

Collaborations for Digital Transformation: Case Studies of Industry 4.0 in Brazil

Clarissa Rocha , Carlos Quandt , Fernando Deschamps , Simon Philbin , and Giovani Cruzara 

Abstract—In today’s digital age, many managers need to find new ways to manage collaborations where complementary partners co-create digital solutions. Collaborations with partners are at the center of digital projects, but managing these collaborations is challenging. This article objective is to investigate how research and development collaborations with scientific and business partners contribute to digital transformation. This has been achieved through an empirical investigation of three Brazilian manufacturers that are already on their journey toward digitalization. The research design involves multiple case studies and qualitative analysis, through data collection by interviews and questionnaires with participants from the tactical and strategic level followed by content analysis as well as nonparticipant observations. The findings indicate that the companies are at the early stage of building a digital ecosystem. However, they have already secured benefits from pursuing open innovation practices in the form of competitive advantage in operational processes. The results indicate that business success depends more on how (disruptive) technologies are developed and used by engaged people to add value to the enterprise, rather than simply adopting new technologies by themselves. Manufacturers need to act now to reshape their mindset, operational processes, and business models, respectively, enabling the understanding that: 1) organizational ecosystems are becoming more open and collaborative; 2) the value of data capture and analysis can be developed and used for data-driven learning, preventive and predictive capabilities, supporting decision-making; 3) customers’ preferences need to be internalized to deliver customized experiences.

Index Terms—Competitive advantage, digitalization, digital transformation, industry 4.0, open innovation, research and development (R&D) collaborations.

I. INTRODUCTION

THE dynamic and competitive business environment in which most organizations operate results in the need for the development of capabilities that are necessary to foster organizational innovation. However, as highlighted by [1], such

Manuscript received 25 March 2020; revised 15 October 2020 and 17 January 2021; accepted 12 February 2021. Date of publication 17 March 2021; date of current version 5 June 2023. Review of this manuscript was arranged by Department Editor R. Quadros. (*Corresponding author:* Clarissa Rocha.)

Clarissa Rocha and Carlos Quandt are with the Business School, Pontifícia Universidade Católica do Paraná, Curitiba 80215-901, Brazil (e-mail: kaclai@gmail.com; carlos.quandt@pucpr.br).

Fernando Deschamps is with the Polytechnic School, Pontifícia Universidade Católica do Paraná, Curitiba 80215-901, Brazil (e-mail: fernando.deschamps@pucpr.br).

Simon Philbin is with the Engineering & Enterprise School, London South Bank University, London SE1 0AA, U.K. (e-mail: philbins@lsbu.ac.uk).

Giovani Cruzara is with the Business School, Universidade Federal do Paraná, Curitiba 83255-976, Brazil (e-mail: giovani.cruzara@outlook.com).

Digital Object Identifier 10.1109/TEM.2021.3061396

capabilities are not developed in isolation and they often depend on innovative processes. This can ultimately lead to the adoption of an open innovation strategy due to the pressure of the competitive and volatile external environment, which encompasses new technologies and more demanding customers [2]. The increasing speed of technological change and the intensification of international competition gives rise to a context where research and development (R&D) collaborative efforts are necessary, since organizations cannot rely solely on their own expertise and resources to innovate in a world of distributed knowledge.

Novel technologies, especially those that have a disruptive nature, cannot be used in isolation, demanding organizational transformation in order to maintain competitiveness, not only in terms of their technological architecture but also regarding strategic, managerial, and social perspectives [3]–[6]. This emerging trend is reflected in the Industry 4.0 concept [7], which is also known as digital transformation in the manufacturing industry [8].

Collaborations with the most diverse organizational actors are at the center of the challenges of Industry 4.0 [9], but this aspect has received little attention in the literature. On the other hand, the need to better understand how interorganizational relationships influence the digital journey of companies is emphasized in [4], [9], and [10]. Therefore, a collaboration-centered approach seems appropriate to investigate the complexity of Industry 4.0 under managerial and social lenses. This research aims to answer the following question: How R&D collaborations with scientific and business partners [11] contribute to the digital transformation of three multinational organizations in Brazil that have initiated the process of manufacturing digitalization?

In order to address this research question, the article explores the literature related to the characterization and main implications of the digital transformation concept for industrial management [7], [12], [13], as well as the literature related to open innovation practices in Industry 4.0 [1], [4], [9], [11], [14], [15]. From this literature, a framework is developed to explore the relationships between open innovation practices and the concept of Industry 4.0. The cases of three Brazilian subsidiaries of multinational industrial companies with headquarters in Japan, Germany, and Sweden are presented and analyzed, thereby discussing the main findings of these cases in view of the literature.

The extant literature lacks a detailed understanding of the social, strategic, and managerial aspects of digital transformation [9], [10]. There is a need to clarify how organizations develop collaborative arrangements to obtain external sources

of information, knowledge, and technologies to incorporate effective digital practices that may lead to competitive advantage. Additionally, while open approaches to innovation have been increasingly adopted in developed countries [16], firms from emerging markets such as Brazil have dropped behind. The research carried out by [17] revealed a large discrepancy between the G7 group of developed countries and the BRICS group of emerging countries, with the latter lagging behind significantly, both in terms of quantity and impact of scientific production in the field. While open innovation has given rise to a growing academic literature [18], it addresses chiefly the context of industrialized economies [19]. As a result, the understanding of the phenomenon in emerging economies, and in Brazil particularly, remains incomplete. Furthermore, the Brazilian context is particularly interesting for open innovation research because its companies are remarkably closed to collaboration in comparison with other countries [20]. This article contributes with the study of the strategic, managerial, and social factors of R&D collaborations for digital innovation in the context of Industry 4.0 in Brazil.

II. LITERATURE REVIEW

To understand R&D collaborations as a factor that supports the operationalization of Industry 4.0, this section presents a literature review on 1) digital transformation and its constituent technologies; and 2) the open innovation perspective and its contribution to the understanding of how manufacturers can apply digital innovations through collaboration with external partners. A conceptual framework has been synthesized that builds on and incorporates the main findings from the literature review.

A. Digital Transformation in Manufacturing Companies

Digital transformation is conceptualized as the creation, and consequently significant change of business products processes and even models that result from the use of digital technologies [12]. Therefore, such transformation requires the company to rethink its management practices. Digital transformation has radically changed the nature and structure of new products and services, generating new ways of creating value [21]. It enables innovations that involve diverse actors with different goals and capabilities, creating a new generation of innovation processes. More broadly, it has the potential to change entire industries through a deep transformation of business activities, processes, competencies, and models [22]. The process of digital transformation in manufacturing is encompassed by the Industry 4.0 concept [3].

