 2018; Reischauer, 2018; Rüßmann et al., 2015). This changes the character of supply-chain relationships from a transaction-based model toward a value cocreation approach (Xu et al., 2018). Because of their distinctive nature, involving interdependency and value cocreation, Industry 4.0 innovation ecosystems have emerged as a more suitable configuration for technology development and provision instead of the linear supply chain approach (Rong et al., 2015). As previously demonstrated by Rong et al. (2015), supply chains in the Industry 4.0 context become very complex, with many players and complex interactions; therefore, the ecosystem perspective is more suitable to analyze this case.

Industry 4.0 innovation ecosystems are especially important for small and medium-sized enterprises (SMEs) due to their limited financial resources to acquire the interdisciplinary knowledge and capabilities required to develop complex solutions independently (Dallasega et al., 2018). However, despite the importance given to Industry 4.0 in the recent years (Liao et al., 2017; Osterrieder et al., 2019), little is known about how to systematize the efforts of SMEs through the promotion of innovation ecosystems for the cocreation of Industry 4.0 solutions. Prior research has predominantly focused on Industry 4.0 technology adopters, i.e., the demand side (e.g., Dalenogare et al., 2018; Frank et al., 2019a), while there is still a gap in the literature referring to the study of technology providers, i.e., the offering side. Recent advances have shown that an ecosystem approach is important in this context and key dimensions supporting these ecosystems have been proposed (Rong et al., 2015). However, the dynamic nature of ecosystem evolution in this context has not yet been addressed. Moreover, since the complexity of Industry 4.0 solutions can be hard to manage with the transactional activities of a classic, linear supply chain (Rong et al., 2015), we propose that a social exchange perspective can be more suitable to explain value cocreation among the actors in this ecosystem (Buhr, 2015; Lusch and Vargo, 2014; Reischauer, 2018). Thus, one question emerges: *How can Industry 4.0 ecosystems consolidate and evolve and how can value be cocreated through the joint development of Industry 4.0 solutions by the companies in the ecosystem?*

To answer this question, we combine the structural view of innovation ecosystems with the social exchange theory to study the case of an Industry 4.0-oriented ecosystem during its 11 years of evolution. We used a longitudinal case study research approach, based on the technology mapping of 87 companies, 37 semi-structured interviews with stakeholders, and a 2.5-year follow-up of a testbed project conducted by 8 companies. As a major contribution of our paper, we provide a framework that helps both policymakers and operations managers. In terms of theory, we stress the key role of using the Social Exchange Theory (SET) as a lens to analyze value cocreation in an Industry 4.0 context. We show how four elements of SET – trust, commitment, reciprocity and power – support interdependency in the ecosystem's structure along its evolution. Our final frameworks show that the ecosystem's mission shifted from accessing R&D sources to Industry 4.0 solution cocreation and, then, to smart business solutions cocreation. As trust and commitment grew, the power structure shifted from the centrality of business association toward a mechanism of neutral coordination of complex projects involving the university and business associations and, lastly, to a platform-driven ecosystem structure, where key technologies emerged as drivers of relationships among the companies and value cocreation. We also show the changes of reciprocity between actors, as well as in value exchange, and expected rewards from the social exchange. Therefore, managers can learn how to establish technology development strategies in Industry 4.0 ecosystems, while policymakers can learn how to organize the evolution of such ecosystems.

The remaining sections of this paper are structured as follows. In Section 3.2, we provide the theoretical background for Industry 4.0 systems, introducing both a structural view of innovation ecosystems and a social exchange view of interaction and value creation within the ecosystem. Section 3.3 introduces the research method, discussing our qualitative approach to study the industrial case. Results are presented in Section 3.4, followed by discussions and conclusions from the findings in Sections 3.5 and 3.6.

3.2 Theoretical background

3.2.1. Innovation ecosystem in the Industry 4.0 context: a structural view

Innovation ecosystems are collaborative networks focused on the cocreation of value (Russell and Smorodinskaya, 2018). Adner (2017, p.40) defines ecosystems as "*the alignment structure of the multilateral set of partners that need to interact in order for a focal value proposition to materialize*". The structural view looks at the micro-level to identify the set of actors that need to interact to cocreate value (Adner, 2017; Lusch and Vargo, 2014). Thus, this view is concerned with the elements of the structure that define an ecosystem and allow it to create value (Adner, 2017; Russell and Smorodinskaya, 2018). The structures of innovation ecosystems can be self-organized or managerially designed with multilayer networks of actors with different attributes to provide a system of innovative products and services (Tsujimoto et al. (2018). These ecosystems can comprise companies with diffuse technological capabilities or be aligned around industry platforms[2] (Gawer and Cusumano, 2014). The attributes of the actors in each ecosystem may vary from technology development to R&D and policy support, comprising the three dimensions of the innovation triple helix (private sector, knowledge sector and government sector) (Frank et al., 2018). Such a variety of actors creates symbiosis and synergistic effects through interaction and support, allowing for the creation of a higher level of value than those without such interconnections (Rong et al., 2015). The innovation ecosystem theory uses an analogy with the biological system to consider two dimensions: the ecosystem lifecycle (Moore, 1993), and the interdependency of structural elements in the business environment (Adner, 2017; Rong et al., 2015). We consider these two dimensions as the pillars of the structural view of ecosystems, as follows.

The first structural aspect is the *innovation ecosystem lifecycle*. According to Moore (1993), the evolution of an innovation ecosystem can be described in four main stages (birth, expansion, leadership and self-renewal or death). The *birth stage* is the stage where actors focus on defining their value proposition (innovation) and how they will collaborate. The second stage, *expansion*, occurs when the ecosystem expands to new levels of competition. In the third stage, *leadership*, ecosystem governance is defined and leading producers must extend control by shaping future directions and investments of key customers and suppliers (Moore, 1993). Finally, the last stage occurs when mature

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[2] We follow Gawer and Cusumano's (2014) definition of industry platforms considering them as technologies that provide the foundation upon which outside firms organized as an ecosystem can develop their own complementary products, technologies, or services.

ecosystems are threatened by the rise of new ecosystems and innovations. There are two potential results of these threats: the ecosystem's *self-renewal* or *death* (Dedehayir et al., 2018; Moore, 1993). As in any other innovation ecosystem, Industry 4.0 innovation ecosystems will also need to deal with lifecycle stages. Prior works such as Reynolds and Uygun (2018) and Dedehayir et al. (2018) have shown how this type of ecosystem needs a regional consolidation process, while many technologies emerge and different economic aspects of the ecosystem tend to consolidate. This has been a key aspect in the success of the German initiative for Industry 4.0 (Kagermann et al., 2013).

The second structural aspect of innovation ecosystems is the *composition of structural elements* necessary to sustain the ecosystem. In this sense, Rong et al. (2015) proposed and studied six main interdependent dimensions that congregate elements of IoT-based business ecosystems, which they called the 6C framework: Context, Configuration, Capability, Cooperation, Construct and Change. The *'Context'* dimension considers the establishment of a coordinated strategy based on the *lifecycle stage* the ecosystem is going through. The ecosystem's mission is defined and drivers and barriers for its constitution are assessed. The *'Cooperation'* dimension considers coordination mechanisms to promote cooperation in an ecosystem and its governance system. The *'Construct'* dimension explains the necessary structure and support infrastructure for an ecosystem. The *'Configuration'* dimension considers the communication pattern with customers and external relationship with other partners or stakeholders. The *'Capability'* dimension reflects the firm's capabilities to organize itself to provide value and foster growth in the ecosystem. Finally, in *'Change'*, Rong et al. (2015) related this dimension to the self-renewal (or death) stage of Moore's (1993) ecosystem lifecycle theory. However, since Industry 4.0 as a concept is still at the early stages of development, we consider in this dimension a firm's ability to change and adapt to the ecosystem's goals in this new industrial scenario. In this sense, we use Teece et al. (1997)'s concept of dynamic capabilities as "*the firm's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments*".

3.2.2. Social Exchange Theory in Industry 4.0 ecosystems

Innovation ecosystems aim to cocreate value between their actors, who interact and exchange value. Therefore, we propose to consider the innovation ecosystem structure and dynamics from the perspective of the Social Exchange Theory (SET), which explains such interactions and value cocreation. SET was defined by Blau (1964) and Emerson

(1976) as an action-reaction system of exchange based on rewarding mechanisms for value exchange. This theory considers direct social interactions between actors. Such interactions are based on trust, reciprocity, and on the expectation of mutual benefits from the voluntary exchanges of value, which generate obligations between the parties involved (Tanskanen et al., 2015). Thus, SET is the counterpoint of transaction costs economics, which is focused on contractual exchanges rather than social interactions (Cropanzano and Mitchell, 2005).

According to Wu et al. (2014), four main elements define interactions in SET: *trust*, *commitment*, *reciprocity*, and *power*. *Trust* is defined as an actor's expectation that other actors, without monitoring or control mechanisms, will perform considering mutual benefit. C*ommitment* implies that actors are committed to making their utmost effort while performing their activities looking at the perpetuity of the relationship. *Reciprocity* means that the actors will maintain their interest on the relationship because it offers fair benefits for both sides. Lastly, *Power* refers to the relative dependence between actors and how this may influence decisions and behaviors (Wu et al., 2014). Considering these four elements, according to SET, interactions between actors consist in voluntary exchanges of value that rely on trust and reciprocity over time (Tanskanen, 2015) and that can generate high-quality relationships (Cropanzano and Mitchell, 2005). The exchange of value generates rewards from the relationship, offering a positive reinforcement for the exchange between the parties (Tanskanen, 2015; Wu et al., 2014).

The exchange of value happens within structures of mutual dependence, while each actor's dependency constitutes a source of power for its partner (Tanskanen, 2015). We propose to use SET as a lens for Industry 4.0 ecosystems because Industry 4.0 solutions are complex systems interconnected through base technologies such as IoT, Cloud, Big Data, Artificial Intelligence (Frank et al., 2019a; Moeuf et al., 2018), and this is only possible if technology providers cocreate solutions. For instance, in a Factory 4.0, sensors from one provider must send data to the Manufacturing Execution System (MES) of a second provider, which must be integrated with the Enterprise Resource Planning (ERP) software of a third provider to return with orders to the collaborative robot of a fourth provider. The more autonomous and intelligent the decision-making is, the more integration is required between the interfaces from different companies. As shown by Frank et al. (2019a), in previous industrial stages, technologies were mostly isolated, while the Industry 4.0 concept focuses on the integration among several technologies to obtain an integrated, intelligent and complex system. This requires knowledge from different domains, such as production management, hardware, software, communication network and data management (Frank et al., 2019a), and a deep interconnection between them that can be only achieved by close integration (Ayala et al., 2017). However, this is a barrier for SMEs, since they cannot afford the whole system integration by themselves and also struggle to establish reciprocal collaboration rules in the supply chain (Piccarozzi et al., 2018; Sommer, 2015). As an alternative, these firms can engage in innovation ecosystems enhanced by social interactions where they can jointly address the required technological capabilities to cocreate Industry 4.0 complex solutions (Müller et al., 2018; Zhong et al., 2017).

Because of the several legally independent actors involved in an Industry 4.0 innovation ecosystem, interaction could hardly be regulated by formal transactions (Russell and Smorodinskaya, 2018). On the contrary, it must be built on social network ties (Tsujimoto et al., 2018). Social Exchange has been recommended to study the relationship between actors in collaborative networks because it is much broader in scope than other theoretical views considering dyadic transactions (Brass et al., 2004; Zhao et al., 2008) and it can include a wide array of tangible and intangible benefits seen as rewards by the actors (Tanskanen, 2015). One of the basic principles of SET is that relationships evolve over time into trust, loyalty, and mutual commitments (Cropanzano and Mitchell, 2005), which may allow firms of the Industry 4.0

3.2.3. Conceptual framework for the empirical research

We aim to build a theory about Industry 4.0 ecosystems based on a deep understanding of the structural elements involved and existing social exchanges. Therefore, a qualitative case study approach is the most suitable research strategy for this goal (Voss et al., 2002; Yin, 2009). A starting point of such an approach is defining a conceptual framework, either graphically or in narrative, that establishes the underlying concepts and categories to be studied and that will guide the data collection and analysis processes (Voss et al., 2002). To that end. we developed the graphical conceptual framework presented in Figure 3.1, which summarizes the main aspects to be considered in the study of innovation ecosystems, according to our theoretical background. The framework is based on the structural view of ecosystems, using the two dimensions proposed in Section 3.2.1: (i) the innovation ecosystem lifecycle and (ii) interdependency of structural elements to sustain the ecosystem. For the ecosystem lifecycle, we use the lifecycle stages proposed by Moore (1993). We explore three stages, Birth, Expansion and Leadership, but not the

Self-renewal stage, since Industry 4.0 is still in its early stages (Frank et al., 2019b). Regarding the structural elements of the ecosystem, we adopted the 6C dimensions of Rong et al. (2015) to define the main elements that we should look at when studying the ecosystem, which provides us a wide range of significant and interrelated aspects in the ecosystem structure.

Based on these two structural pillars of the ecosystem analysis, we aim to understand how the elements of SET (Wu et al., 2014) – trust, commitment, reciprocity and power structure – support the development of an Industry 4.0 ecosystem and what are the value exchanges and rewards obtained by companies in this structure. In this sense, the conceptual framework guides us to discover whether and how the social exchange elements are present and support the Industry 4.0 ecosystem structure.

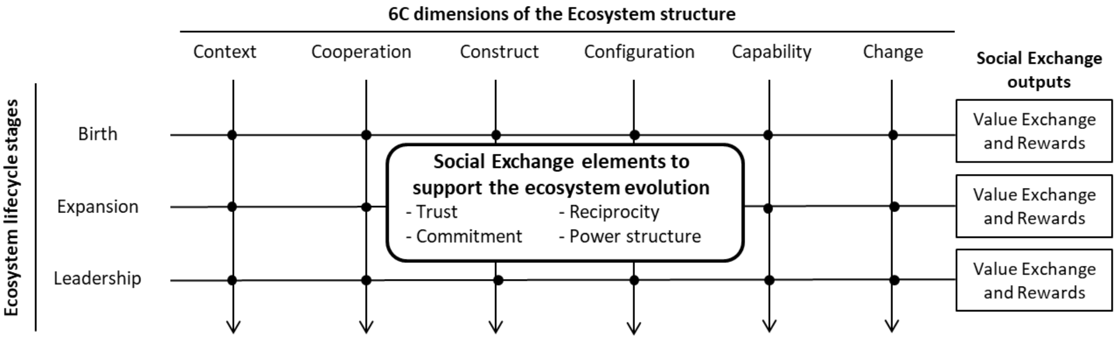

Figure 3.1 – Conceptual framework for the study of an Industry 4.0 ecosystem: using social exchange theory in an innovation ecosystem structure

3.3 Research method

In order to clarify the elements of the conceptual framework presented in Figure 3.1, we adopted a case study approach that allowed us to analyze such elements in a specific innovation ecosystem for Industry 4.0 solutions. This would not be possible with wide data collection and analysis approaches based on quantitative surveys with multivariate analysis methods. Since we aim to understand many details and elements by covering a long period of time in the ecosystem lifecycle, this would only be feasible with an in-depth study (Voss et al., 2002; Yin, 2009). Moreover, we are targeting a unique case that can generate novel insights (Goffin et al., 2019). Our research design followed the guidelines of Voss et al. (2002) for case study research in operations management, as described in the following subsections.

3.3.1. Theoretical sampling

Our case study was focused on an electrical and electronics ecosystem located in Southern Brazil – one of the most industrialized regions in Brazil and the main industrial cluster in automation and control technology providers in the country. We selected this ecosystem for the case study due to its relevance for the Industry 4.0 national initiative and because some important testbeds for Industry 4.0 were born there. Prior studies have also reported on Industry 4.0 initiatives in Brazil – though from the technology adoption perspective – and have shown a low but growing level of implementation of these technologies (Dalenogare et al., 2018; Frank et al., 2019a).

In order to clarify our case study boundaries, we considered only the 120 SMEs with official membership in the 'Automation and Control Regional Association' (shortly referred to as 'business association'), and their related stakeholders in this ecosystem. The business association was created in 2008 with the goal of articulating and leveraging automation and digital solutions for Southern Brazil. Although the initial goal of the ecosystem was not explicitly focused on Industry 4.0 (the concept only came to be conceived in 2011), its capabilities were strongly related to digitization, connectivity and integration aspects, which are all comprised by the Industry 4.0 concept. Most of the companies in the business association have been in the market for decades, providing automation technologies and digital solutions, which are considered prerequisites for Industry 4.0. In the beginning of 2016, perceiving that Industry 4.0 was a growing concern around the world, the ecosystem started focusing specifically on Industry 4.0 with the aim of developing innovative digital solutions to meet the evolving demands and standards of this new market. Our study followed this case from the beginning of 2016 until mid-2019. Additionally, we collected historical data on the previous period (2008-2016) to understand the ecosystem's prior characteristics. Following a SET perspective (Tanskanen, 2015), our unit of analysis was the relationship between the actors engaged in the value exchange, while we considered the structural aspects of the ecosystem (lifecycle and 6C elements) to frame our scope of analysis (Figure 3.1).

3.3.2. Data collection procedures

Since we studied the whole ecosystem, we used different sources of information for all actors involved in order to increase the reliability of our analysis (Yin, 2009) and the internal consistency and construct validity of research (Goffin et al., 2019). We collected data from customers, companies, research centers, government and association representatives. We used a data triangulation approach which combines different data collection sources to understand a phenomenon (Yin, 2009; Voss et al., 2002). As represented in Figure 3.2, we adopted a chronological perspective for data collection using Moore's (1993) lifecycle stages as our main guide. The *birth stage* comprises the period from 2008 to 2016 (Figure 3.2), which is subdivided into two moments: the first one refers to the period when the ecosystem was constituted; and the second one to the time when firms and the business association organized themselves to create a clear strategy to drive business opportunities for the ecosystem. We started our data collection in 2016, concurrently with the beginning of the *expansion stage* (Figure 3.2), when the ecosystem started shifting the focus of its strategy towards Industry 4.0. We conducted semi-structured interviews from 2016 to 2018 to understand the past and present of the ecosystem and how the Industry 4.0 strategy was influencing its orchestration. In 2016, we also conducted a survey (Figure 3.2) with the companies in order to build a technology map that allowed us to understand Industry 4.0 capabilities in the ecosystem. This was followed by a focus group session, in which we presented the technology map for the ecosystem and discussed results with the companies and the business association. The purpose was also to have a review and validation of evidence, which is important to avoid misinterpretations or bias in reviewers' analyses (Goffin et al., 2019). Additionally, in the expansion stage the ecosystem started to implement complex projects (Figure 3.2) focused on advanced solutions for Industry 4.0 demands. From 2017 to mid-2019, we followed the most innovative of these projects, an Industry 4.0 testbed project, to observe its development and outcomes (Figure 3.2). For the leadership stage, we prospected insights and trends from our observations during the testbed project. Our data collection procedures are presented as methodological steps (technology mapping and focus group, semi-structured interviews and testbed follow-up), as described in the following subsections.

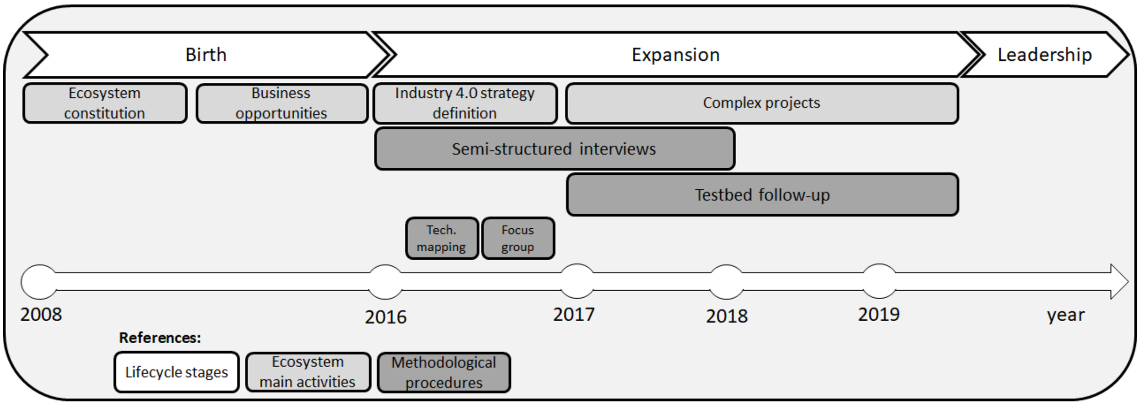

Figure 3.2 – Chronological approach for the data collection process

3.3.2.1. Technology mapping and focus group

Our initial step was focused on understanding the Industry 4.0 technological capabilities existing in the ecosystem, which we mapped with a survey (technology mapping) focused on obtaining descriptive statistics on the ecosystem. The list of technologies used in the mapping was adapted from CNI (2016), Kagermann et al. (2013) and PWC (2016) industrial reports, which provide a wide set of Industry 4.0-related technologies. The questions referring to these technologies were divided into two categories: (i) technology offered by the company, and (ii) technical knowledge the company has on this technology. The latter category was also to help assess the potential for new technology development based on the existing knowledge in the ecosystem. A 5-point Likert scale was used to capture both categories: the level of technology offering ranged from "1- very low or no presence in the company's portfolio", to 5- highly developed in the company's portfolio"; while the level of knowledge on the technologies ranged from "1 - no expertise" to "5- very high expertise". We also surveyed how these companies collaborate with other partners (e.g., consulting firms, universities, etc.) and the barriers for the implementation of these technologies. The lists of collaboration and barrier types were adapted from the Brazilian Innovation Survey (PINTEC, 2014), a well-known industrial survey in the national business context (Frank et al., 2016). The Likert scale used to assess levels of collaboration and existing barriers ranged from "1 – irrelevant" to "5 – extremely relevant" and "extremely impeditive", respectively. For a pretest, the questionnaire was submitted to the review of: three Industry 4.0 experts from the SENAI Innovation Institute – the largest Research-Technology Organization (RTO) in Brazil, which is strongly focused on the provision of innovative solutions for Industry 4.0 needs in Brazil, following the German Fraunhofer Institute model; two business association representatives; and one of the companies in the ecosystem. The final lists of technologies, barriers and potential collaborations used in our technology mapping are presented in the results section, in Tables 3.3 to 3.5.

The questionnaires were sent in the first semester of 2016 through an online survey platform to the 120 companies affiliated to the business association. The respondents were top executives such as technology and product development managers or other professionals with similar technical background. Afterwards, we made phone calls to follow up with companies that had not fully responded the questionnaire. We obtained 87 answers, i.e., a response rate of 72.5%. Such a high response rate was obtained thanks to the support of the business association, which sent personal e-mails to company representatives and promoted the research project in industrial workshops. The sample composition has enterprises distributed as follows: 39% micro (up to 19 employees), 32% small (20 to 99 employees), and 29% medium enterprises (100 to 500 employees), according to the classification of the Brazilian Institute of Geography and Statistics (IBGE, 2015).

The results of this survey were presented in an industrial report on the ecosystem, followed by a focus group session with respondents in the second semester of 2016. The aim of the focus group was to collect impressions on the ecosystem as well as to understand the opportunities and challenges of the ecosystem in the Industry 4.0 context (Kitzinger, 1994). From the 87 companies surveyed, 45% participated in this final discussion. Two researchers presented the findings and moderated discussions, while three assistants recorded comments and discussions.

3.3.2.2. Semi-structured interviews

We performed individual semi-structured interviews with different actors in the ecosystem. The interviews were conducted from 2016 to 2018 using a semi-structured interview guideline adapted from Rong et al. (2015) (Appendix C). The interviews were focused on understanding the 6C dimensions along the different lifecycle stages. We guided the interviewees along the ecosystem lifecycle so that they could explain what happened at each stage regarding all the 6C dimensions. We also put especial emphasis on identifying how trust, commitment, reciprocity and power happen during these stages and the benefits (rewards) obtained by stakeholders in each stage.

For the selection of interviewees, we first interviewed three representatives of the business association and asked them to recommend other potential interviewees (from a list of different types of actors) who were strongly engaged in ecosystem activities. We followed their recommendations and obtained the final list of interviewees shown in Table 3.1. We asked respondents to consider the historical (chronological) aspects of the development of the ecosystem. For each type of actor, we followed a snowball approach, using the next interview to collect new data and compare with the previous one. Discrepancies were discussed and, in a few cases, it was necessary to make phone calls to clarify specific statements. Each interview lasted around 1 hour. Two research assistants took notes of the main comments while interviews were conducted by the main researchers. The interviews were also recorded and later transcribed.