Industry 4.0 is the fusion of the physical and virtual domains of an organization, allowing it to become a cyber-physical system (CPS) [23], [24]. The adoption of the CPS concept triggers a paradigm shift in how organizations create value [25]. This can be achieved by the orchestrated use of digital technologies [23], [25] that collect, transfer, analyze, and make sense of data from internal manufacturing operations as well as external data that are relevant to its operations [26], [27]. This supports the development of connected, Smart Factories [12], [15] that facilitate integration with customers and suppliers [9], [26], [27],

and increase agility and responsiveness to market demands for high-quality, customized products, and services. Industry 4.0 concept embodies technologies such as smart sensors, modeling and simulation, advanced and collaborative robotics, cloud computing, the Internet of Things (IoT), additive manufacturing (or 3D-printing), machine learning, augmented and virtual reality, big data and analytics, among others [23].

From a strategic and managerial point of view, digital technologies allow the integration between manufacturing assets and actors, bringing an interconnectivity that increases the volume and diversity of business data in real-time. Decision-making is made easier and faster by extracting large volumes of data in real-time (i.e., big data), exporting the data to cloud computing, and processing it (i.e., data analytics) through converting it into relevant information. In this regard, many industries have already taken steps toward digital transformation by linking their business processes, from supply to aftermarket, by using digital technologies such as IoT. In this sense, Industry 4.0 aims to promote an integration into a digital value chain [7], [24], [25]. Apart from that, digital solutions also bring other benefits to companies, such as increased productivity, reduction of operational costs and failures, adoption of advanced and autonomous robotics among other digital solutions [7].

These benefits demonstrate that Industry 4.0 is not only about the application and use of a new and advanced technological architecture. It is also about developing a digital strategy, leadership, supporting organizational structure, and, more importantly, an open and collaborative culture that fosters and motivates the adoption of digital technologies to enable enhanced industrial competitiveness [28]. Moreover, it is about building new and distinctive digital capabilities in employees and collaborative networks with external actors, which can be viewed as sources of digital innovation [29]. Considering these benefits, collaboration is gaining momentum in digitized environments. The advancement of automated and integrated processes and objects requires the development of cognitive and analytical competencies among employees and requires a closer relationship with the company's external collaborators. These requirements are relevant to stimulate collaboration for R&D in digital technologies [9].

For [30], the digital transformation, by stimulating new managerial and social practices in the way of operating a business, stimulates the appearance of open innovation practices. For these authors, in the current digital context, it is better to collaborate with partners than to compete alone, when developing relationship networks with external parties. The Internet, as a new communication platform, in its continuous evolution gave rise to new patterns of social interaction that led to the birth of a true digital culture. Today, billions of interconnected individuals can participate in innovation and wealth creation, in ways they could only imagine before [30].

B. Open Innovation Practices

Collaboration can be defined by the intentional and systematized capability to dynamically develop projects in which partners create and share technological and innovative resources to generate competitive advantages that are distinctive and difficult

to imitate [31]. The collaborative process involves multiple organizations working together in a shared activity for a specific period [32]. Collaboration assumes a strategic role, with the potential to create, modify, complement, and expand new knowledge, innovations, and technological resources, allowing organizations to be more competitive in an uncertain and environment [31], [33]. According to [27], the process of business innovation can be stimulated by collaborative arrangements.

Open innovation is defined as “a distributed innovation process that involves purposively managed knowledge flows across the organizational boundary” [34]. In practice, companies apply externally generated ideas and technologies in their own business and let unused internal ideas and technologies be applied by others in their businesses [35]. It is seen as a means to accelerate internal processes and increase the value of innovative efforts [36]. Despite the significant costs related to knowledge absorption, time, and managerial attention [37], open innovation can facilitate access to resources, knowledge, and competencies otherwise unavailable to the company [1], [2].

A collaborative project can be constructed as a sequence of events and depends on temporality and the characteristics of the relationship, such as frequency, duration, and density of interactions between the collaborating organizations. It is similar to the ecosystem concept in the sense that the organization needs to be in continuous interaction and exchange with the environment in order to remain innovative [38]. An ecosystem, in this article, refers to a complex, online or offline, connection of organizational entities and actors and engagements directed toward the creation of business value.

The technological competitiveness of large industrial companies will depend on the ability to access external knowledge and to integrate the capabilities of its operations and technological infrastructure. Costa and Porto [31] have indicated in the case of Brazilian multinationals, they can innovate in a collaborative and dynamic way as a consequence of mobilizing, sharing, and renewing knowledge and technologies through partnerships and networks.

Previous studies have emphasized that scientific and business partners provide organizations with access to various types of knowledge [11], [39]. R&D projects involving scientific and business partnerships foster open innovation [2], [39] and are associated with improved financial performance. In addition, there is evidence that knowledge gained from scientific and business partnerships plays significant but different roles [39].

Collaborations with scientific partners—such as independent research institutes, universities, governmental agencies and research organizations, specialized consultancies as well as startups—are important for companies that do not have well-qualified scientific and technologically focused employees, since scientific partners can provide access to relevant knowledge that enables technological innovations in the company [39]. Furthermore, collaborations with such partners provide an opportunity to obtain technical training for company teams. Thus, when companies intend to make organizational changes, an integrated collaboration with partners is recommended [11].

Scientific partners bring scientific knowledge to the R&D process and in certain cases patentable innovations that are

suitable to the firm’s market. Such collaborative projects also create a temporary market space and access to scientific equipment and research facilities [11], resulting in the acceleration of the process of technological learning [40]. Projects with scientific partners leverage the academic networks in which the involved scientists operate. Due to increased R&D costs in many industries, scientific partnerships are increasingly seen as a less expensive and less risky source of specialized knowledge. These partnerships have grown in scale and scope over time, partially stimulated by government policies to promote public-private research and partnerships [41].

Business partners provide essential operational knowledge to improve management processes, new ideas, feedback on operations as well as improved production and management processes [42]. Suppliers are often knowledgeable about relevant technologies and components that are newly available in the market. Thus, designing and managing innovation communities became an important path for the future of open innovation [35].

While open innovation practices have been successfully applied in high-tech settings, there is still a dearth of research on adopters of open innovation in other settings, such as multi-national manufacturing firms [43]. In this article, the open innovation concept helps to understand the roles and sources of external knowledge and data that are used to facilitate the digital transformation of factories. Industry 4.0 demands not only investments in technology but also in human and relational capital for the operationalization of practices related to industrial digitalization [5]. Open innovation practices became relevant in the digital economy era—bringing together technology and know-how from the manufacturing company and external entities to foster innovation, whether in terms of products, processes, and business models [4], [44].

An open innovation strategy is necessary for periods marked by significant innovation opportunities and great uncertainty in the socio-economic environment. In a global digital context, a series of major challenges brought about by new technologies have been emerging, affecting developed and underdeveloped economies, such as Brazil. Such a context gives rise to the need for more open and collaborative solutions to complex problems [45]. As such, many developing trends will affect innovation practices and policies as they need to be adjusted to face the emerging complexities in the new innovation landscape [4]. At times of momentous transformation and technological change as the one presently brought about digitalization [21], new windows of opportunity emerge for latecomer firms, especially those operating in emerging economies.

The digital age poses new opportunities and challenges for open innovation, as well as implications for research and practice [4], [46], which motivate this research. Collaboration with external partners facilitates R&D on diverse digital technologies, accelerate technological learning, balance relationships, and increase the potential for competitive advantages [47]. Fig. 1 outlines a reciprocal relationship between the constructs Open Innovation and digital transformation in manufacturing. It emphasizes the relevance of collaboration and open innovation practices as drivers for digital transformation [10]. Five theoretical propositions were created based on the constructs of Fig. 1

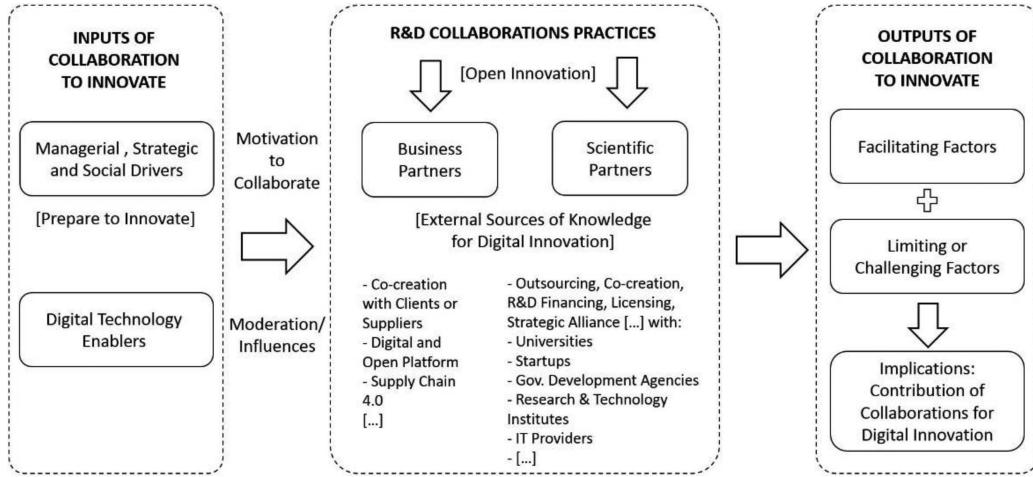


Fig. 1. Conceptual framework of open innovation to support digital transformation.

TABLE I
PROPOSITIONS OF THE THEORETICAL MODEL

Proposition	Main references
P1: Social, managerial, and strategic antecedent factors are relevant to prepare the company for digitalization.	[4], [5], [7], [12]
P2: Social, managerial, and strategic antecedent factors are relevant to motivate the company to engage with external partners for digital innovation.	[9], [31], [38]
P3: Digital technologies are enabling factors that assist collaborations and integration with business partners.	[1], [2], [9], [11], [35], [38]–[40]
P4: Collaborative R&D practices with scientific partners assist digital innovation in manufacturing.	[1], [2], [9], [11], [35], [39], [43]
P5: Collaborations with business and scientific partners, together, contribute to digital innovation in manufacturing.	[11], [21], [25], [39], [40]

prior to data collection and analysis of the case studies. The propositions used for assessing the practices of the case studies are shown in Table I. These propositions are statements about the likelihood of relationships among two or more constructs.

The transition from traditional industrial ecosystems to Industry 4.0 will require not only the development and use of digital technologies but also a new way of thinking and doing business [4], [5]. This requires the development of a digital mindset and new business models at the intra- and interorganizational levels. In other words, digital change in Industry 4.0 involves managing technological change together with cultural change. The social aspects of Industry 4.0 comprise, according to [48]: the emergence of networked learning; human development programs for innovation, including idea generation, collaboration, and co-production; advancing knowledge management and intellectual capital; development of new skills; and the emergence of new professions. Hence, the path toward manufacturing digitization is a gradual and complex process of organizational change, as the company needs to prepare people to understand the value and impact of digital transformation. Employees are seen as agents that drive the transformation [6].

Companies that “skip steps” on the digital path run the risk of adopting digital technologies without the appropriate knowledge to extract value effectively from them. When people are not prepared to be at the center of digital transformation, the results

are bound to be unsatisfactory. Additionally, the structuring of a digital strategy and its prioritization by managers is a key preparatory factor for manufacturing digitization, as pointed out in [6], [7], [24]. In view of these arguments, Industry 4.0 is clearly not just about the development and application of advanced digital technologies. It is also about developing strategy, leadership, culture, and organizational structure that drive the use of using digital technologies for business competitiveness [28]. It is also about building new and distinctive pro-digitization skills for employees, together with collaborative networks with external sources of innovation [6]. These findings from previous research support the elaboration of Proposition 1 (see Table I).

The development of open innovation practices requires a series of preparatory factors, such as a new mindset and culture of agility and openness, as well as new technical and soft skills [10], represented by the left part of Fig. 1, which comprises social, strategic, and managerial drivers. This part of the framework represents the antecedent organizational factors—such as the level of trust between people in the company, knowledge sharing when technological skills are limited, initiatives for collaboration, willingness of employees to learn new technologies continuously. It also includes the level of hierarchical rigidity of the organizational structure and its impacts on the open innovation strategy, the degree of flexibility in decision making, and the elaboration of the business strategy. These factors can facilitate

or hinder the engagement in open innovation practices [46]. These findings from previous research support the elaboration of Proposition 2 (see Table I).