Table 3.1 - List of interviews

Type of actor	Interviews	Interviewees
Business Association	3	Representatives of the association
University	8	University scholars engaged in the ecosystem with Industry 4.0-related projects
Research Center	2	Representatives from the main RTO in the region of the ecosystem
Companies	15	Medium-sized companies leading the business ecosystem
Customers	8	Large-sized companies that are major customers of the business ecosystem
Government	1	Representative of the State Department of Innovation Development, Science and Technology
Total	**37**	

3.3.2.3. Testbed follow-up

For 2.5 years we followed a specific testbed project in the ecosystem with the aim of testing a collaborative and integrative approach with some of the companies using complementary capabilities for a new and complex project. The project consists in the development of an autonomous and real-time reconfigurable manufacturing cell. Eight companies contributed with different capabilities for the development of the joint solution, as follows: (i) operations strategy for digital manufacturing; (ii) modular layout projects for manufacturing processes; (iii) electronic devices, such as programmable logic controller (PLC), human–computer interaction devices, etc.; (iv) IoT solutions, including communication, sensing, traceability, etc.; (v) systems integration, including software programing, mechanical and electronic components integration, etc.; (vi) software development focused on SCADA and MES systems (the company used this project to test a new software platform under development to meet Industry 4.0 requirements); (vii) 3D printing technologies; and (viii) collaborative robotics. We followed each of the monthly meetings and recorded discussions and definitions, focusing especially on ways actors collaborated inside the group and with other external partners such as government agencies, universities, associations, and potential customers of the final solution. This allowed us to have a practical observation of some of the projects developed in the innovation ecosystem, also considering the industry lifecycle of this ecosystem. The project was followed by a team of six researchers, coordinated by the authors of this work.

3.3.3. Data analysis - validity, reliability and interpretation

For construct validity, concerning the correct operational measurement of the concepts, we followed the suggestions of Voss et al. (2002). The first of them is that researchers should bear in mind that a construct measured can be different from all others. Voss et al. (2002) also recommend data triangulation and multiple sources of evidence to strengthen construct validity. Therefore, we used four different data sources: technology mapping, accompanied by a focus group, individual interviews, and follow-up of a testbed project. Moreover, we analyzed documents and website information to understand historical aspects of ecosystem evolution. Data collection from these sources was performed in three different stages of the study, as shown in Figure 3.2. The data was collected following the protocol presented in Table 3.2. The same protocol was used for each lifecycle stage of the ecosystem analysis.

We organized the data collected in the three steps separately, as shown in Table 3.2. We included all the elements of the 6C dimension in the codification protocol (Step 1 in Table 3.2) and this was repeated in separated sheets for each lifecycle stage of the ecosystem. Then, the elements identified (Step 1 in Table 3.2) were combined and integrated, as described in the section ‘Step 2: data integration and validation’ in Table 3.2. As described in this section of Table 3.2, different data sources were useful for each lifecycle stage of the analysis. The identification of elements (6C and SET elements) was based on a content analysis approach following a meaning rule, which consists in identifying common issues and grouping them according to the interpretation given to their meaning and based on predefined labels (Bardin, 1977). The definition of meanings was based on the definition by Rong et al. (2015) of the 6C elements and the definition by Wu et al. (2014) of the SET elements (see Sections 3.2.1 and 3.2.2). Each statement made by the interviewees was labeled as referring to a specific dimension of the 6C framework and/or to a specific element of the SET using the meanings (definitions). For instance, when some of the interviewees mentioned something related to ‘coordination mechanisms in the ecosystem’, we labeled the statement in the ‘Cooperation’ dimension of the 6C framework and/or in the ‘Power Structure’ element of SET. Later, we analyzed the context of this statement to refine our analysis. The same procedure was used with the records from the focus group and from the testbed follow-up, while the technology mapping, since it consisted of descriptive data, was used to confirm and reinforce the conclusions of the analysis. We used three researchers to perform this analysis independently from each other and, then, combined data to compare differences. The last step was to then structure these elements in a matrix as shown in the rows under the label ‘Step 3: final data analysis (SET elements)’ of Table 3.2. We identified how the SET elements were mentioned in the same statements of the 6C dimensions and how these elements from the 6C framework and the SET overlapped in some of our codifications with labels of meaning. We also checked the notes and observations made during the focus groups and testbed follow-up to refine these relationships.

Table 3.2 – Research codification protocol (one sheet per lifecycle stage)

<table>
<tr><th colspan="6">Step 1: Data codification protocol for the Ecosystem Lifecycle stage "X"</th></tr>
<tr><th>Procedures</th><th colspan="5">Variable</th></tr>
<tr><td>Step 1: Tech. mapping and focus group</td><td colspan="5">6C elements identified with this procedure for lifecycle stage X</td></tr>
<tr><td>Step 2: Semi-structured interviews</td><td colspan="5">6C elements identified with this procedure for lifecycle stage X</td></tr>
<tr><td>Step 3: Testbed follow-up</td><td colspan="5">6C elements identified with this procedure for lifecycle stage X</td></tr>
<tr><th colspan="6">Step 2: Data integration and validation</th></tr>
<tr><td>Lifecycle stage: Birth</td><td colspan="5">Crossing data from Steps 1 and 2, counting and identifying the most relevant elements.</td></tr>
<tr><td>Lifecycle stage: Expansion</td><td colspan="5">Crossing data from Steps 2 and 3, counting and identifying the most relevant elements.</td></tr>
<tr><td>Lifecycle stage: Leadership</td><td colspan="5">Prospecting elements from Step 3.</td></tr>
<tr><th colspan="6">Step 3: Final data analysis (SET elements)</th></tr>
<tr><th rowspan="2">Rong's 6C dimensions</th><th colspan="4">SET elements for lifecycle stage X</th><th rowspan="2">Value Exchange and Rewards</th></tr>
<tr><th><i>Trust</i></th><th><i>Commitment</i></th><th><i>Reciprocity</i></th><th><i>Power Structure</i></th></tr>
<tr><td>Context</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Cooperation</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Construct</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Configuration</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Capability</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Change</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

For validation, we crossed data from the three lifecycle stages, counting the most frequent elements and identifying the most relevant ones. For the leadership stage, we used data from Step 3 to prospect possible elements for the stage. We also checked reliability by considering the inter-coding agreements between the three researchers (Goffin et al., 2019). Rather than using a quantitative counting procedure for reliability, we chose to proceed with independent analyses by the three researchers and then discuss differences in codification. We used one representative from the companies and one from the business association to help check divergences between understandings. The following step (external validity), helped us to refine the outcomes, as explained below.

In terms of external validity, our data analysis results were presented in two final workshops, one with the companies and representatives from the ecosystem, and another with the regional chapter of the Brazilian Association of Machinery and Equipment Builders (ABIMAQ) in Southern Brazil – which is located in the same industrial cluster as the Industry 4.0 ecosystem as well as its main customer. The workshop with ABIMAQ companies allowed us to obtain an external comparison, since they also have access to other providers around the world, which allows to compare the characteristics of this ecosystem with global trends. Therefore, these workshops served to validate the coherence of our results considering an external perspective of the customers. Also for reliability, a final report was developed based on the transcription of recorded interviews, observations and data analysis from our survey, and this was made publicly available so that results could be discussed with the industrial community in order to guarantee the reliability and replicability of our findings in the future.

For case presentation and interpretation (Goffin et al., 2019), we used the three lifecycle stages studied (birth, expansion and leadership) as a guideline for our narrative, aiming to provide a chronological narrative of the facts (Voss et al., 2002). In each of the stages, we present a narrative that interrelates the elements of the 6C framework that were evident and most relevant in our data analysis. We focus the interpretation of these elements using the SET perspective, and discussing how each of the four elements – trust, commitment, reciprocity and power structure –, and the outcomes including value exchange and rewards (Wu et al., 2014) were supportive and how they were present in this ecosystem structure. Finally, we summarized our data analysis and case study narrative in a final framework (Figure 3.4) which helped us to consolidate our overview about the evolution of value cocreation in the ecosystem. The final framework also allowed us to compare how elements change along the lifecycle stages, which is useful to understand different strategies followed by the actors in the ecosystem.

3.4 Results

The electrical and electronics industrial ecosystem was conceived in 2008 with the aim of creating synergies between companies working with advanced automation and digital technologies. The representatives of the business association believe that the birth stage extended for about eight years. The ecosystem progressively defined the actors that would be part of it, as well as the collaboration model and value proposition that the ecosystem should pursue. Most of the interviewees agreed that the shift to the expansion stage occurred in 2016, when the ecosystem assumed a strategic role toward Industry 4.0 solutions and redefined its value proposition to focus on the potential delivery of complex Industry 4.0 solutions. The ecosystem focused on combining technological capabilities between actors and stimulating demands for their products. Our research was concentrated in the expansion stage of the ecosystem, using a retrospective and prospective analysis of the birth and leadership stages, respectively. At the end of our observation period, in mid-2019, the ecosystem was planning its shift to the leadership stage, establishing itself as the strongest provider of Industry 4.0 solutions for the Brazilian market. Next, we discuss each of the stages based on the conceptual framework (Figure 3.1)[3].

3.4.1. Birth

The ecosystem started as a formal association of companies in 2008. The initial *mission* of this ecosystem [CONTEXT] was to pursue competitive advantage through the access to resources such as R&D funds, consultancy, training and other shared benefits for the associates. Therefore, initial **rewards** for the engagement were only based on cost reduction to access innovation resources, but cooperation activities were not the main concern of the companies. The main opportunities that companies envisioned to **exchange value** was the promotion of technological competences and the access to market opportunities that SMEs could not achieve alone. At this initial stage, companies' *external relationship*s [CONFIGURATION] followed mainly a transactional approach, based on the supply of components and products to integrate into larger technology systems. The start of an economic crisis in the country and the increased global demand for digital solutions were *drivers* for the association to gain strength, while the difficulty to open and share knowledge between the companies was the main *barrier* for companies that had worked independently for many decades before joining the association.

In this context, there was a need to establish an initial coordination mechanism and a *governance system* structure [COOPERATION] to overcome this individualistic view of the companies and to create more value for the whole ecosystem as a group. As pointed out by one of the business association representatives: "*companies needed to see clear benefits from collaboration, and they usually see this only when they are able to reduce costs*". Therefore, the State Government stimulated the formalization of a seed initiative to promote the ecosystem, and the first action of this program was setting a coordination team for the business association. External government support was progressively reduced in the following stages of the ecosystem lifecycle. The *governance system* allowed to organize *cooperation* activities within the ecosystem. The main tasks of ecosystem coordinators were to arrange regular meetings for networking and knowledge

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[3] Each section follows the ecosystem lifecycle stages (Moore, 1993). We highlight the 6C dimensions (Rong et al., 2015) in capital letters, in brackets, and the 6C specific elements in italic. The SET elements (Wu et al., 2014) are highlighted in bold.

sharing activities on innovation opportunities (funds, concepts, trainings, and consultancy) in order to create an environment of trust between firms. As noted by the interviewed government representative: "*trust is a big barrier in our state when compared to the behavior of companies in other regions of this country. The historical immigrant roots of the region make entrepreneurs proud of what they can achieve by themselves, independently from others, and this can be hard to overcome when we want to obtain better solutions*". Therefore, the government program was focused on fostering a closer approach between the companies. According to the interviewees, geographical proximity and cultural identity were also fundamental elements to promote integration between the actors. However, **trust** was largely limited to the business association, which concentrated the managerial **power** of the ecosystem during this stage, maintaining a dyadic *pattern* of relationship with each company [CONFIGURATION]. In this sense, the building of an *infrastructure* to support networking among actors was crucial for the birth stage of the ecosystem [CONSTRUCT]. This included meeting places, website pages with information about the companies and the association, and the creation of the business association brand. Thus, the *structure* was focused on institutional aspects to frame the ecosystem.

Regarding technological capabilities [CAPABILITIES], our technology mapping (survey) –developed in the beginning of the expansion stage – allowed us to obtain a picture of the capabilities created at the birth stage. As the list of technologies in Table 3.3 shows, the business association was able to bring together in the ecosystem a large set of Industry 4.0-related technologies, although the ecosystem had more conceptual knowledge (knowledge rate) on these technologies than the level of offering (offer rate). When the 39 companies in the focus group were asked about the reasons for these gaps between knowledge and offering of technological capabilities, they agreed that they were mainly due to the financial risks associated to an expansion in the product portfolio, which was also evidenced in the barriers reported in Table 3.4. In this sense, the technological capabilities of the ecosystem at this stage were focused on the availability of a large set of Industry 4.0-related technologies offered independently as 'units' rather than systems. Table 3.4 also shows that organizational rigidity, IT skills, and standardization of industrial communication protocols were not a major concern for these companies. This is indicative of the DNA of the companies: SMEs with enough flexibility to adapt and evolve, and with high levels of expertise in automation, which allows them to deal well with IT and standards. However, there were also some technology gaps in the ecosystem, as shown in Table 3.3 (e.g., machine vision, digital manufacturing, virtual commissioning, robotic systems for industrial automation, human-robot collaboration, virtual or augmented reality, additive manufacturing). This also created opportunities to connect with other stakeholders during the expansion stage, as we will describe below.

Table 3.3 – Industry 4.0 technologies of the ecosystem (n=87 SMEs)

Technologies	**Offer rate**	**Knowledge rate**
Data acquisition	49.43%	72.41%
Sensing, measuring and transduction	49.43%	72.41%
Data presentation software	45.98%	73.56%
Big data analytics in machinery (including AI)	44.83%	70.11%
Standard industrial protocols in equipment	43.68%	67.82%
Digital update of equipment (retrofit)	39.08%	58.62%
IT Infrastructure	37.93%	68.97%
Gateways of industrial communication protocols	34.48%	54.02%
Electric energy efficiency monitoring	31.03%	51.72%
Digital services in products	31.03%	40.23%
Machine-to-machine communication (M2M)	27.59%	39.08%
Process traceability	26.44%	55.17%
Electric energy efficiency improvement	25.29%	48.28%
Products identification (e.g., RFID)	24.14%	55.17%
Manufacturing Execution System (MES) integration with equipment	20.69%	35.63%
Machine Vision	13.79%	28.74%
Digital manufacturing	12.64%	26.44%
Virtual commissioning	12.64%	16.09%
Robotic systems for industrial automation	11.49%	35.63%
Human-robot collaboration	10.34%	24.14%
Virtual or augmented reality	5.75%	9.20%
Additive manufacturing	5.75%	20.69%

Table 3.4 – Main barriers to extend the offering of Industry 4.0 technologies

Potential barriers	**Highly impeditive**
Lack of financial resources	63%
Risks and lack of clarity of return on investment	61%
Costs of technologies/software and/or systems	54%
Uncertainty about customer needs	37%
Lack of identification of potential customers	34%
Lack of trained professionals	32%
Shortage of appropriate external services	31%
Difficulty in adjusting to governmental norms and regulations	24%
Risk for information security	23%
Organizational rigidity	21%
Lack of IT skills	21%
Lack of standardization of industrial communication protocols	13%

3.4.2. Expansion

According to the interviewees, the expansion stage of the innovation ecosystem started in the beginning of 2016, when the business association changed its *mission* from just connecting companies for competitive advantage in accessing resources to an Industry 4.0 joint innovation strategy [CONTEXT]. There were several *drivers* for this evolution. First, by this time large companies in the region had started to demand more integrative solutions for Industry 4.0. For example, one of the scholars we interviewed remarked: "*we were invited by the State Government together with the business association for a meeting with a large company. This company wanted to make a greenfield investment in a factory totally based on Industry 4.0 concepts and prepared to evolve technologically based on the future production growth. [...] But nobody at the table had the whole solution they needed. The SMEs in the association were offering them many disconnected technologies for different types of needs; however, they needed a systemic IoT solution for the factory*". Another example was the strategic plan of the business association for machinery and equipment – a major customer of the ecosystem – that established a national plan to advance in Industry 4.0 solutions in their companies, which also created a new opportunity for the local ecosystem. This is connected to a second *driver,* which was the growth of national programs and initiatives for Industry 4.0 in the country, such as the initiatives for testbeds and IoT innovation. The business association realized there was a need to engage the ecosystem in these new initiatives and seize the opportunity of this trend. Therefore, the strategy shifted from value creation based on information and knowledge exchange towards **value cocreation** based on interaction between companies for the expansion of technological capabilities and the development of integrated Industry 4.0 solutions. Instead of showing the companies the potential reduction of innovation costs through the business association, this association had to start an initiative to enhance the **rewards** for companies from working in collaboration with others to incorporate higher value in their solutions.

For the ecosystem to be able to evolve to this expansion stage, companies needed to *change* their work approach by adapting their *cooperation* strategies [COOPERATION] and using an open innovation approach. However, the lack of **trust** to develop joint initiatives was still a major *barrier*. Therefore, the coordination mechanisms, the governance system [COORDINATION], and external relationships [CONFIGURATION] needed to change. The driver of change was the building of a new **structure of power** for social interaction based on the role of a neutral coordination for joint project initiatives led by the university and the business association. While the business association assumed the policy and political role, the university created and coordinated testbed projects with some selected companies from the ecosystem. This aimed to show the ecosystem new ways it could work and foster team trust based on joint experiences. As one of the companies affirmed in the interview: "*the university played an important role because they are not competitors in the market, so they can help us* *[companies] to deepen relationships with confidence that the university aims at a fair purpose for the whole ecosystem and that it is not biased towards particular interests*". In this sense, the *coordination mechanism* shifted from political institutions to a focus on innovation. The testbed approach was selected as a driver for the expansion in order to show the value of **commitment** in strategic alliances for complex joint projects, since at the beginning of this stage most of the companies only collaborated with their customers, as shown by survey results in Table 3.5. This table shows that competitors, i.e., other companies in the business association, were considered relevant only for 33% of the companies. The testbed projects and other joint activities focused on developing integrated Industry 4.0 solutions for specific demands aimed to change this vision.

Table 3.5 – Relevance of collaboration for companies in the ecosystem at the beginning of the expansion stage (n=87 SMEs)

Relevance of collaboration	Very relevant
Customers	80%
Technical and training centers	46%
Suppliers	44%
Universities	40%
Certification and testing institutes	39%
Research and Technology Organizations (RTOs)	37%
Competitors	33%
Consulting firms	22%

The coordinated development of joint solutions was based on the identification of potential demands and appropriate developers within the ecosystem. In the testbed projects, the university helped to establish the Industry 4.0 requisites and coordinate the interaction between companies, while the companies developed the solution. Besides the creation of team **trust** based on participation in joint experiences and **commitment** based on the strategic alliances for the joint projects, the **reciprocity** of the social exchange between the partners was based on mutual technical benefits due to the synergistic effects of joining capabilities. One of the company interviewees affirmed: "*We can learn from each other, get better technologies and learn how to better connect the technologies each of us develops*"; this reflects a synergy between the solutions. The same was confirmed by the focus group when the results in Tables 3.3 to 3.5 were presented and they were questioned about potential benefits of working in collaboration for technology development at this stage.

The technological capabilities [CAPABILITY] at this stage shifted from a view of technology availability in the ecosystem to a concern with value cocreation through integrated IoT projects. For example, in the testbed project we followed for 2.5 years, the sensors provider could develop new applications for its sensor because its products were embedded in the flexible manufacturing line created by the group. The value changed from what the sensors are (e.g., just RFID sensors) to what the sensors are capable of doing in the whole system (e.g., traceability of the manufactured components in a flexible line). Moreover, the MES provider, which was developing a new real-time MES/APS[4], used the testbed project to learn about the integration of different technology parts (i.e., collaborative robots, RFID sensors, actuators, PLCs, etc.) to develop a more robust system that can collect data from all these devices and better plan manufacturing line operations. Besides their own technological improvements and capability development, companies were also driven by demand, since they were focused on working in integrated projects. In this case, the main question changed from ‘who can buy my products’ to ‘which of my capabilities are needed in this project’. The university played a key role in helping companies to define their capabilities for each of the projects developed in this stage. Additionally, the *capability* gaps reported in the beginning of this stage (Table 3.3), especially those related to digital manufacturing, virtual commissioning, virtual or augmented reality, and additive manufacturing, were filled with the inclusion of external RTOs that could support complex project development. The interviewees recognized that such advanced centers are essential in SME ecosystems where some of the most advanced technologies may be lacking because of the low scale of operation, which makes such technologies inaccessible for them.

3.4.3. Leadership

While the ecosystem was consolidating its expansion stage during our research period, we also dedicated part of our interviews to understanding the strategy that the ecosystem was following for its evolution and how the leadership stage could be achieved. Some of the new elements characterizing the leadership stage started to appear more clearly during the expansion stage as, for instance, the new configuration of power structure (discussed below), while others were prospected based on the current needs and vision of ecosystem actors.

First, regarding the **value** of social exchange between the actors and its expected rewards in the leadership stage, the interviewees acknowledged that the expansion of capabilities is a priority for the short and middle term, but not for the long term, when the target should

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[4] APS: Advanced Planning and Scheduling Software.

be the creation of new business models. This can be illustrated by the words of one of the customer interviewees: “*Companies in the region need to develop new business models, focusing more strongly on service provision, project customization and pay-per-use systems rather than only on technology*”. The **reward** of this would be the development of new markets for the sustainable development of the ecosystem’s business. Therefore, the leadership stage of the Industry 4.0 ecosystem would have its *mission* oriented to smart business rather than only IoT-based technology solutions [CONTEXT]. To that end, the technological capability should shift from the cocreation of integrated IoT projects to the cocreation of new Industry 4.0 businesses [CAPABILITY]. This will require increased proximity of the ecosystem with its customers in order to understand the broader needs of smart factories. With that in mind, during the expansion stage, the business association created a joint project with the university to understand the main solution needs on the customer side. Through this project, the local machinery and equipment market (which is another business ecosystem) was mapped and joint initiatives to integrate companies started to be developed. According to the representative of this customer’s ecosystem “*there is a big potential to integrate companies from the automation sector with those from the machinery and equipment sector, especially because the latter has products that are not currently connected, and the market is increasingly requiring solutions of this kind. Therefore, the automation ecosystem can help to create new solutions for machinery and equipment provision to our sector, not only for technology to address our production line needs*”.

For this shift toward Industry 4.0-related ‘smart’ businesses, we observed important changes in the ecosystem structure [COOPERATION, CONSTRUCT and CONFIGURATION]. Firstly, regarding the *coordination mechanism* and the **power structure**, still in the expansion stage we started to perceive a shift from neutral coordination to the role of a platform and complementors organization. For example, as the testbed project gained maturity and the partners started to prospect opportunities to commercialize the solution as a customized solution, the IoT-based software provider (i.e., real-time APS/MES provider) became the central platform of the project and the system integrator became the connector of this platform with different complementors (e.g., collaborative robots, RFID sensors, IoT devices, PLCs and actuators, etc.). We also observed that, depending on the business solution required, other platforms started to emerge. For instance, an additive manufacturing solution could trigger the integration of 3D printing design software with real-time manufacturing orders, or a collaborative robot could be the trigger of a systemic solution incorporating sensors in the production line for the creation of big data to be analyzed with machine learning to optimize the production line and adjust the collaborative robot action.

This power shift from neutral coordination towards business platforms means that companies can gain confidence in the ecosystem structure and may no longer need the mediation of neutral actors such as the university. This is aligned with what one of the university representatives mentioned when he said, "*the university cannot support the coordination of activities in the ecosystem for a long period, since we have research purposes and goals and we cannot scale up such activities. We can start to move the wheel, but the companies need to take the lead in the long run*". What the university representatives and the business association envision as their roles for the long run is developing new applied research useful to the ecosystem and providing policy support and political representation for the ecosystem as an association, respectively.

In this trend toward a new **power structure** configuration, we observed that **trust** needs to be expanded to become an environmental trust in the ecosystem, rather than just team-based trust. This is because social exchange does not happen only for specific project demands as in the expansion stage; it is a result of the integration between platforms, connectors and complementors depending on different needs. Therefore, trust must be wider. This has been a clear concern of the association's representatives, who expressed the need to strengthen the trust environment, while testbed and specific projects would operate just as inspirational examples to engage more companies in this broader goal. In this sense, **commitment** also started to change between the expansion and leadership stages toward a more organic configuration pushed by market demands instead of closed strategic alliances within the ecosystem. Finally, the companies interviewed explained that the ultimate goal is to achieve a win-to-all market status, creating new market opportunities to all participants in the ecosystem, which we consider a market **reciprocity** in this last stage of the ecosystem. This is illustrated by a comment made by a representative of the business association: "*Companies can sell their products better when they bundle them up in a bigger package to be offered to the customer, as in projects led by some of the companies in the ecosystem*"; this reflects a synergy between the solutions for market purposes.