The increasingly distributed and open nature of innovation in products and processes is seen as an integral aspect of innovations that use digital technologies [48]. The possibilities for open innovation activities have been changed through digitalization. New mechanisms for interaction, collaboration, and processing have become possible through the ability to access mass amounts of information (big data) as well as analyzing it in novel ways (advanced analytics, artificial intelligence, machine learning) at much greater speed through stationary and mobile connections. Open standards and digital platforms for data and knowledge sharing allow actors to seek innovation in an open and collaborative way [10]. The use of collaborative platforms to interact with diverse partners to develop and commercialize customizable digital offerings is pervasive [38]. These new mechanisms for open innovation are offering a broad range of new possibilities for every stage of the innovation process from benchmarking, ideation, and R&D to manufacturing and marketing [10]. These mechanisms are enhanced or leveraged by the current digital context, as represented in the central part of Fig. 1—“R&D Collaborations Practices.” The evidence from the literature supports Propositions 3 and 4 (see Table I).

The open innovation approach emphasizes the relevance of companies to integrate or complement their internal competencies and knowledge with external resources and the consequent development of an ecosystem. The use of various digital solutions can facilitate the company’s connectivity with external actors to become increasingly integrated within a collaborative digital ecosystem. The ecosystem approach helps companies to benefit, and capitalize from, the application of the Industry 4.0 concept [21]. Hence, companies need to search for partners who can further their digital objectives, as an essential step for maintaining their competitiveness and survival, which is represented by the right part of the figure—“Outputs of Collaboration to Innovate.” Many companies may find it difficult to share knowledge, resources, and new technologies with other actors, but they may find it advantageous to engage in a more collaborative and open context [6]. This heterogeneous constellation of organizational actors is seen as an important way to innovate successfully in the digital age [21]. Collaborations for innovation are at the heart of most of the challenges of the 4.0 movement and, therefore, they are seen as a major enabler for industrial digital transformation [9]. The digital age takes place in an environment of intense knowledge sharing. Most digital innovations have been created collaboratively [21]. Although this represents clearly a partial view of the entire issue, interorganizational, multidisciplinary collaborations arguably can help to achieve a broader understanding of the issues involved in digital transformation [9]. Previous research, therefore, supports the elaboration of Proposition 5 (see Table I).

III. RESEARCH DESIGN

The main research objective of the study is to investigate how R&D collaborations with scientific and business partners contribute to digital transformation. In order to address this

research objective with a focus on the strategic, social, and managerial aspects of the digitalization process, three case studies were developed. A questionnaire and an interview script were developed, based on the conceptual framework from Fig. 1. For each element of the framework, questions were prepared to be answered by the interviewees. The constructs and their relationships guided the definition of the preliminary qualitative variables. The case studies results were then compared with the conceptual framework through content analysis [49], allowing the framework to be adjusted according to the contextualized realities under analysis and the findings to be compared with the theoretical approaches. The terms for data collection precluded the disclosure of company names, which are referred to as Omega, Sigma and Theta in the article.

The history of Omega Group began over 130 years ago in Japan. Since then, it has evolved into a global corporation with diversified activities in metallic products, automobile systems, energy, and telecommunications, thereby forming a chain of manufacturing plants all over the world. It has over 100 subsidiaries and modern R&D laboratories that develop new technologies and products. Omega constantly invests in broadband and networking applications, establishing a center of excellence that offers solutions adapted to the most diverse needs in communication network infrastructure. This research was developed in an Omega subsidiary located in the city of Curitiba, Brazil.

Sigma was established in Sweden in 1919 and today has over 55000 employees around the world. It is a global leader in home and professional appliances. Sigma is present in 150 countries and annually sells more than 60 million products. In Latin America, the brand has seven production plants distributed across Brazil, Argentina, and Chile, totaling around 11000 employees. The company arrived in 1926 in Brazil, and its first plant in the country is analyzed in this article.

Theta was established in Germany in 1908 and has become a successful global company with about 26000 employees in 52 plants across 23 countries. Theta is a supplier for the international automotive industry, producing and supplying its mechatronics systems and electric drives for over 80 automobile manufacturers. In 2011, its business group generated a turnover of around USD \$4.4 billion. Today, Theta is the fifth-largest family-owned company among the 100 best suppliers worldwide in the automotive industry.

A comparative analysis of these three companies allows the identifications of differences and similarities among them in terms of collaborative practices with external actors for digital innovation. The industrial sectors of these companies are some of the most mature in terms of awareness, application, and use of digital technologies in Brazil, according to the results of a comprehensive survey of Brazilian industry [6], [28]. In addition, the three cases are large-sized companies, which already face the need to establish collaborations to support digital transformation in their factories [6], [28], as opposed to small industrial firms in Brazil, which, for the most part, have not adopted collaborative R&D projects to digitally innovate yet [28]. The analysis of Omega, Sigma, and Theta was conducted with the expectation of understanding the diversity of their external partners for collaborative R&D in digital innovation,

TABLE II
PROFILE OF INTERVIEWEES

Participant	Level	Current position	Time in Company
Case Omega			
O-1	Tactical	Production Engineer	7 yrs. and 3 mos.
O-2	Strategic	Head of Department of Optical Cable Production	7 yrs. and 8 mos.
O-3	Strategic	Specialist in Automation, Process Control and Traceability	11 yrs.
O-4	Tactical	Full Industrial Technology Analyst	6 yrs. and 3 mos.
O-5	Tactical	Industrial Application Engineer	8 yrs. and 10 mos.
Case Sigma			
S-1	Strategic	Manufacturing Supervisor	1 yr. and 11 mos.
S-2	Tactical	Quality Technician	11 mos.
S-3	Tactical	Business Intelligence Analyst	11 mos.
Case Theta			
T-1	Strategic	Process Engineer	1 yr.
T-2	Strategic	Industrial Engineer Coordinator	2 yrs. and 3 mos.
T-3	Tactical	Process Planner	4 yrs. and 8 mos.

how such partnerships are managed, and what's the degree of relevance of these partnerships to the digital transformation trajectory.