3.5 Discussions

Our results help to obtain a broader comprehension on the evolutionary aspects of Industry 4.0 ecosystems and the different relationships among companies and actors. The prior study of Rong et al. (2015) highlighted the importance of considering how this kind of ecosystem evolves rather than taking a snapshot view of them, and argued that actor roles may change during this evolution. Our results support this view and provide more details and patterns.

Concerning the power structure of the ecosystem, Figure 3.3 summarizes the evolution of relationships. During the birth stage, there was a predominance of dyadic relationships between each company and the business association. In this stage, there was a weak relationship between the companies because they focused only on information and knowledge exchange. At this stage, companies were oriented toward a linear supply chain model in which each Industry 4.0 technology was seen as a unit to be exchanged with other companies. At this stage, the government acted as an external supporter, providing funds for the consolidation of the business association. As shown in the other stages in this figure, government presence became progressively weaker as the ecosystem matured. Figure 3.3 shows a change during the expansion stage, when companies shifted to a project-based arrangement in order to cocreate complex solutions. In this stage, a neutral orchestration between the business association and the university was applied, as well as the external support of RTOs. The use of this neutral orchestration mechanism during the expansion stage helped to deal with the lack of connections between the SMEs, the university and RTOs, similar to Reynolds and Uygun's (2018) recommendations for the Massachusetts advanced manufacturing SMEs ecosystem. Our case study also reported a growing focus on demand-driven solution development during the expansion stage, shifting from supply orientation toward value cocreation.

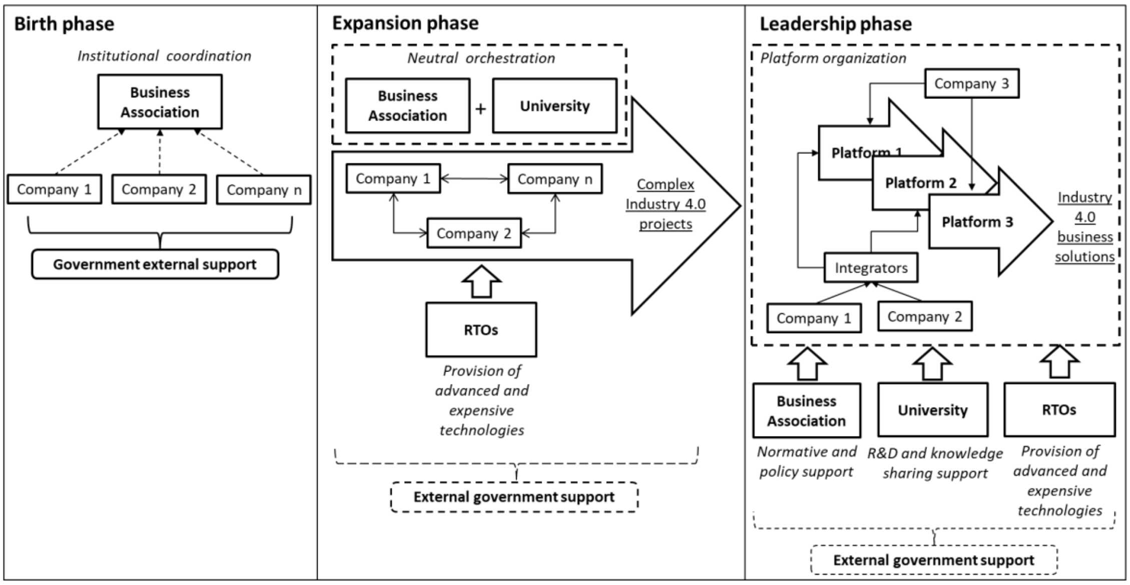


Figure 3.3 – Structure of the Industry 4.0 ecosystem in each lifecycle stage

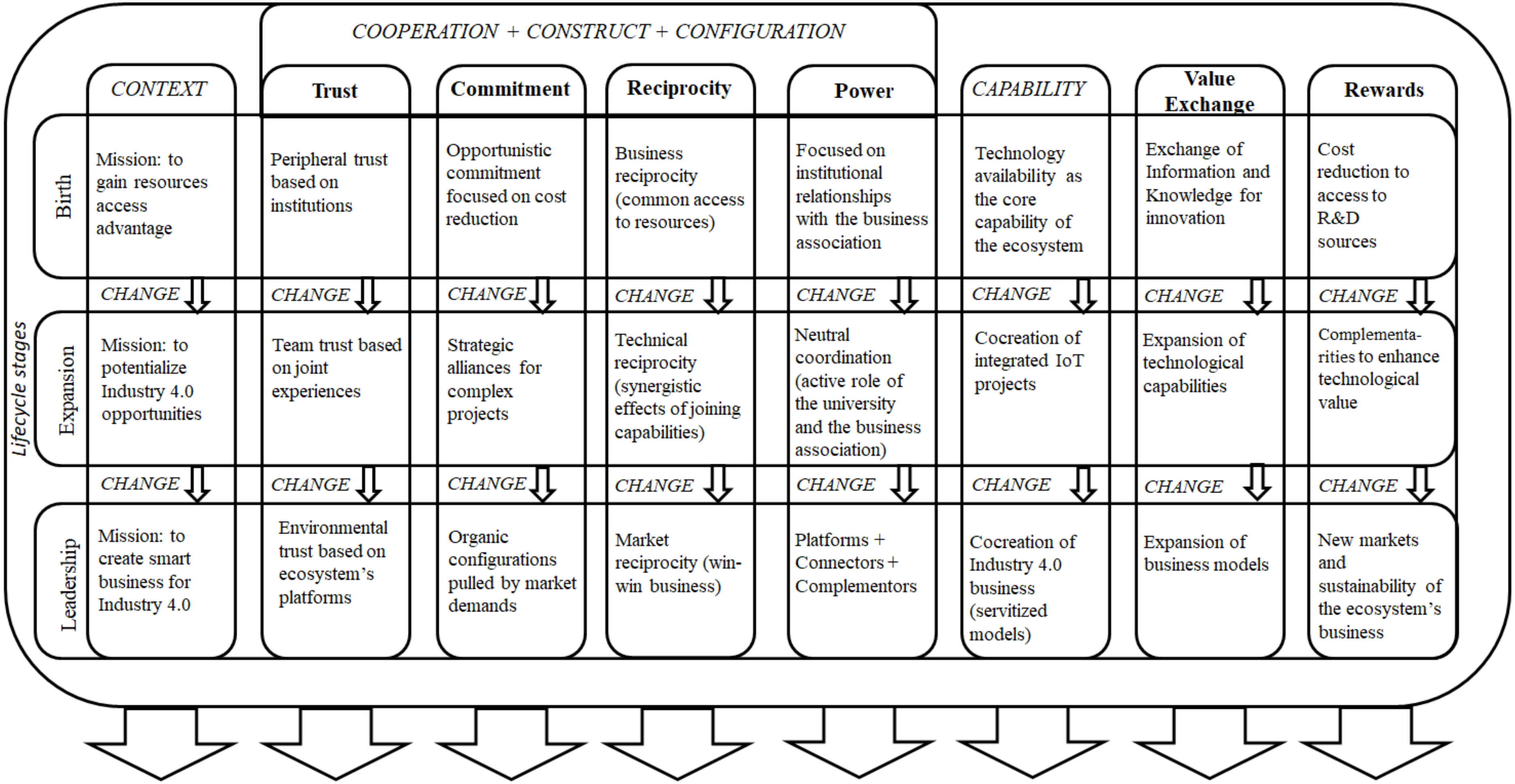
We also reported trends for the leadership stage of the ecosystem. As some technologies became platforms for the ecosystem – meaning that they became central technologies for the solutions and that they connect other technologies as complementors and add-ons (Gawer and Cusumano, 2014) – the neutral orchestrators shifted to an external supporting role in the ecosystem. Therefore, the leadership stage is moving towards a platform-oriented direction and the actors' roles also change in each transition (Dedehayir et al., 2018). Differently from large business platforms that were born from single companies that orchestrated the whole ecosystem (Gawer and Cusumano, 2002, 2014), we observed that, in the SMEs' Industry 4.0 ecosystem, platforms emerged from key Industry 4.0 technologies that pull the inclusion of integrators and add-on technologies based on customer needs. In this sense, this stage is strongly based on the value cocreation between Industry 4.0 providers and customers focused on Industry 4.0 business solutions development (Rong et al., 2015). We reckon this last stage as an equivalent to what is called in the service-dominant logic a 'service ecosystem' (Lusch and Vargo, 2014). According to Lusch and Vargo (2014), such ecosystems cocreate value through the integration of different actors' resources and through the integration of customers and providers who cocreate value rather than providing 'units' of products (technologies) for standard needs. As represented in Figure 3.3 and following Lusch and Vargo (2014), each platform may become a 'small ecosystem' inside the bigger Industry 4.0 ecosystem, as we observed for some of the technologies in our case study. We believe that this last stage may fully converge to service ecosystems in the long run.

Regarding the conceptual framework that we proposed (Figure 3.1), in Figure 3.4 we provide its final version summarizing our findings, which helps us to expand the theoretical understanding of the Industry 4.0 ecosystem from a structural and social exchange point of view. This final figure shows the connections between all these elements and the main findings described in our results, which present an evolutionary perspective of the ecosystem and the value cocreation within it. Firstly, as the figure shows, the mission (context dimension) of the ecosystem changes as the ecosystem evolves and becomes more mature. In this sense, the value exchange and rewards expected are directly connected to the evolution of the ecosystem's mission (Figure 3.4). This means that SMEs' expectations should be different in each stage of the lifecycle and aligned with the ecosystem mission change. For instance, companies aiming to reduce costs to access R&D sources (birth stage) when the ecosystem is moving to the complementarity of technologies to enhance value (expansion stage) will create misalignments. Therefore, actors should be careful not to pursue many different and conflicting benefits at the same time, as this can drive their focus away from what is essential for the ecosystem's evolution (Adner, 2006).

By using the SET perspective, we also show that value exchange, expected rewards, and the Industry 4.0 capability start with a focus on technology but gradually change toward a business perspective. Frank et al. (2019a, 2019b) argued that Industry 4.0 should be considered from the perspective of business model innovation, with companies reformulating the whole business value proposition and not only improving their current products or processes. Thus, our findings provided evidence that, by working interconnectedly, the entire ecosystem must expand its vision towards the digital transformation of customers' businesses. This create opportunities to join IoT-based ecosystems (e.g., Reynolds and Uygun, 2018; Rong et al., 2015) and service ecosystems (e.g., Sklyar et al., 2019) perspectives, which are generally treated as two different streams of research. Our framework (Figure 3.4) shows that, as the ecosystem evolves, a service-dominant view (Lusch and Vargo, 2014) becomes stronger in the value cocreation process, creating opportunities for servitization oriented toward Industry 4.0-related services, as illustrated in the study by Frank et al. (2019b). In such cases, the ecosystem may not provide the technologies as products, but will also be able to use the data generated to create other opportunities such as training based on customer profile, efficiency optimization, reliability assurance through product monitoring, or even new ways to access Industry 4.0 solutions, including pay-per-use or pay-per-results business models (Frank et al., 2019b).

To be able to achieve the aforementioned value exchange and rewards, our results show how the ecosystem framed its internal structure regarding cooperation, construct and configuration dimensions. As shown in Figure 3.4, the use of SET allowed us to see the internal structure from a value cocreation perspective. Our final framework summarizes what is needed in terms of trust, commitment, reciprocity, and power structure – the four elements of SET (Wu et al., 2014) – during the ecosystem's lifecycle. We discussed power structure when we introduced Figure 3.3 with the evolution of the ecosystem's structure. Furthermore, trust follows a progressive process from trust on institutions, through trust on inter-company project teams to ultimate trust on wider ecosystem platforms and their interconnections. Our results showed the centrality of trust, since the other three dimensions (commitment, reciprocity and power) evolve as trust becomes stronger and more widespread. The former study by Wu et al. (2014), which systematized these four SET elements, treated these elements independently. Our findings, however, show that there is a complementary evolution along lifecycle stages. In this sense, the use of Moore's (1993) lifecycle perspective helped us capture the evolutionary correlation between them. The more actors are involved in the process with trust, the more organic is the commitment, the more ambitious are reciprocity expectations, and the less institution-dependent is the power structure.

Our findings also help to expand the understanding of SET in supply chain networks and ecosystems. By analyzing the SET elements from an evolutionary perspective of the ecosystem, we could observe that these elements change over time. Prior studies have predominantly considered these elements from a static view, without considering how they can change along time (e.g. Tanskanen et al., 2015; Wu et al., 2014). Our findings revealed how the SET elements are built and the mechanisms behind them, as well as how they evolve during the ecosystem lifecycle. For instance, we showed that commitment in the early stages of an ecosystem may be opportunistic and we explained the reasons why this happens. We showed that commitment grows as more rewards are perceived from the value exchange between the ecosystem's stakeholders, moving to the creation of strategic alliances and, then, to an organic configuration pulled by the demand (Figure 3.4). Such detail is also described for all the other elements, as represented in Figure 3.4. Therefore, our findings provide many details about the mechanisms of the SET, positioning it in a dynamic perspective which is rare in the current literature.



Lifecycle stages	*CONTEXT*	*COOPERATION + CONSTRUCT + CONFIGURATION*				*CAPABILITY*	**Value Exchange**	**Rewards**
		Trust	**Commitment**	**Reciprocity**	**Power**			
Birth	Mission: to gain resources access advantage	Peripheral trust based on institutions	Opportunistic commitment focused on cost reduction	Business reciprocity (common access to resources)	Focused on institutional relationships with the business association	Technology availability as the core capability of the ecosystem	Exchange of Information and Knowledge for innovation	Cost reduction to access to R&D sources
	CHANGE	*CHANGE*	*CHANGE*	*CHANGE*	*CHANGE*	*CHANGE*	*CHANGE*	*CHANGE*
Expansion	Mission: to potentialize Industry 4.0 opportunities	Team trust based on joint experiences	Strategic alliances for complex projects	Technical reciprocity (synergistic effects of joining capabilities)	Neutral coordination (active role of the university and the business association)	Cocreation of integrated IoT projects	Expansion of technological capabilities	Complementarities to enhance technological value
	CHANGE	*CHANGE*	*CHANGE*	*CHANGE*	*CHANGE*	*CHANGE*	*CHANGE*	*CHANGE*
Leadership	Mission: to create smart business for Industry 4.0	Environmental trust based on ecosystem's platforms	Organic configurations pulled by market demands	Market reciprocity (win-win business)	Platforms + Connectors + Complementors	Cocreation of Industry 4.0 business (servitized models)	Expansion of business models	New markets and sustainability of the ecosystem's business

Figure 3.4 – Summary of findings: Industry 4.0 ecosystem evolution. Notes: Capital letters: 6C framework elements; bold letters: Social Exchange Theory elements

3.6 Conclusions

While most studies on Industry 4.0 have focused on the technology adopters' side (e.g., Dalenogare et al., 2018; Frank et al., 2019a, 2019b), we provide further understanding from the perspective of technology provision in digital transformation towards Industry 4.0. We consider Industry 4.0 as a complex system of interrelated technologies connected through IoT-based technologies which calls for the integration of several technological capabilities shared by a large number of SMEs. Thus, in this paper, we followed an ecosystem approach, which is more suitable than a supply-chain viewpoint for complex interrelationships. Our findings showed the usefulness of this perspective, as previously argued by other authors (e.g., Rong et al., 2015), and these findings also corroborated the complexity of Industry 4.0 solutions. From the perspective of Industry 4.0 technology provision, we aimed to understand how this ecosystem can consolidate and evolve, and how value is cocreated within it to provide Industry 4.0 solutions for the market.

We used a structural view of ecosystems to frame the boundaries of our analysis, and a social exchange theory (SET) that helped us to understand the internal dynamics of relationships between the several actors. For the structural standpoint, we considered the ecosystem's lifecycle stages, which allowed us to see evolutionary aspects of this type of ecosystem. We showed that actors change their role at each stage: those that are central for the ecosystem's beginning and consolidation may become only supporting actors in the leadership stage. We also showed that there is a shift from technology integration for complex project development to technology platforms focused on business solution provision. This evolutionary perspective also allowed us to consider the dynamism of the second structural aspect of our framework: the 6C dimensions proposed by Rong et al. (2015). Regarding these 6C dimensions, our results showed how the ecosystem changes its mission (Context) from technology provision to business development, how the governance mechanisms and structural conditions change (Coordination, Construct and Configuration) from a central role of the business association to the creation of a neutral coordination in which the university took a key role, to a final leadership stage composed by some emerging platforms connecting the parts of the ecosystem. On the other hand, we adopted the SET perspective as a theoretical perspective to look at the factors of the evolving relationships between the actors. We showed that there is a strong interdependence between trust, commitment, reciprocity and power structure: while the former is a driver, the latter is the leverage of trust and the two other related factors. This means that the power structure helps the creation of a trust base in the ecosystem that is to grow and foster more commitment and reciprocity between the actors. Moreover, by combining SET with ecosystems lifecycle, we provide a dynamic perspective of SET elements, showing how they evolve instead of being static, as frequently assumed by the literature.

3.6.1. Practical implications

Our findings offer contributions for both managers and policymakers. Managers can follow our framework to understand how to position themselves as actors in this kind of ecosystem as the ecosystem evolves and how to develop a technology provision strategy for their companies. In this sense, our results show different types of rewards and forms to obtain them throughout the ecosystem lifecycle. Thus, managers can use this reward vision to guide their companies' entry and permanence strategy in the ecosystem. Companies can often seek immediate rewards that, our results show, can only be achieved in mature stages of the ecosystem. Therefore, practitioners should consider what their companies can in fact obtain as benefits in each stage in order to avoid immediate returns that may impact the long-term rewards presented in our findings. Moreover, our results call attention to the relevance of an ecosystem approach rather than a linear supply-chain approach when dealing with Industry 4.0 solutions. Thus, managers should consider this perspective if they want to achieve complex solutions for the Industry 4.0 market. As we showed, the ultimate goal in the evolutionary perspective of Industry 4.0 ecosystems is not technology provision, but rather smart business solutions. Therefore, technology managers should broaden their view toward business solutions and new services that their technologies or those from other connected actors within the ecosystem may provide.

Regarding practical implications for policymakers, our results can be useful for business associations and government agencies that are poised to create mechanisms for the development of such ecosystems. Different national and regional Industry 4.0 initiatives have been recently launched around the world, following the trends of leading countries. Our study can provide them with a conceptual reference that shows dimensions to develop and measure. By using our framework, such actors can have a guideline for the regional development of Industry 4.0 ecosystems. Furthermore, our social exchange perspective highlights the importance of creating strong relationships among the ecosystem's actors. We presented power structure mechanisms that are useful at each stage of the ecosystem lifecycle and how they can support the creation and expansion of trust, commitment and reciprocity at each level of the development. We also provide insights about what values decision makers should enhance in the ecosystem at each stage and how this can be helpful to (re)define the ecosystem's mission along its lifecycle.

3.6.2. Limitations and future research

One limitation of our work is that we are considering the evolution of Industry 4.0 innovation ecosystems without having a complete vision of their evolution, since the case studied has not yet completed its lifecycle. This has pros and cons. From a positive perspective, this allows us to support many ongoing initiatives in a growing area of study. On the other hand, this also implies that we could not fully assess the maturity stage (leadership) which is still in consolidation, neither could we look at the self-renewal or death stages, which are part of an historical analysis after the facts. This also limits our assessment of results. We could verify benefits and assume potential benefits based on our interviews and prior studies in the literature. However, long-term benefits of the leadership stage cannot be assessed in our context. Therefore, future studies should have this in mind and focus on potential outcomes that these initiatives can bring for companies. Moreover, future studies can develop comparative analyses of different regional ecosystems to understand different Industry 4.0 profiles. In this context, it would be relevant to compare large-companies-driven Industry 4.0 platforms and ecosystems with SME ecosystems. This can help to achieve a broader view of the capabilities for the development of this kind of solution and help to understand ecosystem limits and how they can relate to global technology value chains. Finally, future studies can also advance in the analysis of the dynamism of SET elements in evolutionary context as the one considered in this paper. We argued that SET elements have been treated from a static perspective and we provided a dynamic view. This should be included and expanded in future research.

References

Adner, R., 2017. Ecosystem as Structure: An Actionable Construct for Strategy. J. Manage. 43, 39–58. https://doi.org/10.1177/0149206316678451

Adner, R., 2006. Match Your Innovation Strategy to Your Innovation Ecosystem Match Your Innovation Strategy to Your Innovation Ecosystem. Harv. Bus. Rev. 84, 98.

Ayala, N.F., Paslauski, C.A., Ghezzi, A., Frank, A.G., 2017. Knowledge sharing dynamics in service suppliers' involvement for servitization of manufacturing companies. Int. J. Prod. Econ. 193, 538–553. https://doi.org/10.1016/j.ijpe.2017.08.019

Bardin, L., 1977. L'Analyse de Contenu. sl: Presses Universitaires de France.

Blau, P.M., 1964. Exchange and power in social life. NY: John Wiley & Sons.

Brass, D.J., Galaskiewicz, J., Greve, H.R., Tsai, W., 2004. Taking stock of networks and organizations: A multilevel perspective. Acad. Manag. J. 47, 795–817. https://doi.org/10.2307/20159624

Buhr, D., 2015. Social innovation policy for Industry 4.0. Friedrich-Ebert-Stiftung, Division for Social and Economic Policies.

CNI - Confederação Nacional da Indústria, 2016. Industry 4.0: a new challenge for Brazilian industry. Available at: (https://bucket-gw-cni-static-cms-si.s3.amazonaws.com/media/filer_public/54/02/54021e9b-ed9e-4d87-a7e5-3b37399a9030/challenges_for_industry_40_in_brazil.pdf).

Cropanzano, R., Mitchell, M.S., 2005. Social Exchange Theory: An Interdisciplinary Review. J. Manage. 31, 874–900. https://doi.org/10.1177/0149206305279602

Dalenogare, L.S., Benitez, G.B., Ayala, N.F., Frank, A.G., 2018. The expected contribution of Industry 4.0 technologies for industrial performance. Int. J. Prod. Econ. 204, 383–394. https://doi.org/10.1016/j.ijpe.2018.08.019

Dallasega, P., Rauch, E., Linder, C., 2018. Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. Comput. Ind. 99, 205–225. https://doi.org/10.1016/j.compind.2018.03.039

Dedehayir, O., Mäkinen, S.J., Roland Ortt, J., 2018. Roles during innovation ecosystem genesis: A literature review. Technol. Forecast. Soc. Change 136, 18–29. https://doi.org/10.1016/j.techfore.2016.11.028

Emerson, R.M., 1976. Social Exchange Theory. Annu. Rev. Sociol. 2, 335–362. https://doi.org/10.1146/annurev.so.02.080176.002003

Frank, A.G., Cortimiglia, M.N., Ribeiro, J.L.D., Oliveira, L.S. de, 2016. The effect of innovation activities on innovation outputs in the Brazilian industry: Market-orientation vs. technology-acquisition strategies. Res. Policy 45, 577–592. https://doi.org/10.1016/j.respol.2015.11.011

Frank, A.G., Gerstlberger, W., Paslauski, C.A., Lerman, L.V., Ayala, N.F., 2018. The contribution of innovation policy criteria to the development of local renewable energy systems. Energy Policy 115. https://doi.org/10.1016/j.enpol.2018.01.036

Frank, Dalenogare, L.S., Ayala, N.F., 2019a. Industry 4.0 technologies: Implementation patterns in manufacturing companies. Int. J. Prod. Econ. 210, 15–26. https://doi.org/10.1016/j.ijpe.2019.01.004

Frank, Mendes, G.H.S., Ayala, N.F., Ghezzi, A., 2019b. Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective. Technol. Forecast. Soc. Change 141, 341–351. https://doi.org/10.1016/j.techfore.2019.01.014

Gawer, A., Cusumano, M.A., 2014. Industry platforms and ecosystem innovation. J. Prod. Innov. Manag. 31, 417–433. https://doi.org/10.1111/jpim.12105

Gawer, A.A., Cusumano, M.A., 2002. Platform leadership: how intel, microsoft, and cisco drive industry innovation. Boston, MA: Harvard Business School Press.