The data were collected between October 2018 and March 2019. The evidence obtained from primary sources includes:

- 1) semi-structured interviews with strategic and tactical level employees who participate in R&D collaborative projects for the purpose of business digitalization;
- 2) nonparticipant observations regarding the technological infrastructure (e.g., equipment, tools, and software linked to digital technologies and how they are integrated), recorded in field diaries;
- 3) a questionnaire with closed questions that complements the interview script, which was applied to the same interviewees. The questionnaire and interview script were submitted to the review of Industry 4.0 specialists before the field research.

The use of multiple sources of evidence aimed to support construct validity and reliability in order to mitigate misinterpretations or bias in the reviewer's analyses. Many of the interviewees' perceptions were validated by nonparticipating observations and by the responses to the questionnaires. These multiple sources create, once all are documented, a database for the case study and, subsequently, allow a chain of evidence. Interviews lasting an average of one hour each were conducted with a total of 12 participants, as shown in Table II. The main benefit of selecting informants from different hierarchical levels was to guarantee exposure to different perspectives, mitigate personal bias, and allow the cross-checking information from different participants.

The use of *ATLAS.ti* 8.4 software helped in the search for convergences of the collected data. The software assisted in data triangulation, supporting the comparative analysis among the practices observed in the cases and providing elements to cross-check the information. Table III presents the interview script, showing the alignment of the questions with their respective qualitative variables. The variables were extracted from the theoretical framework (see Fig. 1) based on the respective supporting literature.

The technique of content analysis by codification was used for data analysis, supported by the use of *ATLAS.ti* software. The study followed the three phases of content analysis developed by [49], being:

- 1) pre-analysis;
- 2) material exploration or coding and categorization of the written texts;
- 3) treatment of results, inferences, and interpretations.

The qualitative variables from Table III were the first codes entered on *ATLAS.ti*. They are known as *a priori* codes and were used, where appropriate, to codify many of the data quotations. A total of 81 codes were established for the content analysis, comprising 38 that were created *a priori* from the literature review, and 43 that emerged from the coding of interview transcripts. These 43 codes contribute to an improved specification on open innovation practices in the context of Industry 4.0 in Brazil, since they take into account the specificity of each case as well as the level of organizational awareness and maturity.

After the content analysis was performed, it was reviewed by other researchers involved in the project, in order to verify and discuss possible differences in the analysis. The methodology was also reviewed by an expert in *ATLAS.ti* content analysis. Finally, the research results were reviewed by one interviewee of each case, so that the participants could assist in checking for divergences of interpretation.

IV. ANALYSIS AND DISCUSSION OF THE CASES

The analysis began by collecting the most frequent terms that appeared in the interview transcripts and field diaries. The word "process" appears frequently (82 occurrences), in connection with the observation that the use of digital technologies can trigger incremental improvements in the production processes at the shop floor level.

It was also observed that digitalization tends to affect manufacturing processes on the shop floor in order to add value in terms of higher efficiencies and automation, rather than products, as shown in Tables IV and V. Furthermore, social factors were highlighted in many quotations from respondents' perceptions of the three cases. The words "partnerships," "startups,"

TABLE III
INTERVIEW SCRIPT

Variables	Questions
• Industry 4.0 Awareness	<ol style="list-style-type: none"> 1. What are the benefits for manufacturing companies when incorporating the Industry 4.0 concept? 2. What are the challenges for your company in the current digital transformation context? 3. What kind of changes do you believe digital technologies can generate in your company nowadays [short term and long term]? 4. Is the concept Industry 4.0 being carried out strategically in your company? 5. Which digital technologies are being used in your company? 6. Is there any digital solution to be implemented? If yes, why haven't they been implemented yet?
• Antecedents to Encourage Collaboration	<ol style="list-style-type: none"> 1. Is your company prepared to innovate digitally and if yes, how? 2. Are R&D collaborations for digital innovation perceived as important for your company? 3. Do potential partners show interest to collaborate with your company or does your company have to search for them?
• R&D Collaborative Projects for Digital Innovation	<ol style="list-style-type: none"> 1. How many R&D collaborative projects for digital innovation are in the company? 2. Of these projects, how many have been concluded? 3. Has Industry 4.0 changed the way projects were conducted, and if yes, what are the differences? 4. Was it necessary to develop new competences for these projects?
• Open Innovation Practices in R&D Project	<ol style="list-style-type: none"> 1. Who are the business partners that assist digital innovation? 2. Who are the scientific partners that contribute to digital innovation? 3. Do these partners provide any kind of training and do they have expertise to assist with digital technology development and learning? 4. Were these partners considered strategic for your company to get knowledge about Industry 4.0 from the start? 5. Does the use of digital technologies promote a closer customer/supplier interaction in your company? 6. How is each R&D collaborative project managed? 7. Is there any record of shared experiences and knowledge obtained from each project completed or in progress?
• Implications by External Actor	<ol style="list-style-type: none"> 1. Are there any collaborative projects for digital innovation that have already achieved results, and if yes, which are they? 2. What are the critical success factors for partnerships of digital innovation? 3. Which were the challenges for collaborative digital innovation projects?
• Additional Information	<ol style="list-style-type: none"> 1. Is there something you would like to add about the topics above?

“clients,” and “collaborations” (40, 23, 28, and 20 occurrences, respectively) are also evident as relevant factors that facilitate the journey toward digital transformation in manufacturing.

A. Antecedent Factors or Drivers for the Digital Journey

The term Industry 4.0 is known internally at Omega as OSP—Omega Smart Plant. However, interviewee O-5 referred to it as OIS—Omega Industrial System, indicating some inconsistency among the respondents. According to the interviewees, Curitiba’s Omega plant is organizing itself to be prepared for digital transformation. The preparations involve various aspects including technological infrastructure, awareness about Industry 4.0, the provision of training for employees to understand the upcoming digital solutions and their applicability, the need for

“convincing” the board of directors to approve digital projects, and the adoption of a digital mindset throughout the company. Therefore, Omega displays an early stage of maturity toward Industry 4.0, a similar condition to that was found in Sigma and Theta. At Omega, the Industry 4.0 concept first emerged in 2016, through research initiatives of the company’s engineers. The first digital project commenced in 2017. At Sigma, the Industry 4.0 journey started in 2017, and most digital projects began in 2018. Theta also started to develop its digital transformation projects around that time.

At Omega, the journey toward factory digitalization is strategically and deliberately represented by goals, activities, and schedules of the company’s digital project. The project design was completed in 2018 with the development of Guidelines for Industry 4.0 to be operationalized within the next five years.