Goffin, K., Åhlström, P., Bianchi, M., Richtnér, A., 2019. Perspective: State-of-the-Art: The Quality of Case Study Research in Innovation Management. J. Prod. Innov. Manag. https://doi.org/10.1111/jpim.12492

IBGE, 2015. Demografia das Empresas | IBGE [WWW Document].

Kagermann, H., Wahlster, W., Helbig, J., 2013. Recommendations for implementing the strategic initiative INDUSTRIE 4.0. Final Rep. Ind. 4.0 WG 82.

Kitzinger, J., 1994. The methodology of Focus Groups: the importance of interaction between research participants. Sociol. Heal. Illn. 16, 103–121. https://doi.org/10.1111/1467-9566.ep11347023

Liao, Y., Deschamps, F., Loures, E. de F.R., Ramos, L.F.P., 2017. Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. Int. J. Prod. Res. 55, 3609–3629. https://doi.org/10.1080/00207543.2017.1308576

Lu, Y., 2017. Industry 4.0: A survey on technologies, applications and open research issues. J. Ind. Inf. Integr. 6, 1–10. https://doi.org/10.1016/J.JII.2017.04.005

Lusch, R., Vargo, S., 2014. The service-dominant logic of marketing: Dialog, debate, and directions.

Marodin, G., Frank, A. G., Tortorella, G. L., & Netland, T. (2018). Lean product development and lean manufacturing: Testing moderation effects. International Journal of Production Economics, 203, 301-310. https://doi.org/10.1016/j.ijpe.2018.07.009

Marodin, G. A., Tortorella, G. L., Frank, A. G., & Godinho Filho, M. (2017). The moderating effect of Lean supply chain management on the impact of Lean shop floor practices on quality and inventory. Supply Chain Management: An International Journal. https://doi.org/10.1108/SCM-10-2016-0350

Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S., Barbaray, R., 2018. The industrial management of SMEs in the era of Industry 4.0. Int. J. Prod. Res. 56, 1118–1136. https://doi.org/10.1080/00207543.2017.1372647

Moore, J.F., 1993. Predators and prey: a new ecology of competition. Harv. Bus. Rev. 71, 75–86.

Müller, J.M., Buliga, O., Voigt, K.-I., 2018. Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. Technol. Forecast. Soc. Change 132, 2–17. https://doi.org/10.1016/j.techfore.2017.12.019

Osterrieder, P., Budde, L., Friedli, T., 2019. The smart factory as a key construct of industry 4.0: A systematic literature review. Int. J. Prod. Econ. https://doi.org/10.1016/j.ijpe.2019.08.011

Piccarozzi, M., Aquilani, B., Gatti, C., 2018. Industry 4.0 in management studies: A systematic literature review. Sustainability 10, 3821. https://doi.org/10.3390/su10103821

PINTEC, 2014. Pesquisa de Inovação - PINTEC | IBGE [WWW Document]. Pesqui. Inovação - PINTEC.

PWC - PricewaterhouseCoopers, 2016. Industry 4.0: Building the digital enterprise.

Reischauer, G., 2018. Industry 4.0 as policy-driven discourse to institutionalize innovation systems in manufacturing. Technol. Forecast. Soc. Change 132, 26–33. https://doi.org/10.1016/J.TECHFORE.2018.02.012

Reynolds, E.B., Uygun, Y., 2017. Strengthening advanced manufacturing innovation ecosystems: The case of Massachusetts. Technol. Forecast. Soc. Change. https://doi.org/10.1016/j.techfore.2017.06.003

Rong, K., Hu, G., Lin, Y., Shi, Y., Guo, L., 2015. Understanding business ecosystem using a 6C framework in Internet-of-Things-based sectors. Int. J. Prod. Econ. 159, 41–55. https://doi.org/10.1016/j.ijpe.2014.09.003

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., Harnisch, M., 2015. Industry 4.0: The future of productivity and growth in manufacturing industries, Boston Consulting Group.

Russell, M.G., Smorodinskaya, N. V., 2018. Leveraging complexity for ecosystemic innovation. Technol. Forecast. Soc. Change 1–18. https://doi.org/10.1016/j.techfore.2017.11.024

Schiele, H., Veldman, J., Hüttinger, L., Pulles, N., 2012. Towards a social exchange theory perspective on preferred customership — concept and practice, in: Supply Management Research. Gabler Verlag, Wiesbaden, pp. 133–151. https://doi.org/10.1007/978-3-8349-3928-9_6

Sklyar, A., Kowalkowski, C., Tronvoll, B., Sörhammar, D., 2019. Organizing for digital servitization: A service ecosystem perspective. J. Bus. Res. 104, 450–460. https://doi.org/10.1016/j.jbusres.2019.02.012

Sommer, L., 2015. Industrial revolution-industry 4.0: Are German manufacturing SMEs the first victims of this revolution? J. Ind. Eng. Manag. 8, 1512–1532. https://doi.org/10.3926/jiem.1470

Tanskanen, K., 2015. Who wins in a complex buyer-supplier relationship? A social exchange theory based dyadic study. Int. J. Oper. Prod. Manag. 35, 577–603. https://doi.org/10.1108/IJOPM-10-2012-0432

Teece, D.J., Pisano, G., Shuen, A., 1997. Dynamic capabilities and strategic management. Strateg. Manag. J. 18, 509–533. https://doi.org/10.1002/(SICI)1097-0266(199708)18:7<509::AID-SMJ882>3.0.CO;2-Z

Tsujimoto, M., Kajikawa, Y., Tomita, J., Matsumoto, Y., 2018. A review of the ecosystem concept — Towards coherent ecosystem design. Technol. Forecast. Soc. Change 136, 49–58. https://doi.org/10.1016/j.techfore.2017.06.032

Voss, C., Tsikriktsis, N., Frohlich, M., 2002. Case research in operations management. Int. J. Oper. Prod. Manag. 22, 195–219. https://doi.org/10.1108/01443570210414329

Wang, L., Torngren, M., Onori, M., 2015. Current status and advancement of cyber-physical systems in manufacturing. J. Manuf. Syst. 37, 517–527. https://doi.org/10.1016/j.jmsy.2015.04.008

Wu, I.-L., Chuang, C.-H., Hsu, C.-H., 2014. Information sharing and collaborative behaviors in enabling supply chain performance: A social exchange perspective. Int. J. Prod. Econ. 148, 122–132. https://doi.org/10.1016/j.ijpe.2013.09.016

Xu, L. Da, Xu, E.L., Li, L., 2018. Industry 4.0: state of the art and future trends. Int. J. Prod. Res. 56, 2941–2962. https://doi.org/10.1080/00207543.2018.1444806

Yin, R.K., 2009. Case study research: design and methods. Sage, Los Angeles. Cal.

Yin, Y., Stecke, K.E., Li, D., 2018. The evolution of production systems from Industry 2.0 through Industry 4.0. Int. J. Prod. Res. 56, 848–861. https://doi.org/10.1080/00207543.2017.1403664

Zhao, X., Huo, B., Flynn, B.B., Yeung, J.H.Y., 2008. The impact of power and relationship commitment on the integration between manufacturers and customers in a supply chain. J. Oper. Manag. 26, 368–388. https://doi.org/10.1016/j.jom.2007.08.002

Zhong, R.Y., Xu, X., Klotz, E., Newman, S.T., 2017. Intelligent Manufacturing in the Context of Industry 4.0: A Review. Engineering 3, 616–630. https://doi.org/10.1016/J.ENG.2017.05.015

Appendix C – Semi-structured interview guideline (adapted from Rong et al., 2015)

General information

1. Please, briefly introduce your company and its role in the ecosystem (context).

Questions about the Industry 4.0 ecosystem [In case of a technology provider, also ask the same question at the firm-level]

2. Please, describe the development of the ecosystem's Industry 4.0 strategy, in particular what technologies have been developed (context) at different stages of the lifecycle.

3. Please, describe the relationships between the ecosystem companies, and describe how companies work together (cooperation) at different stages of the lifecycle.

4. Please, specify what stakeholders are involved in the ecosystem and their roles in the business (construct) at different stages of the lifecycle.

5. Please, describe the business processes and business models, and explain the importance of platform strategy (configuration) at different stages of the lifecycle.

6. Please, clarify what capabilities are essential to the success of the ecosystem (capability) at different stages of the lifecycle.

7. Please, describe what changes occurred between two stages in the ecosystem and companies' business and how such changes were managed at different stages of the lifecycle.

8. Please, describe how companies relate to each other and how was companies' behavior at different stages of the lifecycle.

4 PAPER 3 – Industry 4.0 platforms: a typology using a boundary-spanning perspective

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Abstract

Industry 4.0 demands high technical standards in terms of connectivity and integration, which are usually built around platforms. Platforms allow companies to organize these standards by integrating technologies in order to manage the information flow within and across borders. Little is known about which Industry 4.0-related technologies can become platforms. We aim to define which Industry 4.0 technologies can operate as a platform. We propose a conceptual framework that classifies four Industry 4.0 platform levels: (i) Operational, (ii) Digital, (iii) Higher-level, and (iv) Business. We adopt a Boundary-Spanning (BS) perspective to analyze when Industry 4.0 technologies can work as platforms, based on the degree of connection that a certain technology has with its surroundings. We measure this in terms of four BS activities (information collection and processing; external representation; task coordination; knowledge transformation) that help to explain when technology connects other technologies as ‘add-ons’, enabling interoperability for the information flow during the product development process. We employ a multiple-case study by scrutinizing 40 cases and then selecting seven of them in which Industry 4.0 technologies are used as platforms. Our results show that, although in practice only IoT and cloud systems are named platforms, there are different levels of platforms in the Industry 4.0 context. Moreover, we show that some technologies can operate for a single purpose or, in fact, as platforms, depending on how their use is designed by a company. Thus, some technologies are intrinsically platforms while others may so become depending on their use.

Keywords: Industry 4.0; platforms; information systems; boundary-spanning; innovation.

4.1 Introduction

The Industry 4.0 concept has been built around three main principles driving the digital transformation of companies. The first one is vertical integration, which considers the interoperation and communication of operational systems with the management level (Dalenogare et al., 2018). Second, end-to-end engineering considers integrating the value-adding process of the company by synchronizing different functional activities of the company (Sony, 2018). Third, horizontal integration aims at a better synchronization of the operation with various actors in the company value network, including suppliers, complementors, and other external actors (Benitez et al, 2020b; Sun et al., 2020). These three principles are based on the real-time connectivity and information sharing provided by the Industrial Internet of Things (IIoT), which is also boosted by other general-purpose technologies of Industry 4.0, such as cloud, big data, and analytics (business intelligence and artificial intelligence) (Frank et al., 2019a).

Industry 4.0 technologies can form industrial platforms that connect and coordinate the information flow between firm departments and external partners. Platforms have been receiving attention in Industry 4.0 literature due to their potential to generate “network effects” where more complex and disruptive solutions are developed through technology addition (Sturgeon, 2019; Benitez et al., 2020a). In general terms, there are two main types of platform configurations (Gawer and Cusumano, 2014): internal or product platforms, and external or industry platforms. Product platforms are a set of product components that are physically connected as a stable sub-assembly in a common structure where a company can develop a stream of derivative products (Muffatto, 1999). On the other hand, industry platforms are technologies that provide the foundation upon which different firms can be organized as an ecosystem developing their complementary products, technologies, or services (Gawer and Cusumano, 2014).

Industry 4.0 technologies provide a set of opportunities for the creation of new digital solutions, including platforms (Frank et al., 2019b; Sturgeon, 2019). Industry 4.0 solutions are usually built on the integration of different technologies to form a complex IoT system (Benitez et al., 2020a). For instance, a real-time flexible and reconfigurable manufacturing system may depend on a broad set of technologies, including sensors, actuators, supervisory systems, manufacturing executing systems, which may also be integrated with advanced robots and/or 3D printers (Dalenogare et al., 2018). Some specific Industry 4.0-related technologies may behave as solution platforms, being the standard used to integrate other technologies as ‘add-ons’ in order to obtain customized solutions (Benitez et al., 2020a). At a higher technology level, IoT/cloud platforms have been acknowledged as 'Industry 4.0 platforms', for instance, GE Predix and Siemens MindSphere IoT solutions (Bowen et al., 2017). The generic concept of platform acknowledges that there are different *levels* of platforms classified according to their purpose (Sturgeon, 2019), and, thus, there might be different *types* of technologies that can operate as platforms (Benitez et al., 2020a).

The Industry 4.0 literature has argued that IoT-based platforms can create opportunities for companies to engage in an innovation ecosystem structure where technologies can be combined on such platforms to provide highly customized solutions and redefine the business value chain (Benitez et al., 2020a; Kahle et al., 2020; Sturgeon, 2019; Weking et al., 2019). In this sense, there is an evidence gap on how Industry 4.0 technologies can be configurated as platforms at different levels of operation and how they integrate other technologies as 'add-ons' to develop new solutions. Finally, although many scholars have stressed the importance of Industry 4.0 for manufacturing performance (e.g., Dalenogare et al., 2018; Tortorella and Fettermann, 2018), the greatest potential of Industry 4.0 is that it allows companies to redesign their business model around ecosystems supported by IoT-based platforms (Frank et al., 2019b). Consequently, platforms originated from Industry 4.0 technologies may create different configurations in this context (Sturgeon et al., 2019; Benitez et al., 2020a). Thus, we propose the following research questions: *what are the Industry 4.0 technologies that can operate as platforms at different business levels? How do these platforms integrate and coordinate information flows across firm boundaries to develop new digital solutions?*

To answer these questions, we chose the technology systems view, which explains platforms as environments structured by technologies focused on complementary innovations (Cusumano et al., 2019). Moreover, we adopt the theory of boundary-spanning, which considers the creation of linkages to integrate and coordinate communication across organizational boundaries (Aldrich and Herker, 1977). Boundary-spanning was adopted as a theoretical lens for this study because it allows assessing the degree to which a specific technology connects with its surroundings defining whether it is a platform or not. Thus, we suggest that some Industry 4.0 technologies can operate as platforms and that they have a boundary-spanning role to support the product development process of a company and its partners in Industry 4.0. We propose four Industry 4.0 platform levels (Operational, Digital, Higher-level, and Business platforms). We aim to understand how Industry 4.0 technologies act at different platforms levels through boundary-spanning activities. In line with this, our study analyses how these platforms manage the information flow to help the innovation process at the company, supply chain, and ecosystem levels.

We hence employ a multiple-case study of seven companies to deepen our understanding of this phenomenon. Our results demonstrate that some technologies may create platform patterns with different goals. For instance, technologies such as 3D printers and flexible lines support firms at the operational level, fostering flexibility in manufacturing and allowing modularity and mass customization in their businesses; on the other hand, technologies such as ERP (Enterprise Resource Planning) and MES (Manufacturing Execution System) systems, when connected with IoT, work as multiplatforms, allowing for the integration of other digital technologies and enabling vertical integration and internal horizontal integration at the firm level. Moreover, base technologies (Frank et al., 2019a) like cloud and IoT, with the support of big data and analytics and artificial intelligence, allow for a higher technology platform configuration enabling external horizontal integration, process traceability in production systems, and management of real-time data at the supply chain level. Lastly, we found that, in some cases, a Higher-level platform evolves its structure from the supply chain to the ecosystem level, becoming a more advanced platform for ecosystem solutions. This platform configuration encompasses a wide array of Industry 4.0 technologies integrated into the PLM (Product Lifecycle Management) software, driving value co-creation through business alliances for end-to-end solutions. Therefore, our work highlights the importance and substantial differences in cases where one or more Industry 4.0 technologies act as a platform. Thus, managers can learn how to establish Industry 4.0 platforms for different purposes and engage in cooperation strategies in supply chain and ecosystems to create and capture emerging business opportunities.

4.2 Theoretical background

4.2.1. Platforms and Industry 4.0

The concept of platform has been developed by scholars in three overlapping waves of research, focused on product development, technological systems, and economic transactions (Gawer, 2011), respectively. The concept was first coined in the 1990s by Wheelwright and Clark (1992) in the product development wave, introducing the term ‘product platform’, described as new products that ‘meet the needs of a core group of customers’ being of easy modification into derivatives through the addition, substitution, or removal of features. In the second wave, technology strategists identified platforms as valuable points of control for innovation at the industry level (Bresnahan and Greenstein, 1999; Cusumano and Selby, 1995). The pioneering works by Cusumano and Gawer (2002) and Gawer and Cusumano (2002) presented platform leadership levers and explained how a company's platform strategy could drive innovation. In the third wave, the industrial economists adopted the term 'platform' to characterize products, services, firms, or institutions that mediate transactions between two or more groups of agents (two-sided or multi-sided markets) (Gawer, 2011; Rochet and Tirole, 2003).

Alongside the evolution of the subject in literature, Gawer and Cusumano (2014) suggested two predominant types of platforms: internal or product platforms, and external or industry platforms. Product platforms are assets organized in a common structure from which a company can efficiently develop and produce a stream of derivative products (Muffatto, 1999). It is the case of car manufacturers that use a single platform to produce different versions of a product, such as sedan, hatchback, and crossover models using the same structure but changing the external body of the vehicle. Industry platforms, in turn, are products, services, or technologies organized as a business ecosystem to drive innovations (Gawer, 2011). Operational systems such as Windows, iOS, or Linux can be considered industry platforms since many different types of software can run as add-ons on them. Moreover, platforms can be divided into transaction and innovation platforms (Cusumano et al., 2019) – transaction platforms are online marketplaces for the exchange of goods, services, or information, while innovation platforms are those that facilitate the development of new, complementary products and services that are built mostly by third-party companies (Cusumano et al., 2020).

Following these definitions and categories, we focus our study on *industry platforms* and *innovation platforms*, as they comprise open environments of technological architectures pursuing complementary innovations. In an Industry 4.0 context, where new products and technologies are pursued, companies and business ecosystems can define technological architectures through industry platforms to develop new digital solutions (Benitez, Ayala, et al., 2020). So, we adhere to a technology system view based on industry and innovation platforms using Industry 4.0 technologies as technological architectures.

4.2.2. Industry 4.0 platforms

Our starting point is the argument that, in some cases, different Industry 4.0 technologies can operate as platforms inside companies, supply chains, and ecosystems. Benitez et al.

(2020a) argue that some Industry 4.0 technologies may become central technologies, operating as platforms in ecosystems for solution development, being able to connect other technologies as complementors and add-ons. In this sense, we propose that Industry 4.0 can be configured into at least four platform levels, as illustrated in our theoretical framework in Figure 4.1.

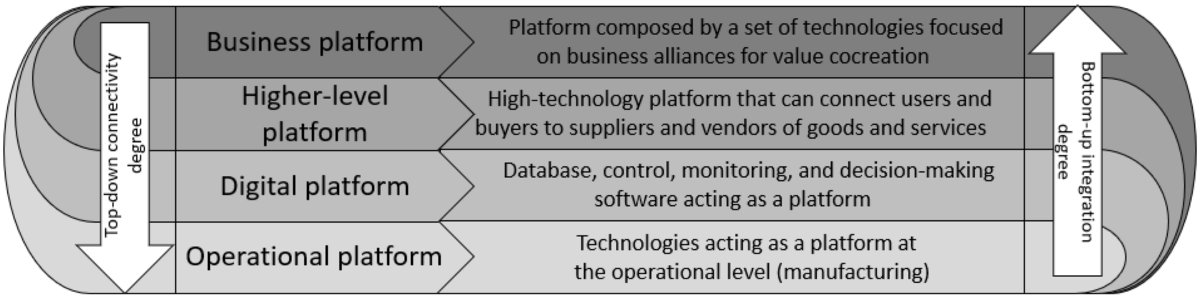

Figure 4.1 – Theoretical framework of Industry 4.0 platform levels.

We propose four distinct platform levels (i.e., *Operational*, *Digital*, *Higher-level*, and *Business platforms*) for Industry 4.0 based on one or more technologies acting as a platform for companies. These four levels were defined based on previous works that mention platform configurations and how they shape businesses for the digital economy (Bowen et al., 2017; Cusumano, 2019; Hein et al., 2019; Sturgeon, 2019). Figure 4.1 presents four distinct levels starting by technologies acting at the operational level on the shop floor until a more advanced one at the ecosystem level. According to Sturgeon (2019), each technology area has its own features, making Industry 4.0 platforms complex environments comprising a set of standards. These standards are related to Industry 4.0 features such as connectivity, interoperability, and integration levels inside factories (Frank et al., 2019a). In this sense, we explain platform complexity levels by illustrating connectivity and integration degrees from layer to layer (Figure 4.1). In other words, all platform configurations connect companies' systems and integrate technologies to varying degrees, making the environment (platform) more complex and technologically developed at the higher levels (Frank et al., 2019a; Sturgeon, 2019).

Consequently, at the first level, we call *operational platforms* when there is a core technology at the factory level (shop floor) acting as a platform in the manufacturing process. This platform level is highly characterized by technologies focused on shop floor processes, providing reconfigurable systems and M2M (machine-to-machine) communication of machinery and equipment (Rüßmann et al., 2015; Wang et al., 2017).

In other words, the entire manufacturing system is managed through the centralization of these technologies in the production line.

At the next level, we introduce *digital platforms* as database, control, and monitoring systems. According to De Reuver et al. (2018, p. 126), a *digital platform* is a 'software-based external platform consisting of the extensible codebase of a software-based system that provides core functionality shared by the modules that interoperate with it and the interfaces through which they interoperate'. This level is characterized by software connected and integrated into one or more systems to manage data. Moreover, in the Industry 4.0 context, software technologies can operate as foundations (platforms) for companies by managing data at the operational level for the product development process (Benitez et al., 2020a; Liu et al., 2020). Generally, the main goal of *digital platforms* is providing, monitoring, controlling, and exchanging information inside company departments and with third parties (Benitez et al., 2020a; Kabugo et al., 2020).

The next level is classified as *higher-level platforms*. Sturgeon (2019) highlights that *higher-level platforms* have their technology architecture rooted in cutting-edge and emerging technologies that can connect users and buyers to suppliers and vendors of goods and services. This platform level refers to a high-technology environment where companies perform operational, tactical, and strategical decision-making in real-time. Some Industry 4.0 technologies like IoT and cloud computing, are frequently portrayed as *higher-level platforms* in technology systems literature (Cusumano, 2019; Fahmideh and Zowghi, 2020; Fan et al., 2019). For example, a cloud platform is an integrated bundle of products and services that aims to create more value for customers and gain competitive advantages (Fan et al., 2019). On the other hand, an IoT platform is a set of technology-enabled entities, including smart physical objects (e.g., sensors and actuators) as well as software services and systems that are connected and work together (Fahmideh and Zowghi, 2020). According to Sturgeon (2019), *higher-level platforms* can support additional platform layers, and their modular system elements can be altered and upgraded without redesigning the entire systems. Therefore, there is no obvious limit to the depth and complexity of this platform configuration in the digital economy. In this sense, when *higher-level platforms* evolve their focus from supply chain to ecosystems, we call this new level *Business platform*. *Business platforms* require the highest integration and connectivity degrees because they focus on business alliances for value co-creation. This platform configuration refers to an ecosystem level managed by a platform. *Business platforms* are technology architectures that focus on business outputs or outcomes such as products, services, and technologies from business alliances (Hein et al., 2019). The term was first introduced by Hein et al. (2019) grounded in the Service-Dominant Logic for service ecosystems. However, management studies by Sarker et al. (2012), Gawer and Cusumano (2015), and Foerderer et al. (2019), initially focusing on product development through business alliances, have molded the concept. Overall, this configuration considers value co-creation practices among partnerships in high-technology environments (Hein et al., 2019). So, this platform configuration is composed of a set of Industry 4.0 technologies focusing on value co-creation for product and services development (complementary innovations) in company ecosystems.