TABLE IV
STATUS OF CASES REGARDING DIGITAL SOLUTIONS

Case	Digital Solutions Used/ Implemented	Solutions in Development/ Pilot Projects/POCs	Ideation phase Solutions - No Budget: "it is in the radar"
Omega	Smart Sensors in machines for performance data collection in the painting process (use of gateways).	Big data and big data analytics (i.e., generation of a complete dashboard for real-time monitoring of the entire production line) for predictive maintenance and improved decision-making.	Integration between different existing information systems (low current vertical integration).
	Process automation via integration between machines' programmable logic controllers (PLCs) with existing systems (autonomous and smarter machines, with low operator dependency), but only for painting and tube processes.	Process automation via integration between programmable logic controllers of machines with existing systems in others production processes.	IoT architecture use to generate environmental sustainability in the factory (for example, managing leaks or water intake)
	Palletizing with advanced robotization (autonomous) instead of manual palletizing.		RFID sensors for product monitoring.
	3D Printer for rapid prototyping.		Machine learning.
	AGVs (Automated Guided Vehicle) for moving materials and stocks on the factory floor.		Augmented reality.
Sigma	Optical fiber <i>Laser Way</i> - Omega product offered in the market.		Collaborative robots.
	Paperless, via Kainexus platform, for production status disclosure (key performance indicator results through digitalization in real-time)	Big data analytics (underutilized and Sigma recognizes it has great potential to generate opportunities in the future).	Cloud Computing - not yet for Data Security issues (S-01).
	Big data via collection from sensors (underutilized).	Machine learning (in a study applied from data collected for 7 months by a specific machine).	Artificial intelligence - Sigma has not yet found a viable environment for this technology.
	Augmented reality (underutilized) for safety training. Smart sensors, e.g., use of RFID (radio-frequency identification) for product monitoring. 3D printers for parts prototyping.	3D printers "to make a digital warehouse". Virtual reality (still in testing and has already been applied tests with a China plant). Exoskeleton ("we're learning from it" - S-01) - for S-02 this solution is still being tested - usability still potential.	Cognitive vision system: Analysis of parts and products by image; enables image quality control - Sigma needs to be trained to better understand the complexity of this solution
	Cobots – Collaborative robots ("recent application, but not yet widespread" - S-1; "will be used in the course of 2019" - S-2)	AGV (automated guided vehicle) - still in tests, rented from local firm. Drones – "already applied for inventory control" - S-1; "are still in tests to map the factory" - S-2.	
Theta	Virtual Reality (VR) for remote maintenance, avoiding production line downtime.	Digital plant tour via mobile application.	Sensing - Intelligent identification of missing parts (although cost still too high for testing).
	Smart sensors in mechanical robot arms to measure productivity and speed of these robots in real time.	Connecting the programmable logic controllers of machines with existing information systems thereby providing machine network relations.	
	Digital work instruction using monitors (instructions in videos) solution developed by Theta Headquarters still in an incipient stage	Value chain integration - connectivity with customers to have real-time inputs for machine production via automatic confirmation solution. This solution is a feedback by customers on how many parts (electrical components) must be produced for customers and which exact sequence to produce.	
	Intelligent internal and external logistics for route tracking/traceability - use of sensors that verifies, in real time, the time of loading, and where the trucker is with the load.	Augmented reality - Theta bought the glasses, but did not use them yet in a real situation. The company already has an AR pilot project in training for safety for risk conditions in the factory.	
	Manufacturing execution system (MES) for connectivity and automated data collection of production, but is still expanding. Lack of training. MES will assist in paperless project	Software for paperless design - Mapping of the forms and other documents that must be digitized has already been done.	

Following those guidelines, Omega will be focused on updating a legacy system and corresponding digital technology architecture around the use of IoT architecture. Such a formal strategy for digitalization is highlighted in the literature [7], [24] as one of the main factors to support Industry 4.0 implementation.

As for Sigma, the organization headquarters structured in 2016 the digital strategy to be followed by its subsidiary plants. The Smart Factory document, created initially by the headquarters, represents the planning and development of Industry 4.0 practices. Sigma's regional factories are free to adapt and customize this strategy so that it is applicable to the context and needs of each plant. The corporation aims to create a transparent relationship with its subsidiaries according to the guidelines of this document. The corporation aims to create a transparent relationship between its subsidiaries and headquarters according to the guidelines of this document. There is a digital Committee at the Sigma subsidiary, which monitors the status of the digital journey. More specifically, the members of this committee and their leader discuss, monthly, the status of projects aimed at the Smart Factory and discuss what are the next steps toward digitalization.

Similar to the Omega case, Sigma also has people as "digital sponsors" tasked to foster and motivate digital initiatives, and who are focused on securing the board of directors' approval to fund these initiatives. Sigma depends on its local digital sponsors to have these projects developed and approved. These sponsors are considered extremely important, as highlighted in the *ATLAS.ti* codes "Strategic Driver" and "Managerial Driver" of the analysis, which are antecedent and preparatory factors for digital innovation.

Social drivers represent another antecedent factor for preparing manufactures for digitalization in the factory. Employees, ranging from shop floor operators to senior-level managers, need training on the fundamentals, applicability, and implications of digital technologies. As complex as it is, a "Digital Mindset" needs to be internalized by employees, regardless of their hierarchical level, in order to develop skills and resilience to adapt to a smart and digital factory.

Managerial, strategic, and social drivers have been deployed by Omega, which includes dedicated professionals to the search for digital technology and the development of competencies to deploy digital solutions in the factory. They also engage in