Although these levels help to understand platform patterns in Industry 4.0, many uncertainties remain in the literature. For example, platform studies on Industry 4.0 mention opportunities for data collection through IoT or cloud platforms, but they do not provide a better explanation of how relationships are established for value co-creation (Alcácer and Cruz-Machado, 2019; Weking et al., 2019). Moreover, the literature does not explore how different technologies can be configured as platforms in the Industry 4.0 context. However, there are some perspectives that can help to clarify these uncertainties. First, some works suggest that platforms of different levels can be developed through value co-creation practices (Benitez et al., 2020a; Hein et al., 2019). Second, for each level, different technologies can operate as platforms for different purposes impacting various business levels (Sturgeon 2019; Weking et al., 2019). Finally, by aggregating these perspectives, it is possible to consider that each platform level can create opportunities for companies to manage their information flows through an interoperability between technologies to develop more complex solutions (Benitez et al., 2020a; Kahle et al., 2020). Therefore, understanding how Industry 4.0 platforms transfer and transform information is imperative for companies to achieve higher innovation levels and create and capture emerging business opportunities. In this sense, we aim to identify which Industry 4.0 technologies can operate as technology platforms that allow us to create more integrative and complex solutions involving different technology providers. To that end, we use boundary-spanning theory to define technology features that can characterize them as platforms.

4.2.3. Boundary-spanning theory in Industry 4.0 platforms

Industry and innovation platforms configure technological environments of network effects that generate innovations and complementary technologies (Cusumano et al., 2019; Gawer and Cusumano, 2014). Therefore, we propose to consider these network effects inside technological environments from the perspective of the Boundary-Spanning (BS) theory. This theory explains coordination and communication activities in organizations. In this sense, BS can help understand how companies connect through technologies to obtain valuable information and create more complex solutions (Aldrich and Herker, 1977; Piercy, 2009). BS has been defined as the creation of linkages that integrate and coordinate communication across organizational boundaries (Aldrich and Herker, 1977). This theory considers a set of activities by which an organization connects to its environment. Such activities are based on collecting, assimilating, transforming, and representing information (Aldrich and Herker, 1977; Leifer and Delbecq, 1978). BS has been studied from an array of views, including network analyses and business ecosystems (Cano-Kollmann et al., 2016; Tsvetkova et al., 2014).

According to Aldrich and Herker (1977), boundary-spanning encompasses two main activities: *information collection and processing* and *external representation*. *Information collection and processing* is the selection, transmission, and interpretation of information around the organization. *External representation* reflects actions that persuade other parties by creating favorable impressions about the product or organization to obtain resources, high levels of commitment, and financial support. Alongside the expansion of the theme in literature, two other activities have been suggested as paramount for innovation: *task coordination* and *knowledge transformation*. *Task coordination* was first introduced in organizational studies by Ancona and Caldwell (1992) to account for the facilitation of effective decision-making and intergroup dependencies. *Knowledge transformation* was introduced in management studies as the activity to transform knowledge across organizations' boundaries into new opportunities for innovative and creative outcomes (Schotter et al., 2017; Tippmann et al., 2017).

We argue that the boundary-spanning theory and its four related activities can support the understanding of how platforms operate in Industry 4.0. Indeed, BS activities can be used to assess when a technology can be a platform, given that BS allows us to measure the degree of connection that a certain technology has with its surroundings. Firstly, *information collection and processing* can help to conceive how technologies, when connected, allow for interoperability in processes. Secondly, the *external representation* activity can clarify how to foster collaboration and consequently shape businesses through platforms. In the case of *task coordination*, this activity can explain how technologies are integrated to work organically to develop more complex solutions.

Finally, as stated by Tippmann et al. (2017), *knowledge transformation* is a key activity in the innovation and product development process. Thus, we include this activity in an Industry 4.0 context where companies pursue new digital solutions. So, this activity can help understand how platforms based on Industry 4.0 technologies may operate to develop complementary innovations.

Moreover, these platforms support firms in an Industry 4.0 context where innovative or creative outcomes are desired by managing the information flow through interoperability (Chen and Lin, 2017). In this sense, our work focuses on platforms as boundary-spanning objects in the Industry 4.0 context. Boundary-spanning objects are artifacts (technologies) where inter-organizational relationships are coordinated to acquire knowledge, develop new products, and foster innovation (Star and Greisemer, 1989; Stephenson Jr and Schnitzer, 2006). We propose that using platforms as boundary-spanning objects will stimulate innovation inside firms and business opportunities at the company, supply chain, and ecosystem levels. Thus, this approach supported by BS activities can help explain how inter-organizational exchanges occur to stimulate business and, consequently, how platforms contribute to complementary innovations.

4.3 Research method

We adopted an empirical case study research approach based on qualitative data collection and analysis (Yin, 2009). We chose this research approach because it is useful to deeply investigate complex phenomena to generate novel insights (Goffin et al., 2019; Yin, 2009). We selected a multiple-case approach rather than a single-case analysis to augment external validity and reduce potential observer bias (Voss et al., 2002). We employed a conceptual framework (Figure 4.2) to ground the research and guide our empirical study. Figure 4.2 summarizes the main aspects to be considered in the study and the classification variables from our case studies. Our research design followed the guidelines of Voss et al. (2002) for case study research, as described in the following subsections.

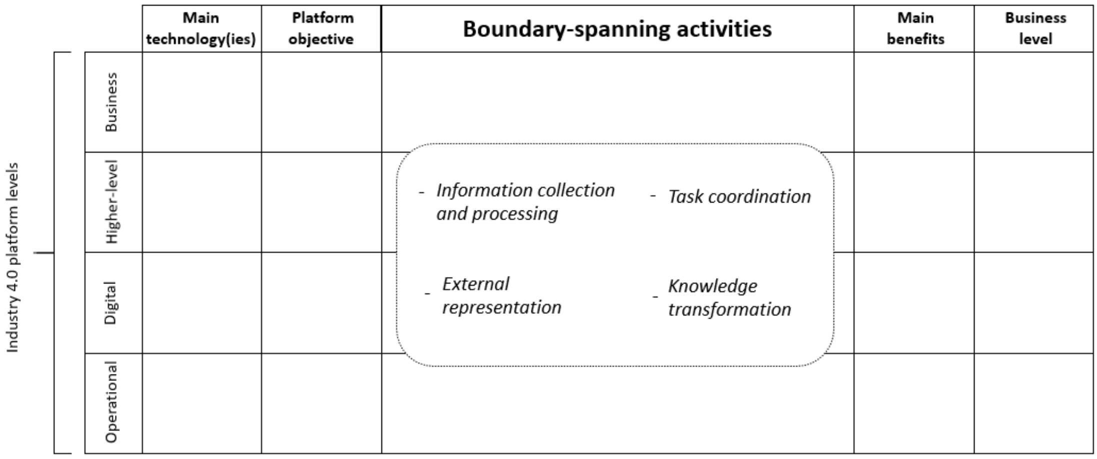

Figure 4.2 – Conceptual framework for the study of Industry 4.0 platforms: using BS activities to classify platform levels.

4.3.1. Industry 4.0 technologies analysis

Our initial step was an in-depth analysis of Industry 4.0-related technologies to conceive which technologies could be evaluated in our analysis. As a result, Table 4.1 presents 17 technologies related to Industry 4.0. We leveraged previous works from Dalenogare et al. (2018), Frank et al. (2019a), and Benitez et al. (2020a) as a guideline to select such technologies. Moreover, we analyzed the Industry 4.0 literature to classify and define each technology. Several works have proposed different types of technologies that can be considered part of the Industry 4.0 concept (e.g., Bartodziej, 2016; Dalenogare et al., 2018; Frank et al., 2019a; Kahle et al., 2020). Some works have considered that Industry 4.0 only comprises disruptive technologies, especially those based on Artificial Intelligence (AI) and the Internet of Things (IoT) (Almada-Lobo, 2016; Yin et al., 2018). In contrast, other works have integrated classical advanced manufacturing technologies, including robotics and automated machines (Frank et al., 2019a; Osterrieder et al., 2019). Moreover, although some technologies such as ERP, MES and SCADA have existed in industrial automation since the 3rd Industrial Revolution, they have been considered in the Industry 4.0 context as key enablers of vertical and horizontal integration (Jeschke et al., 2017; Gilchrist, 2016). Ultimately, Dalenogare et al. (2018) considered a list of technologies that are usually seen in different industries, while Frank et al. (2019a) have suggested that Industry 4.0 should be seen from a set of ‘base technologies’ – namely IoT, Cloud Computing, Big Data, and Analytics and Artificial Intelligence (AI) – that support a variety of applications called ‘front-end technologies’, including robotics, information systems, smart machines, among others. In Table 4.1, we summarize different technologies frequently associated to the Industry 4.0 concept in the literature.

Table 4.1 – Industry 4.0-related technologies

Categories	Technologies	Definition
Vertical Integration	Enterprise Resource Planning (ERP)	Systems that can integrate all data and processes needed to manage a company (Gilchrist, 2016)
	Manufacturing Execution System (MES)	Systems that work in real time to enable the control of multiple elements of the production process (Almada-Lobo, 2016; Jeschke et al., 2017)
	Supervisory Control and Data Acquisition (SCADA)	Systems for monitoring shop floor operations through real-time data collection (Jeschke et al., 2017).
Base technologies	Internet of Things (IoT)	Systems of interrelated computing devices and physical devices that are connected to the internet with the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction (Fahmideh & Zowghi, 2020; Frank et al., 2019a).
	Cloud computing	Type of computing that relies on shared computing resources rather than having local servers or personal devices to handle applications (Fan et al., 2019; Frank et al., 2019a).
	Big data	A large amount of data accumulated that may be analyzed computationally to reveal patterns, trends, and associations, especially relating to human behavior and interactions (Frank et al., 2019a; Gilchrist, 2016).
	Analytics and Artificial Intelligence (AI)	Analytics is the capacity for analyzing data with advanced techniques such as artificial intelligence. Artificial intelligence is a wide-ranging branch of computer science concerned with building smart machines capable of performing tasks that typically require human intelligence (Frank et al., 2019a; Sturgeon, 2019).
Virtualization	Virtual commissioning	Debug real data of the equipment in a virtual environment, simulating the automation equipment virtually, validating its operation in the production line (Da Costa et al., 2019; Jeschke et al., 2017).
	Digital manufacturing	Use of data management systems with data management technologies and simulation technologies for manufacturing optimization, before starting production, supporting the ramp-up phases (Rüßmann et al., 2015).
	Machine vision	Detection of the positioning of objects by image processing systems for quality control (Tao et al., 2018).
	Augmented and virtual reality	Real-scene integration with computer-generated information. Integration of the real with the virtual world (Frank et al., 2019a; Rüßmann et al., 2015).
	Edge computing	Cloud computing systems that perform data processing at the edge of the network, near the source of the data, thus avoiding latency (Kabugo et al., 2020; Tseng et al., 2018).
	Smart grids	Systems of the electricity network to optimize energy efficiency with the exchange of real-time information by integrating information and communication technologies with the existing power grid (Park et al., 2014).

Categories	Technologies	Definition
Flexibility	3D printing (additive manufacturing)	Versatile manufacturing machines for flexible manufacturing systems (FMS), transforming digital 3D models into physical products (Garrett, 2014; Weller et al., 2015).
	Collaborative robots	Robot systems with sensors and processors, enabling direct cooperation with human operators (Bartodziej, 2016; Gilchrist, 2016).
	Industrial robots	Processes automated by internal robotic mechanisms, without human intervention (Gilchrist, 2016; Tao et al., 2018).
	Flexible lines	Self-organized systems (production lines) that can be dynamically reconfigured to adapt to different product types where massive information is collected and processed to make the production process transparent (Wang et al., 2016a; 2016b)

The technologies presented in Table 4.1 are often considered enablers of the connectivity and integration processes in IIoT (Industrial Internet of Things) (Gilchrist, 2016; Jeschke et al., 2017). Consequently, these technologies were also selected because these two processes are considered platform standards in the Industry 4.0 context (Sturgeon, 2019; Frank et al., 2019b). We organized the technologies in four main groups characterized in the literature as: (i) vertical integration technologies – SCADA, MES, and ERP systems; (ii) base technologies – IoT, cloud computing, big data, and analytics and AI; (iii) virtualization technologies – virtual commissioning, digital manufacturing, machine vision, augmented and virtual reality, edge computing, and smart grids; and (iv) flexibility technologies – 3D printing (additive manufacturing), collaborative robots, industrial robots, and flexible lines (Frank et al., 2019a; Sturgeon, 2019; Benitez et al., 2020). We analyzed these 17 technologies in a multiple-case study to comprehend which of them can be classified as platforms (and how) in the Industry 4.0 context. Thus, we selected companies that offer or have adopted at least one of these technologies. All technologies presented in Table 4.1 are related to one of these companies. Next, we describe the case study selection procedures.

4.3.2. Case study selection

Our cases were selected by means of theoretical sampling. Cases were selected because they are relevant to shed light on the constructs under scrutiny (i.e., platforms levels) (Eisenhardt and Graebner, 2007). As a first step, we identified and selected companies committed with the provision or adoption of Industry 4.0 technologies. We intentionally split our sample into technology providers and technology adopters to produce contrasting results that can offer a broader picture of the phenomenon and facilitate the generalization of the results (Yin, 2009; Goffin et al., 2019). This distinction was necessary to conceive how some technologies were developed to be operated by technology providers and how they are operating inside firms (i.e., technology adopters). In other words, providers deliver the technologies presented in Table 4.1, while adopters widely implement one or more of these technologies. So, we considered two surveys[5] employed in previous Industry 4.0 works (Frank et al., 2019a; Benitez et al., 2020a; Kahle et al., 2020). One survey was performed on 87 technology providers in a major industrial cluster in automation and control in Brazil (Benitez et al., 2020a; Kahle et al., 2020). The other survey involved 92 manufacturing companies as technology adopters from the machinery and equipment industry in Brazil (Frank et al., 2019a). In the case of technology providers, since the survey only involved SMEs, we also selected and contacted large and multinational technology providers to complement our sample. These companies were chosen using the following four criteria: (i) be a leading global technology provider; (ii) have a Brazilian branch (where the survey was conducted); (iii) be committed with Industry 4.0 trends (according to websites, reports, and news); and (iv) be a provider of one or more Industry 4.0-related technologies (Table 4.1). Thus, we selected 40 enterprises strongly related to Industry 4.0 technology provision or adoption. From these companies, 21 were technology providers, and 19 were technology adopters, which were connected with at least one of the Industry 4.0 technologies presented in Table 4.1.

We scrutinized the 40 company profiles based on the above criteria, and then chose seven cases (Table 4.4 presents the research codification protocol for inclusion and exclusion of cases). In one of them, we analyzed three different and independent business units due to the existence of very distinct business units. These cases were examined at this level because we were investigating which technologies could be classified as platforms. As a result, we selected five cases related to technology providers offering an Industry 4.0 technology acting as a platform. The list of selected companies comprises technology providers ranging from traditional automation technologies such as MES/SCADA systems and flexible lines to disruptive technologies such as IoT and cloud computing. Moreover, differently from most cases encompassing multinational enterprises, we selected two medium-sized technology providers (B and C) for our final analysis. These

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[5] The resulting industrial reports can be consulted in https://www.ufrgs.br/neo/.

companies were selected due to their core businesses, which were specific to provide an integrated and connected platform for their customers. We also chose two technology adopters with one Industry 4.0 platform implemented in their systems. From these two cases, we selected one which established a complete vertical integration having its ERP system as the main technology and another, which has a 3D printer as the leading technology in its manufacturing system. Thus, we studied and classified each of these cases into one of our four proposed platform levels (*Operational*, *Digital*, *Higher-level*, or *Business*) in Section 4.2.2. In all cases, we classified the technology-as-platform and platform level by analyzing the presence of BS activities (a more detailed description is provided in Section 4.3.4). Finally, each case was organized by platform level and described in our results. Table 4.2 provides a brief description of each case study. Companies' and respondents' names were omitted to preserve anonymity.[6]

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[6] The identification and contacts of the companies were provided to the editorial board of this journal in order to ascertain the transparency of the data collection process.

Table 4.2 – Background of the cases

Case company	Description	Size	Business Unit analyzed	Classification	Data Source
A	Multinational company from the control and automation industry focused on pneumatic and electrical automation	+20,000 employees	Brazilian branch	technology provider	Product Portfolio Manager
B	Brazilian national company from the IT industry focused on software and data processing	50-100 employees	Headquarters (HQ)	technology provider	Development Director
C	Brazilian national company from the electronics industry focused on IoT solutions	50-100 employees	Headquarters (HQ)	technology provider	CEO
D	Multinational company from the IT industry focused on computer, hardware and IT services	+150,000 employees	Cloud + AI Group	technology provider	Senior Product Manager
E	Multinational company from the automation, digitization and electrical industries	+385,000 employees	Digital Factory Division Software Division Business Division	technology provider	Business Developer Engineer Portfolio Development Executive Product and Marketing Engineer
F	Multinational company from the manufacturing industry focused on auto and aerospace parts	+55,000 employees	Brazilian branch	technology adopter	Launch Manager Leader
G	Multinational company from the automotive industry focused on heavy vehicles	+50,000 employees	Brazilian branch	technology adopter	Executive Manager

4.3.3. Research instruments and data collection procedures

Since we proposed four distinct platform levels, we conducted a multiple-case study to collect data from different sources (Yin, 2009). We first employed semi-structured interviews with enterprises classified as technology providers. Afterwards, we interviewed technology adopters, i.e., enterprises that adopted and implemented one or more Industry 4.0 technologies in their systems. The interviews were conducted from March 2019 to March 2020 using a semi-structured interview guideline adapted from Rong et al. (2015), Müller et al. (2018), and Benitez and colleagues (2020a) Industry 4.0-related works (Appendix A). The interviews were focused on capturing cases where

Industry 4.0 technologies act as platforms in the companies. Moreover, we also investigated how they affect businesses at the company, supply chain, and ecosystem level. To achieve these goals, our interviews placed specific emphasis on identifying how BS activities (i.e., *information collection and processing*, *external representation*, *task coordination*, and *knowledge transformation)* are present and occur in each case. For instance, if some technology did not display connection with a BS activity, it was discarded from our analysis as a potential platform case – in Section 4.5, discarded cases are contrasted and compared with the platform cases selected. Moreover, we asked the interviewees to provide arguments and examples on how their technologies work and affect their business to capture enough information to consider the case in our analysis. In some cases (from our final sample, only case G), we visited technology adopters to observe how their Industry 4.0 technologies are operating in their systems. For technology providers, we complemented our research through the analysis of secondary data (reports and websites). Table 4.3 describes our secondary data collection and relation to each case from our final sample.

Table 4.3 – Secondary data organization

Case company	Complementary data
A	Technical visit; industrial report; video; website; and news.
B	Technical visit; industrial report; and website.
C	Technical visit; industrial report; and website.
D	Industrial reports; website; video; industrial fairs; government records; and news.
E	Industrial reports; website; social media; video; industrial fairs; government records; books; and news.
F	Website; video; industrial report; and website.
G	Technical visit; video; industrial report; and website.

Finally, for each interview, we followed a snowball approach, using the next interview to collect new data and contrast statements (in this case, compare the interviews of technology providers and technology adopters). The responses were analyzed, and, in a few cases, it was necessary to make phone calls to clarify specific statements. We performed one interview per company, totalizing 40 interviews that lasted around 1.5h each. At least two research assistants took notes of the main comments, while interviews were conducted by the main researchers. The interviews were also recorded and later transcribed.

4.3.4. Data analysis - validity, reliability, and interpretation

For construct validity, we followed Voss and colleagues' (2002) guidelines for the correct operational measures from our cases. In terms of external validity, we conducted a multiple-case study and compared evidence on a selection of different companies that had strong involvement with Industry 4.0 technologies. Thus, we followed a research codification protocol, as shown in Table 4.4. We structured our codification protocol based on previous works by Ayala et al. (2017) and Benitez et al. (2020a) for qualitative analysis. Moreover, Voss et al. (2002) recommend data triangulation and multiple sources of evidence for construct validity. Therefore, we used secondary data (e.g., industrial reports) about companies related to Industry 4.0 technologies provision and, in some cases, company websites and news. In addition, we visited some technology adopters to deepen our understanding of their Industry 4.0 applications. Finally, all procedures in our research were performed in four different stages of the study, as described in Table 4.4.

Table 4.4 – Research codification protocol

Step 1 - Profile: Identifying Industry 4.0 technology(ies) and core business

Type: Technology provider ( ) Technology adopter ( )
Technology(ies):
Business:

Step 2 – Industry 4.0 technologies analysis and case study selection: Identifying if the technology performs BS activities

I4.0 technology/ BS activities	Information collection and processing	External representation	Task coordination	Knowledge transformation	Conclusion
Technology 1	X	X	X	X	Platform
Technology 2	X	X			No
Technology 3		X		X	No
...					...

Step 3 – Data triangulation: Identifying general aspects related to this technology acting as a platform

Technology provider: Elements and examples identified in providers and their customers (interviews and secondary data).
Technology adopter: Elements and examples identified in adopters (interviews, visits, and secondary data).

Step 4 - Platform level: Defining which levels the platform operates by analyzing where BS activities are stronger in the selected case

Organizational levels/BS activities	Level of information flow				
	Inside borders (only in manufacturing)	Inside borders (across departments)	Outside borders (suppliers)	Outside borders (end-to-end)	Conclusion
Shop Floor (Operational)	X				Operational
Company departments (Digital)					
Supply Chain (Higher-level)					
Ecosystem (Business)					

In Step 1, we identified which Industry 4.0 technologies the enterprise provides/uses, and the company's core business. This step was the starting point to understand how providers sell their Industry 4.0-related technologies and how adopters apply these technologies. In Step 2, called 'Industry 4.0 technologies analysis and case study selection', we analyzed the presence of the four BS activities to classify them as technology-as-platform or not. In many cases, the companies had more than one single technology to be analyzed, so, besides this analysis, the profile scrutiny and technology applications helped us as a complementary analysis to classify each case. Finally, if the case fulfilled these requirements, we selected it for our final data compilation; if not, we excluded it from our analysis. In Step 3, called 'Data triangulation', we used multiple sources of information by including data from websites, reports, and notes from industrial visits to the companies investigated, which were combined with our transcribed interviews to analyze each technology classified as a platform. We also checked the notes and observations made during the interviews to refine our findings. We verified similarities and patterns among the technologies applied as platforms by analyzing BS activities adopting a content analysis approach. This approach followed a meaning rule, which consists of identifying common issues and grouping them according to the interpretation given to their meaning and based on predefined labels (Bardin, 1977).

In Step 4, we analyzed where the presence of BS activities are stronger by measuring the degree of BS activities presence at the shop floor, company, supply chain, and ecosystem levels, and classified the platforms according to our proposed levels (i.e., *Operational*, *Digital*, *Higher-level*, and *Business*). Moreover, in terms of reliability, we proceeded with independent analyses with the support of three research assistants and then discussed our insights. We used interview records and the enterprises' websites to check divergences between understandings, and contacted the interviewees again for further clarification when necessary.

Finally, we summarized our data analysis and case study narrative in an overall classification framework (Figure 4.3). This framework helped us to consolidate our overview of how Industry 4.0 technologies operate as platforms and on which level they operate (i.e., company, supply chain, and ecosystem). The overall classification framework also allowed us to visualize how BS activities are present in each technology and on each platform level.

4.4 Results

Table 4.5 shows the companies' classification according to our research codification protocol presented in Table 4.4. We organized our results, subdividing the sections into two main points: (i) a general overview of each platform level; and (ii) description of each case study relation and how BS activities are present in each platform. In the case of Higher-level and Business platforms, we only have technology provider cases. All cases are classified with an additional letter in brackets in the text. In the next subsections, we describe each classification.

Table 4.5 – Classification of companies according to our research codification protocol

Platform level and technology(ies) as a platform			
Operational	Digital	Higher-level	Business
Technology provider - Company A (Flexible lines)	Technology provider - Company B (real-time MES system)	Technology provider - Company C (IoT platform)	Technology provider – Company E (PLM software + Industry 4.0 base technologies)
Technology adopter - Company F (Aerospace Division - 3D printer)	Technology adopter - Company G (Heavy vehicles – ERP system)	Technology provider - Company D (Cloud platform)	

4.4.1. Operational platforms

Operational platforms refer to a specific technology acting as the foundation (platform) in manufacturing. Next, we describe operational platform cases.