TABLE V
STATUS OF CASES REGARDING PARTNERSHIPS

Case	Partnerships in progress	Digital solutions in progress	Solution applicability and benefits
Omega	<p>CITS (Institute of Science and Technology), which is focused on software development.</p> <p>RAVI (Institution for R&D) jointly acting with the Federal University of Ceará State</p> <p>Government Agency via "Informatics Act" that provides resources for R&D collaborative projects in Industry 4.0</p> <p>SENAI (National Industrial Learning Service parastatals of Brazil) of the state of Paraná (SENAI PR) and of São Paulo (SENAI SP)</p>	<p>Integration between information systems and machines (continuity and development of the solution initiated by a private company).</p> <p>Communication of different information systems.</p> <p>Creation of data collection system from the factory floor to generate a global dashboard.</p> <p>Practically all the digital projects are being realized through "Informatics Act" assistance.</p> <p>Offering projects in their laboratories inviting companies like Omega to contribute to the construction of a Factory 4.0. Omega disclosed the part of cabling, routing, connection of machines.</p>	<p>Industrial automation (painting step and tube step of manufacturing process completed).</p> <p>Industrial automation (painting step of manufacturing process completed).</p> <p>Real-time information for improved decision making.</p> <p>[Applications developed in partnership with RAVI, CITS and a private company]</p> <p>These projects are a way for Omega to disclose and offer its connectivity solutions to interested actors.</p>
	Completed partnerships	Completed digital solutions	Solution applicability
	A private company - Machine Programming Company	Offered initial know-how in integration between machines and information systems	Industrial automation.
	Intra-organizational collaborations between people of different hierarchical levels.	Operators' initiative to automate production process via connected tablets (the idea was later operationalized through RAVI).	Automated and digital checklists
	Prospected partnerships	Prospected digital solutions	Solution applicability
	Startups. Universities.	Not yet, but there is interest for this partner type.	[Not known, but there is future interest]
Sigma	Partnerships in progress	Digital solutions in progress	Solution applicability and benefits
	European consultancy company contracted by the Swedish headquarters of Sigma.	Not applicable.	Bring initial awareness about what the Industry 4.0 concept is, its advantages, benefit and challenges for firms, but it was necessary for Sigma employees to make appropriate adaptations to the Brazilian reality.
	Public Institution of Science and Technology - ABDI (Brazilian Agency for Industrial Development).	[some solutions mediated by ABDI; ABDI intermediary role]	ABDI has opened a specific public notice called "Startup-Industry" where Sigma has registered a real problem to be solved and ABDI mediates the finding of startups and digital solutions developers that can solve this problem.
	Startups (incubated at FIEP or universities) and participation in Innovation Hub, or in accelerating co-workings of startups such as the Cubo and Inovabra accelerators.	Big data and big data analytics.	Collection and processing of large data quantity/diversity on factory status and external conditions of the firm, optimizing products, decision making; making factory processes more efficient. Generation of useful information, which suggests necessary changes in processes and / or optimizing actions so that firm can adapt to the new market demands.
	Universities in the city of Curitiba.	Training course on Industry 4.0 for employees of some hierarchical levels of Sigma [negative experience with one; "did not work for the timing of the work pace of the researchers" - S-01].	Create awareness and learning to understand the relevance and challenges of Industry 4.0, as well as present the Industry 4.0 solutions and possibilities of industrial applications (UFPR).
	FIEP (Federation of Industries of Paraná State), IEL, SESI, and SENAI-PR (Brazilian parastatals).	Offer of specialized training courses in Industry 4.0 and digital leadership for employees of industrial organizations in Paraná.	Generation of greater awareness and learning of what Industry 4.0 is, its challenges and competitive advantages for factories.
	Intra-organizational collaborations between people of different hierarchies, between plants of the Group, or with Headquarter. Strong exchanges of ideas and mutual assistance between Sigma Group subsidiaries.	Digitalization and monitoring of employees' medical forms. In other branches: intelligence body support in big data and big data analytics, which has collected data for 7 months from sensors on machines. This external team will study and analyze the data, deliver the reports and will be willing to answer Sigma Curitiba's questions.	Project focused on health and safety of employees' work, promoting preventive occupational health. From the analysis of these data predictive maintenance actions can be planned to anticipate possible problems - this analysis has been generating learning for Sigma Curitiba.
	Completed or interrupted partnerships	Completed digital solutions	Solution applicability
	Startups.	Augmented reality (AR).	Safety training done by all factory floor workers and by employees in the Administrative sector.
	Prospected partnerships	Prospected digital solutions	Solution applicability
	Institutions of science and technology.	[Not yet, but there is interest for this type of partner]	[Not known, but there is future interest]
	Consumers.	Collaboration would be mediated using a digital solution such as Telemetry; promoting horizontal integration/Value Chain 4.0. This is under study, nothing concrete.	Monitor how consumers are using Sigma products; offer future customized products / services.
	Input suppliers.	[Integration between information systems - horizontal integration for Value Chain 4.0]	Potentialize Just in Time production; Placing orders in digital form (Call-off) allowing fast delivery of inputs in the factory; greater transparency in information exchange with suppliers.
Theta	Partnerships in progress	Digital solutions in progress	Solution applicability and benefits
	Customers (such as car assemblers) as a business partner, which send the programming they wish directly to Theta to produce. This exchange is undertaken electronically.	Automatic confirmation software on the production line - about how many parts to produce (electrical components) for customers and what exact sequence to produce. This software was created with the assistance of an external partner	Greater integration with customers; Agile manufacturing processes; Machine produces and prints labeling automatically, however this is still applied in only one production line. Hence, only serves one customer for now.
	Infosystem, a technology company that adapts its 4.0 solutions together with Theta to meet its needs.	Paperless project (few manufacturing processes are 100% digitized; future prospect for all processes)	Agile and greater integration between manufacturing processes; Improved responsiveness & decision making.
	Company X - Brazilian company focused on industrial automation that adapts its specialized Industry 4.0 solutions together with Theta to meet its needs	Smart sensors - Connection between PLCs of different machines; and Connection between Theta machines and software	Improved integration and collaboration of machine-to-machine; Improved Information sharing; Real-time monitoring of operations.
	Option (when the partnership was established, Option was a Startup, now it is no longer a Startup. Already graduated)	Augmented reality.	Management of workers' perceptions of risk; better identification of risk situations for workers.
	Company X and Company Y, that are US partner companies of Theta Group (Industrial Technology Companies) + Theta Group (<i>Intra-organizational collaborations</i>)	MES - Manufacturing Execution System - digitalization of forms present in the manufacturing processes	Agile and greater integration between manufacturing processes; connectivity improvements.
	Completed partnerships	Completed digital solutions	Solution applicability
	Company T - technology company that adapts 4.0 solutions together with Theta to meet its needs.	Intelligent internal and external logistics project for the inputs of the products and parts produced by Theta	Traceability; on-time parts location verification and quick incorporation of decisions into production processes.
	Prospective partnerships	Prospected digital solutions	Solution applicability
	Universities in the city of Curitiba. University in the city of Campinas, but without success due to the incompatibility of schedules (deliveries and deadlines problems)	[Theta aims to put researchers in Industry 4.0 projects, but does not know in which project; it also aims to promote hackathon events by inviting researchers/Ph.D. professors]	[Not known, but there is future interest]
	Specialized consulting in Industry 4.0.	[Not yet, but there is interest for this type of partner]	[Not known, but there is future interest]

informal benchmarking practices, scouting for digital initiatives in other manufacturing companies, and successful cases of digital solutions. This characterizes the initial stage of the trajectory toward the digitalization of the company.