Technology provider – Flexible lines (company A)

Company A is a worldwide leader in automation and a world market leader in technical training and development. Its headquarters are located in Europe, and it has a vast industrial park in southern Brazil, as well as branches, distributors, and representatives all over the country. Company A had begun its business as a wood machinery repair service provider and quickly started to develop its own tools reaching the industrial automation market. Its core business is based on providing technology and tools for industries to accelerate their productivity. Its portfolio includes factory automation robots, saws, sanders, drills, and mechanical parts for industrial automation. With the advent of Industry 4.0, Company A started to shift the focus its operations in this direction. According to its Product Portfolio Manager: *"Industry 4.0 is a kind of journey to connect almost everything in a way to get the best of the automation in the industry, to minimize costs and to increase production with flexibility through connected systems".* In this sense, Company A is a member of a large Industry 4.0 initiative in Europe and is involved in all key standards associations and initiatives on the topic. Today, Company A is engaged with the concept of flexibility in Industry 4.0, offering flexible and reconfigurable lines to its customers. Flexible lines are self-organized systems (production lines) typically comprising computer numerical control (CNC) modular machines that can be dynamically reconfigured to adapt to different product types (Wang et al., 2016a). These lines enable the production of different kinds of products in small batches, with minimum loss of productivity and a higher level of flexibility in processes (Wang et al., 2016b). For instance, it offers the automotive sector a level of flexibility which comports a larger number of variants (modularization and customization) on a single production line. According to the interviewee: *"[...] any production line has its limits, so the problem is [that] there is no integration between the areas, all the automated areas in a company [...] and that is the problem of flexibility from my point of view [...] so, our company offers a flexible line following the Industry 4.0 concept, integrating and connecting all industrial processes"*. In this sense, we found that these flexible lines work as a platform for industrial manufacturing, being the core technology in manufacturing that receives complementary technologies (add-ons) as cobots, industrial robots, and MES systems to automatically reprogram its functions during the product development process.

These lines were considered *operational platforms* acting in manufacturing due to the presence of BS activities and their ability to integrate 'add-ons', i.e., receive the plug-in of more technologies to command their operations at the shop floor level. Regarding BS activities, this platform provides *information collection and processing* through M2M (machine-to-machine) communication, exchanging data for flexibility along with all manufacturing processes. Concerning *external representation* and *task coordination*, we evidenced that the capability to connect other technologies as complementors and add-ons to the flexible line demands a commitment and partnerships with integrators and third parties for process integration and improvement in the platform. In other words, a flexible line platform is continuously involved with other players providing external support for its operations. Moreover, since this platform has a high level of openness to plug-in new technologies, companies have to coordinate their efforts to improve this platform's performance. Finally, regarding *knowledge transformation*, as this platform integrates many technologies, it has a continuously evolving system which allows for higher levels of product customization, modularization, and process flexibility at the shop floor level.

As a result, this platform helps firms to achieve the Smart Manufacturing[7] dimension in Industry 4.0.

Technology adopter – Aerospace Division – 3D printer (company F)

Company F is dedicated to the provision of auto and aerospace parts. This European multinational has given special attention to Industry 4.0 in its aerospace division. This division is focusing on product development through the establishment of a 3D printing platform. This platform is connected to customers to provide customized solutions. As argued by the Launch Manager Leader: *"We have many kinds of products, any kind of joints (modules) that we can produce, and in terms of machinery our aerospace division has one 3D printing platform which connects our line with our customers"*. According to the interviewee, the aerospace division is using 3D printing to reshape the possibilities in manufacturing and achieve new businesses through the connection with its customers. Moreover, citing what the Senior Vice President of Engineering & Technology said about 3D printing, *"[...] we believe the array of processes that fall under the 'additive' umbrella will revolutionize manufacturing across every industrial sector[...]",* the interviewee said: *"[...] therefore, we are working to turn this into a global standard for all company units, especially the automobile branches in which, nowadays, in terms of Industry 4.0, we are only working with traceability of auto parts"*. Thus, we noticed that when 3D printers operate as platforms, they need more technologies connected in manufacturing to perform all tasks in the product development process. In other words, 3D printing platforms also have an openness level to receive add-ons in manufacturing. For example, while previous ICT revolutions have enabled consumers to take an ever-increasing part in production processes, 3D printing is the 'last piece of the puzzle' that allows consumers to intervene at any stage in the production process (Rayna et al., 2015). In this sense, 3D printers work as the central technology in manufacturing, operating as a platform connected with digital and automation systems for the product development process.

Referring to BS activities, this platform has an online system that collects and shares information among its users for open design and printing. Regarding *external representation,* it connects its users and fosters their participation in product development initiatives, further engaging its customers in the use of this platform. The 3D printing

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[7] Smart manufacturing is a fully integrated, collaborative manufacturing system that responds in real time to meet changing demands and conditions in the factory, in the supply network, and in customer needs (Kusiak, 2018).

platform also promotes co-creation activities for product design, allowing *task coordination* by incrementing the product development process with its users' ideas. For *knowledge transformation*, this platform co-creation activities achieve mass production and mass customization through crowdsourcing practices that integrate user inputs for product design in its manufacturing.

Main findings for operational platforms

Our results suggest that flexible lines and 3D printers can be configured as operational platforms in the Industry 4.0 context. Moreover, our results imply that this level of the platform is highly associated with manufacturing processes for product development. We evidenced two cases where BS activities occur when these technologies act as the core technology in manufacturing. Firstly, a flexible line is a technology compound by self-organized systems (production lines) that can be dynamically reconfigured to adapt to different product types where a piece of massive information is collected and processed to make the production process transparent (Wang et al., 2016a). This technology operates as a platform when the entire manufacturing system is reconfigured by these self-organized systems, receiving other technologies as 'add-ons' or plug-ins to work organically for product development. Secondly, 3D printers can only be considered a platform when the entire manufacturing system operates based on information and commands from this technology. In other words, the entire information flow for manufacturing execution stems from a 3D printer, which leads the production line. In addition, one prominent feature of this platform configuration is its dependence on highly automated environments with many automation technologies (e.g., industrial robots) as support for the product development process. Finally, although this platform configuration does not connect all systems at the company (vertical integration) and supply chain (horizontal integration) levels, it engages partners for technology integration and product co-creation activities, fostering process improvement, mass customization, mass production, and modularization at the shop floor level.

4.4.2. Digital platforms

Digital platforms refer to software-based platforms to manage and collect data for decision-making. Next, we describe digital platform cases.

Technology provider – real-time MES system (company B)

Company B is a medium-sized enterprise from an automation and control industrial cluster located in southern Brazil. Nowadays, its core business is centered on the energy and manufacturing sectors. This company started its activities in the 1980s as an IT service provider. After a few years, its structure grew, the number of people working with the service increased as well, and it started working with software provision only. Initially, Company B provided SCADA software for data acquisition in the manufacturing industry. Alongside the growth in interest in Industry 4.0, it perceived the need to transform its business into a platform aligned with its customers' needs. Hence, it started to develop a real-time MES system to connect people, machines, and processes. This MES connected to the SCADA system collects and analyzes information in real-time to perform tasks and organize the production with an integrated module of the Advanced Planning System (APS). The integration of these technologies allowed Company B to develop factory monitoring solutions, especially focused on energy management. According to its Development Director: *"[...] we can provide integration of the energy management system of the companies with our real-time MES/SCADA system"*. The company provides a software platform through its real-time MES system, making the APS more effective by providing greater data visibility and improved analytics integration. By aligning the APS flow, this real-time MES enables an organic system, creating vertical integration systems for enterprises. In other words, this MES system can operate with different sensors, actuators, and robotic systems, becoming the key technology in manufacturing with the potential to receive many other technologies (add-ons) to support decision-making at the shop floor level. So, this real-time MES system allows companies to achieve the vertical integration that characterizes Industry 4.0.

Company B is also participating in an Industry 4.0 collaborative project, using its real-time MES system as a proxy in a flexible and reconfigurable manufacturing cell (Benitez et al., 2020a). The main goal of this project is to achieve vertical integration by using this technology to connect all departments in the company. In this context, Company B realized the need to find joint solutions in Industry 4.0 by using cooperation and competition strategies inside ecosystems. As stated by the interviewee: *"Very quickly we realized that when we talk about Industry 4.0, it involves many actors, it involves a lot of knowledge"*. Concerning BS activities for smart grids, this platform has a distribution channel through IT for the sharing of information (*information collection and processing*) about energy consumption among its users when it integrates MES/SCADA systems. Moreover, this platform requires a high level of commitment from its users when applied in the energy sector (*external representation*), as they must open their internal systems to share energy consumption data. This also requires *task coordination* for energy distribution among partners because it needs to coordinate the capabilities of all generators, grid operators, and its users to make electricity distribution to all parts of the system as efficient as possible. In the case of manufacturing, this real-time MES system allows transparency and communication between all elements in manufacturing. Furthermore, because this platform needs many add-ons to be able to perform industrial tasks, a high level of commitment (*external representation*) is required from other technology providers and suppliers. This is necessary because they need to coordinate efforts (*task coordination*) to make different technologies operate organically through MES commands. Finally, in relation to *knowledge transformation,* this platform is constantly pursuing optimal energy distribution among its users when operating as a smart grid by readapting its generators and operators through data collection, analysis, and MES system commands . At the same time, in manufacturing cells, the lines respond quickly and adaptively to changes in demand.

Technology adopter – Heavy vehicles – ERP system (company G)

Company G is a European multinational manufacturer of trucks and buses. This company has operations worldwide, having one Brazilian assembly branch in the southeastern region. When Industry 4.0 started to become a world trend, this company understood the importance of renewing its manufacturing line. So, it began to connect all the systems in the factory, from sensors and PLCs on the shop floor to its ERP system. Today, this company has Industry 4.0 vertical integration in its Brazilian branch managed by an ERP software. We ascertained this during our interview with its Executive Manager who said: *"Yes, today we have a complete vertical connection, starting in simulation, going to the product demand, managing the manufacturing, supervising and sending orders to the robots, which are totally flexible according to customer needs [...] so, we have ERP, we have MES, we have SCADA [...], and then we have the equipment connected, using IoT, which is one of the pillars of Industry 4.0".* This company has a real-time ERP system that allows for the connection of many modules such as CAD/CAE, MRP, and logistics management, making this system the platform operating in the factory. Furthermore, we noticed the need for the connection of other technologies with this system, making it able to execute decision-making commands inside the factory. In addition, this system also has an openness level to connect other technologies as add-ons to improve the platforms' performance by integrating all company departments. As a result, this ERP system has become a central point for internal horizontal integration of departments between areas, allowing for the connection of subsidiaries and suppliers close to the company.

We classified this case as a digital platform due to the BS activities performed by Company G's ERP system. This platform shows high levels of *information collection and processing* through the integration of all manufacturing using its ERP system. All data inside Company G is visualized and disseminated in real time through this platform. Moreover, in what comes to *external representation,* this platform achieves at least some results when applied in external environments. For instance, Company G works with the concept of raw material traceability with its suppliers and subsidiaries having a certain level of commitment from their partners in its supply chain. However, this level of external representation is limited to data sharing and does not enable external horizontal integration for Company G. Regarding *task coordination*, this platform aligns all company departments (internal horizontal integration) by synchronizing work in the product development process. Besides, in terms of external collaboration, this platform works with traceability, allowing for some coordination of replacement parts with suppliers. For *knowledge transformation*, this platform enables the company to respond appropriately and with agility to changing market signals and new opportunities by aligning all company departments.

Main findings for digital platforms

Our results suggest that ERP and MES software can be configured as digital platforms in the Industry 4.0 context. We found that digital platforms are mainly focused on data collection and management inside enterprises, which is the strongest BS activity of this platform configuration. We also noticed that this platform level allows for vertical integration inside firms and internal horizontal integration between firm departments. Furthermore, we found cases, namely two German multinational companies, one from the automotive industry and another from the engineering and technology industry, and one British multinational company from the automotive industry, which had adopted ERP or MES software as the core technologies inside their systems. However, we detailed just one case of a technology adopter where all technologies are connected through an ERP system working as a platform inside the company. Finally, in some cases, digital platforms connect companies with third parties, but only for specific tasks such as traceability and energy efficiency (smart grid), not connecting firms at supply chain or ecosystem levels for product development.

4.4.3. Higher-level platforms

Higher-level platforms refer to high-technology environments acting as a platform to connect companies with third parties (e.g., suppliers and buyers). Next, we describe two cases, one based on IoT platforms and the other on Cloud and AI.

Technology provider – IoT platform (company C)

Company C is a medium-sized company from an automation and control industrial cluster located in southern Brazil. This company started its activities in the late 1990s selling sensors and making systems integration. In recent years, it began to work in Industry 4.0 IoT solutions, providing what they call an IoT platform. Company C started to internalize the technologies and systems by connecting hardware, cloud, and high-level software with an IoT platform to develop advanced solutions. As stated by its Founder and CEO: *"Large companies in Brazil still have a tiny amount of usable data on the manufacturing process, and our company connects all systems through our IoT platform"*. Today, the company is working on joint projects to develop Industry 4.0 solutions using its IoT platform to provide intelligence and connectivity to their customers. As the CEO affirmed: *"during this process of transition [to Industry 4.0], we shifted from being a company that sells products to one that sells intelligence through our platform to solve industrial automation problems".* We found this IoT platform composed by technology-enabled entities allowing for the connection of several apps, BI (business intelligence) commands, and add-ons. This makes companies achieve external horizontal integration because their users (platform owner and partners) have access to data, technology, and several tools for coordination in decision-making.

This platform has advanced BS activities as compared to the other platforms presented. Regarding *information collection and processing,* its IoT systems allow for connectivity between supply chain partners for joint decision-making, thus contributing to create a Smart Supply Chain. With reference to *external representation*, the IoT platform achieves a high level of commitment from external partners by connecting systems and providing analytical tools for solution development. As this is an open environment, cybersecurity is a concern, conditioning the access of its partners to data acquisition and analytical tools to contractual relationships. These partnerships through contracts are effected to guarantee cybersecurity and user access to analytical tools for supply chain management. Moreover, *task coordination* is enhanced in the supply chain by this platform because it has the support of big data and analytical tools to overcome breakouts in the chain. Finally, regarding *knowledge transformation*, this platform has an open environment for the leading company to pursue external capabilities to complement its product/service development. However, it still lacks connectivity with customers for end-to-end solutions.

Technology provider – Cloud platform (company D)

Company D is a multinational company selling computer software, electronics, computers, and personal services. This company has always focused on trending and emerging technologies, making high investments in technology platforms and software development in its R&D department since its origins. We interviewed members of the Cloud + AI group that develops a cloud platform. This cloud platform offers analytical tools as AI algorithms and IoT connection for its customers to build their apps and solutions. As stated by its Senior Product Manager: *"The point is we do not provide the solution, we help these customers to build their solutions and, obviously, these solutions leverage our software and cloud services to work with them [...] but the end consumer owns the service and resells it in its ecosystem".* So, this company is strongly engaged in Industry 4.0 high-tech environments through a cloud platform for its customers to develop their own solutions. The Senior Product Manager concluded: *"On our side, we offer the cloud platform and the tools, the technology so that the customers can build their own solutions themselves and keep control of the related know-how"*. Moreover, this platform has a level of openness allowing to plug-in new technologies and apps to improve its operational capability for its users. In this sense, this platform connects all systems in manufacturing, enabling the insertion of new technologies as add-ons.

Regarding BS activities, this platform operates as a general server where *information collection and processing* are shared among its users. *External representation* occurs inside this platform through contracts, as it requires commitment from its users who are sharing data in the same space with common goals (e.g., app development). In what comes to *task coordination*, this platform offers software applications for product and software development, requiring coordination between third parties and the platform owner. Finally, in relation to *knowledge transformation*, cloud platforms offer a set of analytical tools helping the company to develop its own solutions and improve them by using advanced algorithms in the AI field at the company level. At the supply chain level, this platform integrates suppliers for complementary capabilities and parts replacement in the product development process.

Main findings for higher-level platforms

We found that, with the support of big data, analytics, and AI, IoT and cloud platforms can be configured as higher-level platforms in the Industry 4.0 context. In general terms, higher-level platforms have Industry 4.0 base technologies (e.g., IoT, cloud, big data, analytics, and AI) as core technologies. When working together, these technologies achieve external collaboration at the supply chain level, helping to develop Smart Supply Chains[8]. In other words, these platforms provide external horizontal integration for companies, providing strong ties with suppliers in their supply chain. We found cases in which IoT and cloud technologies, acting as platforms, can connect enterprises and their supply chains. Besides, the integration of skills and capabilities in these supply chains occurs with the support of big data and analytics techniques, including AI. Furthermore, companies that adopt these platforms usually have a high-technology architecture embedded in their systems with a considerable level of openness to technology synchronism and connection (add-ons). However, we highlighted different examples of implementation in these platforms. For instance, in the case of D, higher-level platforms are only used internally for apps and service development, whereas in the case of C they connect enterprises horizontally in their supply chain. We also noticed that although this platform connects the entire supply chain, it has weak ties with customers, not providing end-to-end solutions. So, higher-level platforms certainly offer better integration and connectivity degrees than other platforms (operational and digital), but they struggle in value practices at the ecosystem level because of their weak ties with customers.

4.4.4. Business platforms

Business platform refers to a higher-level platform that evolved its concept from the supply chain to the ecosystem, focusing on business alliances for value co-creation. Next, we discuss one representative case to illustrate such features.

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[8] Smart Supply Chain is defined as the exchange of information and integration of the supply chain through digitization, production synchronization with suppliers to reduce delivery times, and information distortions that produce bullwhip effects (Frank et al., 2019a; Wu et al., 2016).

Technology provider – General Industry 4.0 technologies (company E)

The last case, Company E, is a European multinational with a vast product, service, software, and technology portfolio. To account for such a variety, three different interviews with the Digital Factory Division, Software Division, and Business Division were made. It was verified that this company could provide more than one type of Industry 4.0 platform, but we focused mainly on Business platforms because it is the most advanced level that this company can offer to its customers. When questioned about Industry 4.0, the Business Development Manager said: *"Industry 4.0 technologies are much more than something that makes the company more efficient and takes away the workforce [...] we see that Industry 4.0 is enabling some business models to change in quite drastic ways"*. In this sense, today, Company E can offer in its portfolio a very advanced platform focused on product development through business relationships. This platform is based on Industry 4.0 base technologies such as IoT and AI, together with PLM (Product lifecycle management) software. As stated by its Product and Marketing Engineer: *"We have a famous use case with a German automotive multinational company where we are developing their product platform over ours. This company will integrate production to the dealer, so from production to the dealer to IoT, and, for example, when the customer buys a car, she or he will know where the car is in the process; besides, part of the platform will make predictive maintenance and all the automation thing for production [...] thus, we are connecting the end consumer to this platform through our PLM software to have all the links in the ecosystem"*. Thus, we found that this platform composed by PLM with Industry 4.0 base technologies (IoT, big data, and AI) encompasses several technologies connected as add-ons in manufacturing, resulting in an accomplishment of the end-to-end concept. The Portfolio Development Executive corroborated this statement by saying: "*That is because Industry 4.0 asserts the following: you need to integrate all your company departments and processes, and then, at the endpoint, you have to perform the integration in your equipment that is there in your customer's field."*

About BS, this platform manages all activities through its PLM software in the product development lifecycle process. This platform establishes projects among its users for value creation inside the ecosystem. Companies inside this ecosystem can engage in different projects managed by the PLM software. For *information collection and processing*, all project activities are detailed in the PLM software from the platform owner to all partners in the ecosystem. Whereas its partners can engage in simultaneous projects, they can also propose other projects or develop their own solutions making complementary innovations inside the ecosystem. In the case of *task coordination*, workflows are managed inside this platform by actors selecting their roles in each project, having the final goal to present new products to the market. Lastly, for *knowledge transformation*, as many partners can co-develop solutions, there are many interdependencies in this platform. This means that some partners are also customers or intermediaries in the platform. This is supported by a complete overview of the product lifecycle stages in each project. So, this platform provides end-to-end solutions to bring the concept of Smart Products[9] to life. These end-to-end solutions are built through the access to other capabilities and analytical tools in the platform.

Main findings for business platforms

In a general overview, by comparing this case with the above case of Higher-level platforms, we highlight that when Industry 4.0 base technologies integrate with other more advanced software products like PLM (Product lifecycle management), they can be configured as Business platforms in the Industry 4.0 context. We found one case that illustrates examples of a platform that offers end-to-end solutions and focus on B2B relationships at the ecosystem level. We realized that Business platforms have the same technological features of higher-level platforms, but the concept is quite different. While higher-level platforms are more focused on contractual arrangements at the supply chain level, Business platforms go a step further to establish business alliances through product projects for value co-creation at the ecosystem level. Since this platform pursues value co-creation by B2B alliances, many complementary innovations are linked to each other. In this sense, we perceived that many developers inside this ecosystem are also intermediaries[10]: hence, Business platforms fulfill the end-to-end[11] concept inside the ecosystem.

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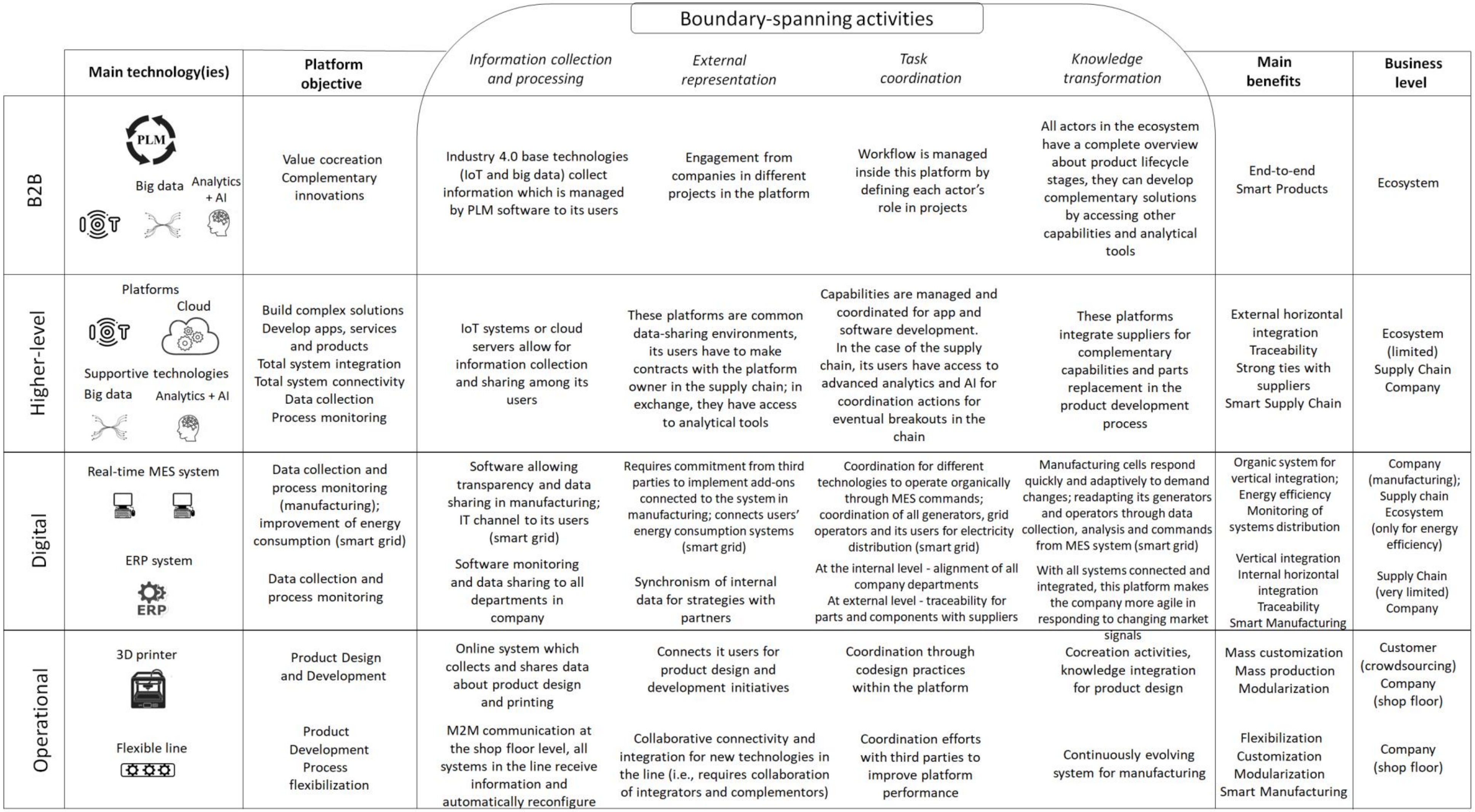
[9] Smart Products can provide data feedback for new product development (Tao et al., 2018) as well as they can provide new services and solutions to the customer (Porter and Heppelmann, 2015).

[10] Actors that must adopt an innovation before it reaches the end consumer (Adner, 2006).

[11] The end-to-end engineering across the entire product life cycle describes the intelligent cross-linking and digitalization throughout all phases of a product life cycle: from the acquisition of raw materials to the manufacturing system, product use, and product end of life (Sony, 2018).



			Boundary-spanning activities					
	Main technology(ies)	**Platform objective**	*Information collection and processing*	*External representation*	*Task coordination*	*Knowledge transformation*	**Main benefits**	**Business level**
B2B	PLM Big data Analytics + AI IoT	Value cocreation Complementary innovations	Industry 4.0 base technologies (IoT and big data) collect information which is managed by PLM software to its users	Engagement from companies in different projects in the platform	Workflow is managed inside this platform by defining each actor's role in projects	All actors in the ecosystem have a complete overview about product lifecycle stages, they can develop complementary solutions by accessing other capabilities and analytical tools	End-to-end Smart Products	Ecosystem
Higher-level	Platforms IoT Cloud Supportive technologies Big data Analytics + AI	Build complex solutions Develop apps, services and products Total system integration Total system connectivity Data collection Process monitoring	IoT systems or cloud servers allow for information collection and sharing among its users	These platforms are common data-sharing environments, its users have to make contracts with the platform owner in the supply chain; in exchange, they have access to analytical tools	Capabilities are managed and coordinated for app and software development. In the case of the supply chain, its users have access to advanced analytics and AI for coordination actions for eventual breakouts in the chain	These platforms integrate suppliers for complementary capabilities and parts replacement in the product development process	External horizontal integration Traceability Strong ties with suppliers Smart Supply Chain	Ecosystem (limited) Supply Chain Company
Digital	Real-time MES system	Data collection and process monitoring (manufacturing); improvement of energy consumption (smart grid)	Software allowing transparency and data sharing in manufacturing; IT channel to its users (smart grid)	Requires commitment from third parties to implement add-ons connected to the system in manufacturing; connects users' energy consumption systems (smart grid)	Coordination for different technologies to operate organically through MES commands; coordination of all generators, grid operators and its users for electricity distribution (smart grid)	Manufacturing cells respond quickly and adaptively to demand changes; readapting its generators and operators through data collection, analysis and commands from MES system (smart grid)	Organic system for vertical integration; Energy efficiency Monitoring of systems distribution	Company (manufacturing); Supply chain Ecosystem (only for energy efficiency)
	ERP system	Data collection and process monitoring	Software monitoring and data sharing to all departments in company	Synchronism of internal data for strategies with partners	At the internal level - alignment of all company departments At external level - traceability for parts and components with suppliers	With all systems connected and integrated, this platform makes the company more agile in responding to changing market signals	Vertical integration Internal horizontal integration Traceability Smart Manufacturing	Supply Chain (very limited) Company
Operational	3D printer	Product Design and Development	Online system which collects and shares data about product design and printing	Connects it users for product design and development initiatives	Coordination through codesign practices within the platform	Cocreation activities, knowledge integration for product design	Mass customization Mass production Modularization	Customer (crowdsourcing) Company (shop floor)
	Flexible line	Product Development Process flexibilization	M2M communication at the shop floor level, all systems in the line receive information and automatically reconfigure	Collaborative connectivity and integration for new technologies in the line (i.e., requires collaboration of integrators and complementors)	Coordination efforts with third parties to improve platform performance	Continuously evolving system for manufacturing	Flexibilization Customization Modularization Smart Manufacturing	Company (shop floor)

Figure 4.3 – Overall framework for Industry 4.0 technologies operating as platforms at a company, supply chain, and ecosystem levels

4.5. Discussions

Our results help to obtain a broader understanding of the influence of Industry 4.0 technologies on platform configurations. Overall, the platform concept is classified into two main configurations – product and industry – as proposed by Gawer and Cusumano (2014) and previously discussed from different perspectives in product development, economic transactions, and technology systems literature (Wheelwright and Clark, 1992; Rochet and Tirole, 2003; Gawer, 2011). We focused on the technology systems view, which explains platforms as environments of technology architectures pursuing complementary innovations (Den Hartigh et al., 2016; Cusumano et al., 2019). In this sense, our work points to different Industry 4.0 platform levels (*Operational*, *Digital*, *Higher-level,* and *Business*), giving examples of technologies acting as a foundation or platform in different contexts. Moreover, our results provide evidence of when some Industry 4.0 technology acts as one of the proposed platform levels through the presence of Boundary-Spanning activities. Hence, we explain on which business level each technology-as-platform has a stronger influence by covering their BS activities. We summarized our findings in Figure 4.3, aiming to illustrate the features of each platform level in Industry 4.0. We propose this framework (Figure 4.3) to guide the discussion of our findings and to clarify the main aspects of each platform configuration. The framework also illustrates how BS activities occur in each technology-as-platform and at which business level (company, supply chain, and ecosystem) they operate.

Our results indicate that Industry 4.0 platform configurations are not only composed of general-purpose technologies such as Cloud and IoT. We also found applied technologies such as flexible lines, ERP, and MES systems operating as platforms at different business levels. However, our findings suggest that these technologies work as platforms only in certain circumstances. These circumstances are linked to the presence of BS activities, which grounded our research by showing how the technologies may connect with their surroundings to work as a platform. Moreover, in accordance with Benitez et al. (2020a), our research draws attention to the importance of ‘add-ons’ for platforms in the Industry 4.0 context. Our findings point to the need for the integration of other complementary technologies as ‘add-ons’ with these core technologies. Thus, these core technologies (Figure 4.3) can perform BS activities as a platform by orchestrating the add-ons to work organically (Schroeder et al., 2019; Benitez et al., 2020a).

Another interesting result from our study is that, most of the time, Industry 4.0 technologies are operating for other purposes, normally related to industrial automation or Smart Manufacturing, as suggested by Dalenogare and colleagues (2018) and Frank and colleagues (2019a), but not as platforms. For instance, we found cases (previously excluded from our analysis due to our research codification protocol) in which 3D printer technology only operates as a service provider, manufacturing tools, and components for machinery maintenance. In addition, we also analyzed cases where MES and ERP systems are not connected to other technologies, only performing simple dashboard commands in computer software. We also found cases where cloud technology only operates as a server for data storage without any integration in technologies or analytics techniques for process improvement. Likewise, we noticed that IoT technology is present in several cases but simply connecting systems through a Wi-Fi connection, not using RFID or connected sensors for systems integration and data management. Thus, our results show these technologies operate as platforms when the business vision and business strategy are tightly related to technology management (Bharadwaj et al., 2013). Therefore, the concept of platform opportunity in technology systems should guide technology structuring for the establishment of technology-as-platform in the Industry 4.0 roadmap (Mittal et al., 2018; Schumacher et al., 2016). Furthermore, by using BS activities, we identified technologies-as-platforms by measuring the degree of connection that a certain technology has with its surroundings. Then, our study identified and discussed BS activities as characteristics that change depending on the type and level of each platform.

Concerning *information collection and processing*, we evidenced internal information sharing for Operational and Digital platforms and external information sharing for Higher-level and Business platforms as the two predominant patterns for this activity. Following Longo and colleagues' (2017) and Andersson and colleagues' (2016) works about internal knowledge transfer in technological environments, we identified the necessity of open systems with interoperability skills for data processing through software. Thus, our results portray platforms with these characteristics (e.g., Operational – M2M communication; and Digital: vertical integration), evidencing the connection of the knowledge transfer process with the *information collection and processing* activity. Despite these similarities, in some specific cases, information sharing crosses firm boundaries in Operational and Digital platforms reaching third parties. This occurs in 3D printing platforms that share their data with customers for the NPD (new product development) process; and in ERP platforms which share data with other firms' subsidiaries and close suppliers (internal horizontal integration). Moreover, in the case of external information sharing, we noticed that this activity is intrinsically linked to external partners at the supply chain and ecosystem levels in Higher-level and Business platforms, respectively. This occurs due the role of IoT and cloud technologies to connect users. Our cases show evidence that these technologies are key enablers for external collaboration in the Industry

4.0 context. On these platform levels, IoT and cloud technologies allow for transparency and real-time data sharing along the value chain with company partners. This is in accordance with Li and Du (2015) and Nord and colleagues (2019), proposing cloud and IoT technologies as boundary-spanning objects for data sharing in collaborative networks.

Regarding *external representation*, following Benitez et al. (2020a), we observed that this activity occurs in some cases through technology implementation and coordination with technology providers. In this sense, we evidenced a strong presence of outside-in and inside-out Open Innovation approaches in platforms. According to Chesbrough (2003), Open Innovation is defined as: '*the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and to expand the markets for external use of innovation, respectively*'. Thus, an outside-in approach refers to a series of activities that help with the integration and interaction with external sources of knowledge for internal innovation, while inside-out refers to collectively engaging a larger audience to support an idea and thereby achieves outside innovation in new markets (Chesbrough, 2012). Our results show cases in which Operational and Digital platforms (e.g., flexible lines, 3D printing, real-time MES system) execute an outside-in approach by pursuing external knowledge for internal innovation (implementing add-ons) to improve their performance and for NPD. In other cases, Digital platforms (i.e., ERP system and real-time MES system as a smart grid) do not adopt Open Innovation approaches to connect third parties but rather acquire their commitment through aligned strategical goals (e.g., traceability and energy consumption). Moreover, in higher layers (Higher-level and Business), these platforms reach external representation commitment through inside-out approaches. In the case of the Higher-level, these platforms establish contractual relationships at the supply chain level by opening their environment and providing analytic tools for its users to develop apps and solutions or align supply chain strategies. In Business platforms, in turn, the inside-out approach is used to bring ideas to the market through collaborative and joint projects for value co-creation at the ecosystem level. Both approaches are cited by Weking et al. (2019), who refer to them as business models in the Industry 4.0 context, corroborating our initial proposition that this activity fosters collaboration and thus shapes businesses in platforms.

Referring to *task coordination*, we show that coordination most often occurs for platform owners who have their strategies aligned to Smart Manufacturing, supply chain, or NPD. In this sense, platforms in Industry 4.0 stress the need for complementary capabilities and technologies to be plugged into them to optimize processes and develop new products (Benitez et al., 2020a). Benitez et al. (2020b) and De la Prieta et al. (2019) call attention to complementary capabilities and technologies from competitors for technology development in the Industry 4.0 context. Our findings suggest task coordination as a key activity to orchestrate these skills and resources for technology development in platforms. Firstly, regarding flexible lines in Operational platforms, *task coordination* is required to connect all complementary technologies (add-ons) to be operated by the core technology. The same occurs for the real-time MES system in Digital platforms, which needs all technologies connected for the MES system to be able to operationalize them organically. These examples illustrate that *task coordination* is an activity that may happen to upgrade and improve technological environments, as suggested by Kahle et al. (2020). Otherwise, ERP systems acquire ubiquitous internal coordination through internal horizontal integration by aligning all firm departments; they also achieve some coordination with suppliers and subsidiaries at external levels. However, this connectivity is limited to the traceability of parts and components, establishing weak ties within the supply chain. Regarding Higher-level platforms, we noticed that many coordination tasks are related to preventing supply chain breakouts by accessing analytics tools. In addition, as IoT and cloud computing platforms are highly associated to app, services, and software development, platform users need coordination with the platform owner to manage all capabilities within this platform. Thus, coordination is still linked to obligations defined by contractual relationships granting users the rights to use the tools of that platform. As suggested by Ma et al. (2020), such a coordination is beneficial in the supply chain manufacturer-supplier relationship, where revenue-and-cost-sharing contracts could coordinate the supply chain perfectly. In the case of Business platforms, all tasks are managed through the definition of project roles for value co-creation inside the ecosystem. This behavior is similar to the leadership stage in Industry 4.0 innovation ecosystems suggested by Benitez et al. (2020a), who affirm this stage moves towards a platform-oriented environment where the actors’ roles change according to each project phase. Thus, our results suggest that Industry 4.0 platforms have their tasks mainly coordinated for technology development and operationalization.

Regarding *knowledge transformation*, our results provide insights about the presence of absorptive capacity (Cohen and Levinthal, 1990) in platforms through dynamic capabilities based on Industry 4.0 features such as interoperability, real-time data management, systems reconfiguration, data analytics, and end-to-end. Thus, following previous studies by Kahle et al. (2020) and Müller et al. (2020), Industry 4.0 design and implementation require absorptive capacity from firms, consequently demanding that their R&D departments have the ability to cooperate and utilize external knowledge for innovation. Our findings show that Industry 4.0

platforms embed absorptive capacity by recognizing the value of new information, assimilating it, and transforming it for market purposes or strategic goals. Thus, the aforementioned Industry 4.0 features working as dynamic capabilities are paramount for innovation generation inside firms. Liu et al. (2019) argued that dynamic capabilities as systems reconfiguration, integration, and connectivity between users and systems are enablers of radical innovation in Industry 4.0. Moreover, we found the presence of systems reconfiguration and interoperability at lower levels at the shop floor in Operational platforms. For Digital platforms, we noticed a strong presence of real-time data management in MES and ERP systems. Besides, interoperability and systems reconfiguration also occurs at this level, but it is not its main dynamic capability. One level above, in Higher-level platforms, the stronger dynamic capability to transform knowledge is related to data analytics, helping third parties to complement capabilities alongside supply chain ties. Finally, in relation to the Business platform, this configuration allows for the visualization of the entire product lifecycle through PLM software, enabling the end-to-end concept with the inclusion of intermediaries in co-creation practices. Thus, this follows Reynolds and Uygun's (2018) suggestions for the Massachusetts advanced manufacturing SMEs ecosystem about the importance of the presence of intermediaries who aid the technology transfer process in ecosystems before reaching the end customer.

4.6. Conclusions

Our study contributed to the characterization and definition of Industry 4.0 platforms. We considered four distinct platform configurations (Operational, Digital, Higher-level, and Business) that were defined using a boundary-spanning (BS) perspective that considers how a certain technology connects with its surroundings. Moreover, we used BS to investigate the business level each technology-as-platform reaches when disseminating and transforming information between companies, as previously done by other studies in the business context (e.g., Johnson and Sohi, 2003; Zhao et al., 2019). We highlight two main contributions to our study. First, we showed that although in practice, only IoT and cloud systems are named ‘platforms’, there are different levels of platform around which the business system can be designed. We showed how this provides value for companies since they can achieve higher levels of business integration, which is a keystone of the Industry 4.0 concept. Second, we show that some technologies can operate for a single purpose or, in fact, as platforms, depending on how the company designs their use. This is the case of 3D printing, which can be used as a single technology for the production process, or as a pivot, a central platform of the manufacturing system that will operate based on it, as shown in our case study. Thus, some technologies are intrinsically platforms, while others may become one depending on how they are used.

4.6.1. Practical implications

The platform view can help managers and practitioners look inside their industrial environment and understand how these technologies can be organized. We provided examples of how different technologies operate as platform levels. Our recommendation is for practitioners to build Industry 4.0 systems around such platforms at the different levels considered. By doing so, companies can be more flexible since such platforms allow them to add other complementary technologies depending on specific needs. In this sense, the platforms investigated provide system coherence, allowing for better integration and interoperability of the different technologies that comprise the Industry 4.0 complex system.

4.6.2. Limitations and future research

One limitation of this study is that we were not exhaustive with the whole set of technologies to ensure that there are no other platforms on these levels. Moreover, we did not investigate several cases for each technology to consider the extension of these technologies as platforms. In this sense, we can only describe those investigated here, and to the extent of their use in the cases analyzed. Future studies can further this research by expanding this study and systematizing our findings in quantitative research to help understand the extent of such application in companies. In other words, new research could specifically determine the number of companies using such platforms as a platform rather than as a single technology, and the level of integration of such platforms to other technologies in the business systems. Another research limitation was the platform perspective adopted, since we focused only on industry and innovation platforms in the technology systems view. Some perspectives like two-sided markets and multi-sided markets from transaction economics (e.g., Rochet and Tirole, 2003) could be linked to BS activities, helping to deepen the understanding of how platforms shape businesses in the Industry 4.0 context.

References

Adner, R. (2006). Match Your Innovation Strategy to Your Innovation Ecosystem Match Your Innovation Strategy to Your Innovation Ecosystem. Harvard Business Review, 84(4), 98.

Alcácer, V., & Cruz-Machado, V. (2019). Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems. Engineering Science and Technology, an International Journal, 22(3), 899–919.

Aldrich, H., & Herker, D. (1977). Boundary spanning roles and organization structure. Academy of Management Review, 2(2), 217–230.

Almada-Lobo, F. (2016). The Industry 4.0 revolution and the future of Manufacturing Execution Systems (MES). Journal of Innovation Management, 3(4), 16–21.

Ancona, D. G., & Caldwell, D. F. (1992). Bridging the Boundary: External activity and performance in organizational teams. Administrative Science Quarterly, 37(4), 634–655.

Andersson, U., Dasí, À., Mudambi, R., & Pedersen, T. (2016). Technology, innovation and knowledge: The importance of ideas and international connectivity. Journal of World Business, 51(1), 153–162.

Ayala, N. F., Paslauski, C. A., Ghezzi, A., & Frank, A. G. (2017). Knowledge sharing dynamics in service suppliers' involvement for servitization of manufacturing companies. International Journal of Production Economics, 193, 538–553.

Bardin, L. (1977). L'Analyse de Contenu. sl: Presses Universitaires de France.

Bartodziej, C. J. (2016). The concept Industry 4.0: An Empirical Analysis of Technologies and Applications in Production Logistics. Springer.

Benitez, G. B., Ayala, N. F., & Frank, A. G. (2020). Industry 4.0 innovation ecosystems: an evolutionary perspective on value cocreation. International Journal of Production Economics, 228, 107735.

Benitez, G. B., Ferreira Lima, M. J. do R., Ayala, N. F., & Frank, A. G. (2020). Industry 4.0 technologies development: the moderating role of supply chain partners to support technology providers. In Supply Chain Management: An International Journal. Working paper.

Bharadwaj, A., El Sawy, O. A., Pavlou, P. A., & Venkatraman, N. (2013). Digital business strategy: toward a next generation of insights. MIS Quarterly, 37(2), 471–482.

Bowen, P., Goel, A., Schallehn, M., & Schertler, M. (2017). Choosing the Right Platform for the Industrial IoT - Bain Brief - Bain & Company. In Bain & company. https://www.bain.com/insights/choosing-the-right-platform-for-the-industrial-iot

Bresnahan, T. F., & Greenstein, S. (1999). Technological competition and the structure of the computer industry. Journal of Industrial Economics, 47(1), 1–40.

Cano-Kollmann, M., Cantwell, J., Hannigan, T. J., Mudambi, R., & Song, J. (2016). Knowledge connectivity: An agenda for innovation research in international business. Journal of International Business Studies, 47(3), 255–262.

Chen, S. H., & Lin, W. T. (2017). The dynamic role of universities in developing an emerging sector: a case study of the biotechnology sector. Technological Forecasting and Social Change, 123, 283–297.

Chesbrough, H. (2012). Open innovation: Where we've been and where we're going. Research Technology Management, 55(4), 20–27.

Chesbrough, H. W. (2003). Open innovation: The new imperative for creating and profiting from technology. Harvard Business Press.

Cohen, W. M., & Levinthal, D. A. (1990). Absorptive Capacity: A New Perspective on Learning and Innovation. Administrative Science Quarterly, 35(1), 128.

Cusumano, M. A., Gawer, A., & Yoffie, D. B. (2019). The business of platforms: Strategy in the age of digital competition, innovation, and power. New York, NY: HarperCollins.

Cusumano, M. A., Yoffie, D. B., & Gawer, A. (2020). The future of platforms. Mit Sloan Management Review.

Cusumano, M., & Gawer, A. (2002). The elements of platform leadership. MIT Sloan Management Review, 43(3), 51. http://search.proquest.com/openview/4492afa976940a18b9065e2e1eeca3eb/1?pq-origsite=gscholar&cbl=26142

Cusumano, M.A., & Selby, R. W. (1995). Microsoft Secrets: How the World's Most Powerful Software Company Creates Technology, Shapes Markets and Manages People. New York: Free Press.

Cusumano, Michael A. (2019). Technology strategy and management the cloud as an innovation platform for software development How cloud Computing Beca Me Aplatform. Communications of the ACM, 62(10), 20–22.

Da Costa, M. B., Dos Santos, L. M. A. L., Schaefer, J. L., Baierle, I. C., & Nara, E. O. B. (2019). Industry 4.0 technologies basic network identification. Scientometrics, 121(2), 977–994.

Dalenogare, L. S., Benitez, G. B., Ayala, N. F., & Frank, A. G. (2018). The expected contribution of Industry 4.0 technologies for industrial performance. International Journal of Production Economics, 204, 383–394.

De la Prieta, F., Rodríguez-González, S., Chamoso, P., Corchado, J. M., & Bajo, J. (2019). Survey of agent-based cloud computing applications. Future Generation Computer Systems, 100, 223–236.

De Reuver, M., Sørensen, C., & Basole, R. C. (2018). The digital platform: A research agenda. Journal of Information Technology, 33(2), 124–135.

Den Hartigh, E., Ortt, J. R., Van De Kaa, G., & Stolwijk, C. C. M. (2016). Platform control during battles for market dominance: The case of Apple versus IBM in the early personal computer industry. Technovation, 48–49, 4–12.

Eisenhardt, K., & Graebner, M. (2007). Theory building from cases: Opportunities and challenges. The Academy of Management Journal, 50(1), 25–32.

Fahmideh, M., & Zowghi, D. (2020). An exploration of IoT platform development. Information Systems, 87, 101409.

Fan, J., Yu, S., Chu, J., Chen, D., Yu, M., Wu, T., Chen, J., Cheng, F., & Zhao, C. (2019). Research on multi-objective decision-making under cloud platform based on quality function deployment and uncertain linguistic variables. Advanced Engineering Informatics, 42(June), 100932.

Foerderer, J., Kude, T., Schuetz, S. W., & Heinzl, A. (2019). Knowledge boundaries in enterprise software platform development: Antecedents and consequences for platform governance. Information Systems Journal, 29(1), 119–144.

Frank, A. G., Dalenogare, L. S., & Ayala, N. F. (2019a). Industry 4.0 technologies: implementation patterns in manufacturing companies. International Journal of Production Economics, 210, 15–26.

Frank, A. G., Mendes, G. H. S., Ayala, N. F., & Ghezzi, A. (2019b). Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective. Technological Forecasting and Social Change, 141, 341–351.

Garrett, B. (2014). 3D Printing: New Economic Paradigms and Strategic Shifts. Global Policy, 5(1), 70–75.

Gawer, A. (Ed.). (2011). Platforms, markets and innovation. Edward Elgar Publishing.

Gawer, A., & Cusumano, M. A. (2002). Platform leadership: How Intel, Microsoft, and Cisco drive industry innovation. Boston, MA: Harvard Business School Press.

Gawer, Annabelle, & Cusumano, M. A. (2014). Industry Platforms and Ecosystem Innovation. Journal of Product Innovation Management, 31(3), 417–433.

Gawer, Annabelle, & Cusumano, M. A. (2015). Business Platforms. In International Encyclopedia of the Social & Behavioral Sciences: Second Edition (Second Edi, Vol. 3). Elsevier.

Gilchrist, A. (2016). Industry 4.0: the industrial internet of things. Apress.

Goffin, K., Åhlström, P., Bianchi, M., & Richtnér, A. (2019). Perspective: State-of-the-Art: The Quality of Case Study Research in Innovation Management. Journal of Product Innovation Management.

Hein, A., Weking, J., Schreieck, M., Wiesche, M., Böhm, M., & Krcmar, H. (2019). Value co-creation practices in business-to-business platform ecosystems. Electronic Markets, 29(3), 503–518.

Jeschke, S., Brecher, C., Meisen, T., Özdemir, D., & Eschert, T. (2017). Industrial Internet of Things and Cyber Manufacturing Systems. Springer.

Johnson, J. L., & Sohi, R. S. (2003). The development of interfirm partnering competence: Platforms for learning, learning activities, and consequences of learning. Journal of Business Research, 56(9), 757–766.

Kabugo, J. C., Jämsä-Jounela, S. L., Schiemann, R., & Binder, C. (2020). Industry 4.0 based process data analytics platform: A waste-to-energy plant case study. International Journal of Electrical Power and Energy Systems, 115(August 2019), 105508.

Kahle, J. H., Marcon, É., Ghezzi, A., & Frank, A. G. (2020). Smart Products value creation in SMEs innovation ecosystems. Technological Forecasting & Social Change, 156(February), 120024.

Kusiak, A. (2018). Smart manufacturing. International Journal of Production Research, 56, 508–517.

Leifer, R., & Delbecq, A. (1978). Organizational/Environmental Interchange: A Model of Boundary Spanning Activity. The Academy of Management Review, 3(1), 40–50.

Li, K., & Du, T. C. (2015). Building a boundary-spanning service for coopetition. Expert Systems with Applications, 42(22), 8413–8422.

Liu, W., Tan, R., Cao, G., Zhang, Z., Huang, S., & Liu, L. (2019). A proposed radicality evaluation method for design ideas at conceptual design stage. Computers and Industrial Engineering, 132(April), 141–152.

Liu, X. L., Wang, W. M., Guo, H., Barenji, A. V., Li, Z., & Huang, G. Q. (2020). Industrial blockchain based framework for product lifecycle management in industry 4.0. Robotics and Computer-Integrated Manufacturing, 63(November 2019), 101897.

Longo, F., Nicoletti, L., & Padovano, A. (2017). Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context. Computers and Industrial Engineering, 113, 144–159.

Ma, X., Wang, J., Bai, Q., & Wang, S. (2020). Optimization of a three-echelon cold chain considering freshness-keeping efforts under cap-and-trade regulation in Industry 4.0. International Journal of Production Economics, 220.

Mittal, S., Khan, M. A., Romero, D., & Wuest, T. (2018). A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). Journal of Manufacturing Systems, 49, 194–214.

Muffatto, M. (1999). Introducing a platform strategy in product development. International Journal of Production Economics, 60, 145–153.

Müller, Julian M., Buliga, O., & Voigt, K. I. (2020). The role of absorptive capacity and innovation strategy in the design of industry 4.0 business Models-A comparison between SMEs and large enterprises. European Management Journal.

Müller, Julian Marius, Buliga, O., & Voigt, K.-I. (2018). Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. Technological Forecasting and Social Change, 132, 2–17.

Nord, J. H., Koohang, A., & Paliszkiewicz, J. (2019). The Internet of Things: Review and theoretical framework. Expert Systems with Applications, 133, 97–108.

Osterrieder, P., Budde, L., & Friedli, T. (2019). The smart factory as a key construct of industry 4.0: A systematic literature review. International Journal of Production Economics.

Park, C. K., Kim, H. J., & Kim, Y. S. (2014). A study of factors enhancing smart grid consumer engagement. Energy Policy, 72, 211–218.

Piercy, N. F. (2009). Strategic relationships between boundary-spanning functions: Aligning customer relationship management with supplier relationship management. Industrial Marketing Management, 38(8), 857–864.

Porter, M. E., & Heppelmann, J. E. (2015). How smart, connected products are transforming companies. Harvard Business Review, 93(10), 96–114.

Rayna, T., Striukova, L., & Darlington, J. (2015). Co-creation and user innovation: The role of online 3D printing platforms. Journal of Engineering and Technology Management - JET-M, 37, 90–102.

Reynolds, E. B., & Uygun, Y. (2018). Strengthening advanced manufacturing innovation ecosystems: The case of Massachusetts. Technological Forecasting and Social Change, 136, 178–191.

Rochet, J. C., & Tirole, J. (2003). Platform competition in two-sided markets. Journal of the European Economic Association, 1(4), 990–1029.

Rong, K., Hu, G., Lin, Y., Shi, Y., & Guo, L. (2015). Understanding business ecosystem using a 6C framework in Internet-of-Things-based sectors. International Journal of Production Economics, 159, 41–55.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., & Harnisch, M. (2015). Industry 4.0: The future of productivity and growth in manufacturing industries. In Boston Consulting Group.

Sarker, S., Sarker, S., Sahaym, A., & Bjorn-andersen, N. (2012). Exploring value cocreation in relationships between an ERP vendor and its partners: a revelatory case study. MIS Quarterly, 36(1), 317–338.

Schotter, A. P. J., Mudambi, R., Doz, Y. L., & Gaur, A. (2017). Boundary Spanning in Global Organizations. Journal of Management Studies, 54(4), 403–421.

Schroeder, A., Ziaee Bigdeli, A., Galera Zarco, C., & Baines, T. (2019). Capturing the benefits of industry 4.0: a business network perspective. Production Planning & Control, 30(16), 1305–1321.

Schumacher, A., Erol, S., & Sihn, W. (2016). A maturity model for assessing industry 4.0 readiness and maturity of manufacturing enterprises. Procedia CIRP, 52, 161–166. https://www.sciencedirect.com/science/article/pii/S2212827116307909

Sony, M. (2018). Production & Manufacturing Research Industry 4 . 0 and lean management : a proposed integration model and research propositions Michael Sony. Production & Manufacturing Research, 6(1), 416–432.

Star, S. L., & Greisemer, J. R. (1989). nstitutional ecology,translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology. Social Studies of Science, 19(3), 387–420.

Stephenson Jr, M., & Schnitzer, M. H. (2006). Interorganizational trust, boundary spanning, and humanitarian relief coordination. Nonprofit Management and Leadership, 17(2), 211–233.

Sturgeon, T. J. (2019). Upgrading strategies for the digital economy. Global Strategy Journal, October, 1–24.

Sun, J., Yamamoto, H., & Matsui, M. (2020). Horizontal integration management: An optimal switching model for parallel production system with multiple periods in smart supply chain environment. International Journal of Production Economics, 221.

Tao, F., Qi, Q., Liu, A., & Kusiak, A. (2018). Data-driven smart manufacturing. Journal of Manufacturing Systems, 48, 157–169.

Tippmann, E., Sharkey Scott, P., & Parker, A. (2017). Boundary Capabilities in MNCs: Knowledge Transformation for Creative Solution Development. Journal of Management Studies, 54(4), 455–482.

Tortorella, G. L., & Fettermann, D. (2018). Implementation of industry 4.0 and lean production in brazilian manufacturing companies. International Journal of Production Research, 56(8), 2975–2987.

Tseng, M., Canaran, T. E., & Canaran, L. (2018). Introduction to edge computing in IIoT. Industrial Internet Consortium (IIC) White Paper, Tech. Rep.

Tsvetkova, A., Gustafsson, M., & Wikström, K. (2014). Business Model Innovation for Eco-innovation: Developing a Boundary-Spanning Business Model of an Ecosystem Integrator. In S. Azevedo, M. Brandenburg, H. Carvalho, & V. Cruz-Machado (Eds.), Eco-Innovation and the Development of Business Models. Greening of Industry Networks Studies, vol 2. Springer, Cham.

Voss, C., Tsikriktsis, N., & Frohlich, M. (2002). Case research in operations management. International Journal of Operations & Production Management, 22(2), 195–219.

Wang, S., Wan, J., Zhang, D., Li, D., & Zhang, C. (2016). Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination. Computer Networks, 101, 158–168.

Wang, Shiyong, Wan, J., Li, D., & Zhang, C. (2016). Implementing Smart Factory of Industrie 4.0: An Outlook. International Journal of Distributed Sensor Networks.

Wang, Y., Ma, H. S., Yang, J. H., & Wang, K. S. (2017). Industry 4.0: a way from mass customization to mass personalization production. Advances in Manufacturing, 5(4), 311–320.

Weking, J., Stöcker, M., Kowalkiewicz, M., Böhm, M., & Krcmar, H. (2019). Leveraging industry 4.0 – A business model pattern framework. International Journal of Production Economics.

Weller, C., Kleer, R., & Piller, F. T. (2015). Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited. International Journal of Production Economics, 164, 43–56.

Wheelwright, S. C., & Clark, K. B. (1992). Creating Project Plans to Focus Product Development Harvard Business Review. Harvard Business Review, 70–82.

Wu, L., Yue, X., Jin, A., & Yen, D. C. (2016). Smart supply chain management: a review and implications for future research. The International Journal of Logistics Management, 27(2), 395–417.

Yin, R. K. (2009). Case study research: design and methods. Sage, Los Angeles. Cal.

Zhao, Y., von Delft, S., Morgan-Thomas, A., & Buck, T. (2019). The evolution of platform business models: Exploring competitive battles in the world of platforms. Long Range Planning, July, 101892.

Appendix D – Semi-structured interview guideline

General information

1. Please briefly introduce your company background and involvement with Industry 4.0.

Questions about Industry 4.0 technologies [For technology providers].

2. Please describe which Industry 4.0 technologies your company provides and how this (these) technology(ies) operate(s) for your customers.

3. Please specify the main advantages at internal and external levels for companies to acquire your Industry 4.0 technology(ies).

Questions about Industry 4.0 technologies [For technology adopters].

1. Please describe which Industry 4.0 technology(ies) your company adopted and the reason(s).

2. Please clarify how your firm works with this(these) technology(ies) at internal and external levels.

Questions about BS activities [For both respondents].

1. Please, describe how this(these) technology(ies) capture(s), process(es), and disseminate(s) information *(information collection and processing)* at the company, supply chain and/or ecosystem levels.

2. Please describe how this(these) technology(ies) help(s) to engage *(external representation)* departments and external partners for value creation at the company, supply chain and/or ecosystem levels.

3. Please describe how this(these) technology(ies) coordinate(s) *(task coordination)* processes, tasks, decisions, and partners at company, supply chain and/or ecosystem levels.

4. Please describe how this(these) technology(ies) transform(s) information *(knowledge transformation)* into value at the company, supply chain and/or ecosystem levels.

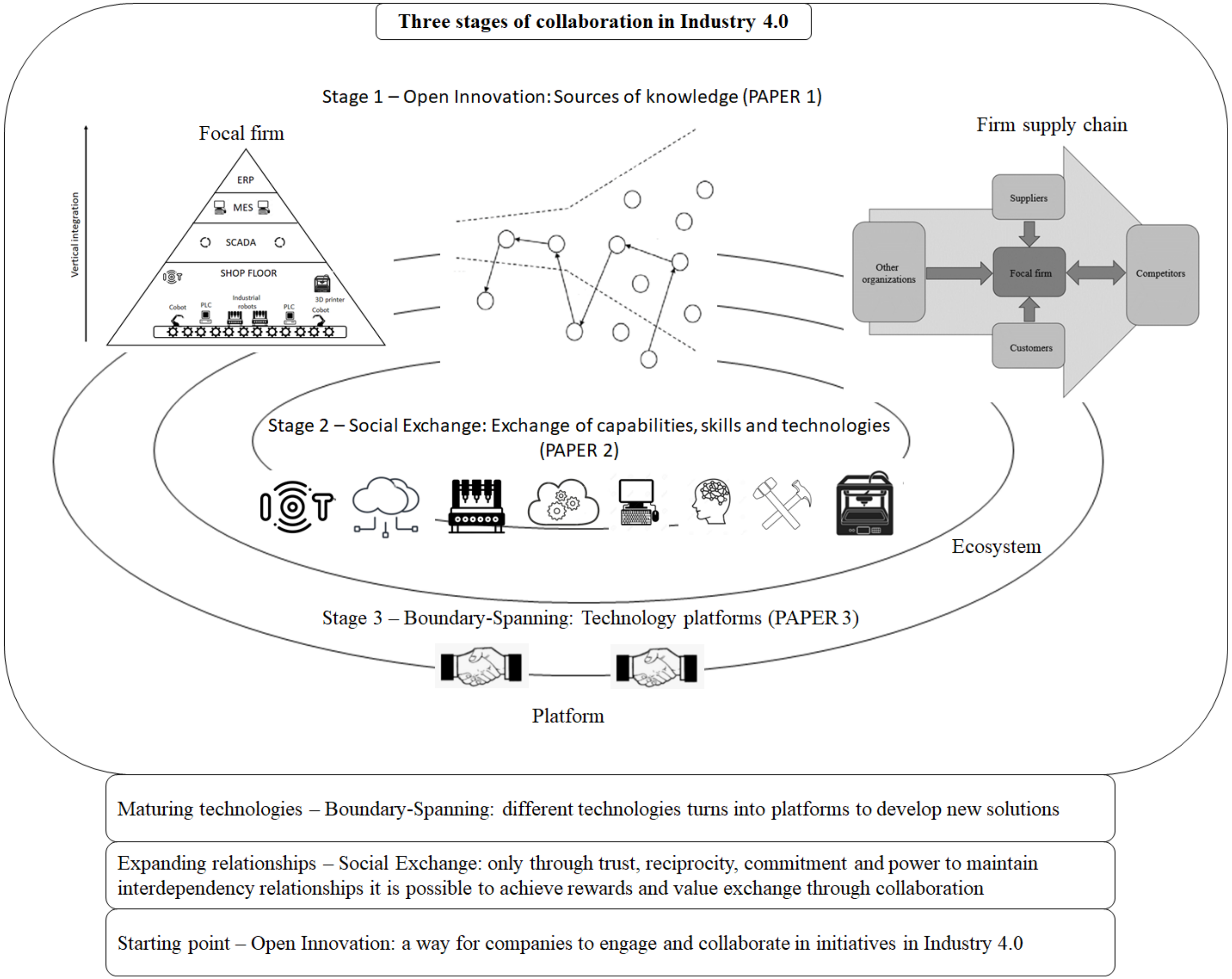
5 FINAL REMARKS

This chapter presents the final discussions, academic and practical contributions, and the opportunities for future research. These points are discussed in the following subsections.

5.1 Final discussion

This thesis proposes that collaboration for the development of technologies and solutions for Industry 4.0 can be promoted by integrating different actors of the supply chain in innovation ecosystems, which may assume specific roles in the outputs of such collaboration. The thesis also proposes that some Industry 4.0 technologies can also enable the integration of such different partners. The thesis shows that different lenses can contribute to such analysis, including Open Innovation, Social Exchange Theory, and Boundary-Spanning. In this sense, as a result, the present thesis provides and discusses a conceptual model with different collaborative approaches for the development of solutions and technologies in the context of Industry 4.0.

To define this model, three articles that used several types of methodological procedures were developed, providing richness to this research's descriptive and exploratory nature. In this way, both qualitative and quantitative research was used. From a qualitative perspective, techniques such as content analysis, individual interviews, focal groups, and multiple case studies were explored. On the other hand, from a quantitative perspective, techniques such as exploratory factor analysis (EFA) and multiple linear regression (OLS) were used. Because Industry 4.0 is still a relatively new topic in the literature (first publications started in 2013), this thesis is one of the early works that explore in-depth quantitative aspects related to the development of 4.0 technologies in Industry 4.0. Based on these methods, it was possible to consolidate the findings in a final conceptual model, which explains the role of collaboration for the development of technologies and solutions in Industry 4.0. Thus, the three articles' findings helped in the construction of the conceptual model presented in Figure 5.1.



Maturing technologies – Boundary-Spanning: different technologies turns into platforms to develop new solutions

Expanding relationships – Social Exchange: only through trust, reciprocity, commitment and power to maintain interdependency relationships it is possible to achieve rewards and value exchange through collaboration

Starting point – Open Innovation: a way for companies to engage and collaborate in initiatives in Industry 4.0

Figure 5.1 – Industry 4.0 collaboration conceptual model

The conceptual model explains that approaches based on Open Innovation (Chesbrough, 2003) can prepare the way for companies to start to collaborate for the development of solutions in the Industry 4.0 context. This is stimulated because of the difficulty in adopting a certain technology or developing solutions in this context in a volatile market where technological shifts occur fast (CNI, 2016; DALENOGARE et al., 2018). Kahle et al. (2020) also point out that the main barriers associated with small and medium-sized enterprises (SMEs) in the Brazilian context are related to costs and uncertainties regarding investment. In this sense, the Open Innovation strategy, where companies bring resources and knowledge from external sources of collaboration, has been proven in this study as an alternative to help companies engage in technology development in an emerging economy such as Brazil. Furthermore, for relationships that can be established and have a healthy long-term run, social exchange theory is a key point. Through commitment and trust, companies that collaborate with third parties will achieve their strategic objectives and enter into new markets (WU, 2014). However, companies need to understand that there are higher goals beyond their own individual goals within these collaborations, especially in the Industry 4.0 context. By understanding this, reciprocity is shaped for the exchange of values and eventual rewards within these relationships. Finally, the power of bargain to maintain interdependent relationships is essential for the collaboration keeping a healthy evolutionary exchange of capabilities and skills in supply chains and ecosystems.

After the first stages (starting point and horizon expansion) are achieved, the model also explains how to broaden borders and achieve different business levels (firm, supply chain, or ecosystems). In this sense, through the dissemination and transformation of information using platforms as boundary objects, i.e., environments that transmit and transform data, it will be possible to mature technologies to receive other ‘add-ons’ and develop scalable solutions and technologies in the Industry 4.0 context.

Thus, this thesis connects three different theoretical approaches to explain collaboration in Industry 4.0 to better prepare firms for technology development. The findings presented in this thesis show three stages: (i) how to start collaborating (PAPER 1); (ii) how to expand relationships in collaboration (PAPER 2); and (iii) how technologies mature and turn into platforms (PAPER 3).

5.2 Theoretical contributions

Several methodological procedures were used for the study, providing greater richness to the combined (exploratory and descriptive) nature of this research. In this sense, Paper 1 analyzed a sample of 87 companies in the electronics sector of an automation and control industrial cluster in the country's southern region. For the statistical tests, 77 companies were selected from the initial sampling. The potential for collaboration in these companies' supply chain was analyzed based on the inbound Open Innovation strategy for the development of Industry 4.0 technologies. From this analysis, it was possible to highlight the potential for collaboration of different actors within a supply chain and verify that an ecosystem-oriented model with a greater number and diversity of actors could bring more comprehensive results when firms collaborate in the context of Industry 4.0.

Then, Paper 1 shed light on the research for Paper 2, which expanded the analysis to an ecosystem approach within these 87 companies, including other actors in the research. From the social exchange perspective, it was possible to analyze how these 87 companies and other actors (e.g., government and university) collaborate in an ecosystem configuration for the development of solutions in the context of Industry 4.0, which demands more resources, technologies, and capabilities (DALENOGARE et al., 2018; FRANK et al., 2019a; KAHLE et al., 2020). The theory allowed to verify how the relations expand within the ecosystem, as well as its shifts during evolutionary lifecycle stages (birth, expansion, and leadership) proposed by Moore (1993; 1996). The results demonstrated that the most advanced lifecycle stage of innovation ecosystems (leadership) has a platform organization, guiding the research to Paper 3.

Based on that, Paper 3 investigated how different technologies in Industry 4.0 are configured and operate as platforms connecting stakeholders to reach different levels of business. To this end, boundary-spanning theory (Aldrich and Herker, 1977) helped to understand how these technologies are configured as platforms to transmit and transform knowledge between company departments and external actors for product development. Thus, through these three articles, the following results were obtained: (i) the identification of the potential of collaboration from different actors within a supply chain oriented to develop technologies for Industry 4.0; (ii) the understanding of the impacts generated through the collaboration with supply chain external partners on Industry 4.0 technologies; (iii) the understanding about evolutionary lifecycle stages of an innovation ecosystem focused on Industry 4.0; (iv) the understanding on how collaboration helps three evolutionary lifecycle stages to develop Industry 4.0 solutions; (v) the understanding on how technologies are configured and operate as platforms; and (vi) the understanding in how these platforms achieve different levels of business. With this, the present thesis consolidates the role of collaboration in the context of Industry 4.0, presenting results in different scenarios from different perspectives.

5.3 Practical implications

Considering that this thesis's objective arose from a practical problem for companies with the insertion of the Industry 4.0 concept in the global scenario, the obtained results have direct implications for entrepreneurs who sought to adopt strategies in this context. This can be evidenced both in the individual studies (three articles) and in the final model that consolidated all the findings and presented a conceptual view about the role of all theories that helped to guide the study. Based on the results, entrepreneurs and managers can understand how to develop specific technologies and engage in collaborative practices to assist them in the Industry 4.0 roadmap.

Therefore, the specific contributions of this thesis to the business environment are the following: (i) companies can determine which partners to acquire or strengthen ties in their supply chain for a specific strategy related to the development of products and technologies; (ii) companies can understand how to acquire new partners and collaborate at different levels of the business to develop technologies; (iii) companies can understand how to strengthen relationships and maintain them in the long term within their businesses; (iv) the results explain how companies can manage and operate different Industry 4.0 technologies as platforms; (v) the final model helps companies to engage in collaborative practices in the context of Industry 4.0; (vi) the final model shows how these relationships can evolve over the lifecycle of the business; and (vii) the final model shows how collaboration can reach different levels of business for companies.

5.4 Opportunities for future research

From the results found in this thesis, opportunities for future research arise. Among them, it is worth emphasizing the need for further details on how the collaboration should be initiated and how to operationalize it for its practical application for companies. This can be done by crossing the main R&D activities to develop products and technologies with collaborative activities in the context of Industry 4.0. Thus, it would be possible to associate each R&D task with collaboration activities related to Industry 4.0 technologies to understand how each partner could collaborate. This analysis could be applied from the perspective of the Relational View Theory. Thus, it would be possible to analyze how the establishment of external partnerships helps in the development of technologies and solutions through the analysis of (i) assets related to R&D; (ii) knowledge sharing routines for R&D; (iii) complementary resources and capabilities from the partners; and (iv) effective governance structure for R&D.

In addition, there are opportunities for quantitative validation of the model by bringing more companies and different actors to assess the role and impact of collaboration in different contexts. Future studies can also analyze the relationship of collaboration within different environments and Industry 4.0 technologies verifying their effects on different business strategies. In relation to business, there is also a proposal for analyzing collaboration in the business models of companies in Industry 4.0. Future research can check how different collaboration types can develop business models or support a particular model used by a company. These propositions of studies could help companies, especially SMEs, to move towards Industry 4.0 with different strategies for their businesses.

Finally, there is a need for more empirical evidence about the impacts generated by collaboration for technology development. For instance, this thesis is focused on collaboration for technology development projects in innovation ecosystems. Future studies could consider other ecosystems, such as the ones that develop technology demonstrators or are focused on knowledge dissemination. Only with more empirical evidence would it be possible to draw a roadmap for companies that do not have enough resources or skills to buy or develop technologies individually. Developing a roadmap that focuses on collaboration in Industry 4.0 and not on adopting technologies like most of the proposed studies in the literature (Schumacher et al., 2016, Mittal et al., 2018; Ghobakhloo, 2018) do can be an alternative way for companies in an emerging country like Brazil to remain competitive in Industry 4.0 era.

References

ALDRICH, H.; HERKER, D. Boundary spanning roles and organization structure. **Academy of management review**, v. 2, n. 2, p. 217-230, 1977.

CHESBROUGH, H. Open innovation: The new imperative for creating and profiting from technology. **Harvard Business Press**. 2003.

CNI. **Industry 4.0: a new challenge for Brazilian industry**. Confederação Nacional da Indústria (CNI). Industrial Report, 2016. Retrieved from: http://www.portaldaindustria.com.br/publicacoes/2016/8/challenges-industry-40-brazil/

DALENOGARE, L.S.; BENITEZ, G.B.; AYALA; N.F., FRANK, A.G. The expected contribution of Industry 4.0 technologies for industrial performance. **International Journal of Production Economics**, v. 204, p. 383–394, 2018.

FRANK, A.; DALENOGARE, L.; AYALA, N. Industry 4.0 technologies: implementation patterns in manufacturing companies **International Journal of Production Economics**, p. 210, 15–26, 2019a.

GHOBAKHLOO, M. The future of manufacturing industry: A strategic roadmap toward Industry 4.0. **Journal of Manufacturing Technology Management**, v. 29, n. 6, p. 910-936, 2018.

KAHLE, J.H.; MARCON, É.; GHEZZI, A.; FRANK, A.G. Smart Products value creation in SMEs innovation ecosystems. **Technological Forecasting and Social Change**, v. 156, p. 120024, 2020.

MITTAL, S.; KHAN, M.A.; ROMERO, D.; WUEST, T. A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). Journal of manufacturing systems, v. 49, p. 194-214, 2018.

MOORE, J. F. Predators and prey: a new ecology of competition. **Harvard business review**, v. 71, n. 3, p. 75-86, 1993.

MOORE, J. F. The death of competition: leadership and strategy in the age of business ecosystems. **New York: HarperBusiness**, 1996.

SCHUMACHER, A.; EROL, S.; SIHN, W. A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. **Procedia CIRP**, v. 52, p. 161–166, 2016.

WU, I.-L.; CHUANG, C.-H.; HSU, C.-H. Information sharing and collaborative behaviors in enabling supply chain performance: a social exchange perspective. **International Journal of Production Economics**, v. 148, p. 122–132, 2014.