A similar situation is displayed by Theta and Sigma in terms of their trajectory toward digitalization, as these organizations have been trying to improve transparency so that all employees, regardless of their hierarchical level, receive training and attend events promoted by the company. Such events are aimed at raising awareness not only about the technical aspects and applicability of digital solutions but also about managerial and social aspects of both business and workforce implications of using these digital solutions. The promotion of clear and transparent lines of communication can enable employees to be engaged in using digital technologies once they can recognize the value of adopting such technologies.

The cases highlight another aspect that characterizes the construction of the Digital Mindset, which is the need to open up to different potential partners, seeking the exchange of ideas about digital technologies and how to apply them in the manufacturing context. This requires a more flexible, open, and proactive stance toward interorganizational collaboration to support their digital innovations. Such mindset facilitates the understanding that people—employees, customers, and other external partners—are the protagonists of digital innovation. To achieve this desired mindset, the company needs, among other aspects, to develop relational skills to promote empathy, linkages, and knowledge sharing among different people. The use of this mindset is relevant for the attraction of external partnerships and the construction of an organizational structure that allows flexibility, agility, and co-creation. In their self-diagnosis in terms of internal capabilities and resources, weaknesses and threats, the investigated companies conceded that they need to innovate urgently and digitally to be competitive in a volatile, unstable, and competitive context, and acknowledged that innovation is facilitated by involvement with external actors. This research presented the “human side” as one of the preparatory factors that facilitate the companies’ openness to external partnerships.

B. Perceived Challenges Regarding the Digitalization Process

The analysis of the cases indicates that the evolutionary journey toward factory digitalization poses several obstacles and challenges to be overcome. These challenges pertain not only to the technological domains but also to social and managerial spheres. The interviews also revealed that such a scenario can be aggravated by the economic crisis in Brazil and the lack of digital readiness that is prevalent in the market and particularly in Brazilian universities. The content analysis codes characterize the complexity of the perceived challenges of Industry 4.0, revealed by the codes that received the higher number of quotations at the interviews and field diaries.

The adoption of the new technologies that constitute Industry 4.0 was identified as a challenging task in the three cases studied. This can be a challenge in the early stages of technology implementation, because of the potentially high impact of digital change on manufacturing operations and business strategy.

Theta and Sigma are seeking to start the digital journey through the gradual launching of pilot projects, which are used to test future technology implementations. Once proven successful, they will serve as the basis for larger and more complex digital transformation projects.

The complexity of the technological architecture was highlighted by various interviewees as one of the main technological challenges to be overcome in order to operationalize digital practices. More specifically, several challenges were cited, including difficulties to provide Wi-Fi signal throughout the manufacturing plant; difficulties in implementing interoperability among different information systems; a rigid data security policy that hinders, for example, the use of cloud computing; as well as outdated industrial plants where the firms are located, as is the case in Brazil. The reported issues can lead, for example, to connectivity issues when trying to apply intelligent sensors on old machinery.

Many managerial challenges were perceived in all the cases. Some of them are as follows:

- 1) a closed organizational structure with a lack of integration and limited knowledge sharing among subsidiaries, and also between the subsidiary and its headquarters;
- 2) difficulty to change people’s mindsets, particularly those at the strategic level. Senior managers with more experience in the company can be more resistant to change, and thus may be slow to perceive the relevance of Industry 4.0;
- 3) difficulty to accurately demonstrate the real gains of digital projects, such as through payback and return on investment (ROI).

Regarding the financial aspects, ROI decisions related to digital transformation can lead to struggles in budget approval by the company’s board. For instance, S-3 stated that: “*They [managers] only approve if there is a very attractive payback, otherwise they don’t approve.*” This situation exemplifies the “trade-off” between the need to innovate and update the factory’s technological infrastructure in order to remain competitive, versus the conservatism represented by the difficulty of approving funding for digital projects, as noted by [7]. This occurs because projects for digitalization are linked to emerging technologies that have recent applicability with few success cases in the industry. Furthermore, the benefits for such projects are not always realized in a short timeframe and this can further hamper payback and ROI-based investment decisions. The lack of a digital mindset by the board of directors can be characterized as an “Innovation Killers”—their resistance to change and risk aversion are perceived as an obstacle for the operationalization of Industry 4.0 practices.

Among the social challenges, the need to develop employees’ digital skills was emphasized. In this regard, managers from Theta stated that they tried to be as “transparent” as possible with employees to inform and make them aware of the digital journey the company has been going through and the relevance for the business as well as for work dynamics of all employees. This practice was also observed among Sigma interviewees. However, it was identified that Sigma is struggling to raise awareness among employees about this matter, as they appear to not be interested in attending training courses and workshops

on Industry 4.0 that are provided by the company. According to some interviewees, socially related challenges can induce a tendency to seek for “outside support” in order to accelerate the implementation of digital solutions in the company. This external support is represented by the need to seek and engage with actors outside the corporation that have proven experience in digital practices in order to complement knowledge and resources linked to digitalization. This can demonstrate a lack of internal capability and skills regarding how to undertake research, development, testing, and implementation of customized digital solutions in order to meet the specific requirements of the factory.

In this regard, the companies in the study recognize that they do not have the in-house technological capabilities to comprehensively deliver digitalization initiatives, which raises the need to collaborate with external partners that have the required digital technology skills. This represents the need for open innovation practices of the outside-in type [2]. Table IV summarizes and compares the three cases regarding the main findings about the respective status of technologies that are part of the fourth industrial revolution. These are organized in three phases: those that are already being used by the factories, those that are in development and testing phase, and those that are still in the ideation phase.

C. Open Innovation Practices to Accelerate the Digitalization Process

The search for in-house professional capability has raised the need for Omega to undertake partnerships with suppliers to gain more knowledge about digital solutions, which involves seeking market actors who can assist in facilitating the desire to become a “smart factory.”

The only production process of Omega which was fully automated and digitalized is the painting process. Its digitalization was made possible by financial resources from tax exemptions of the Brazilian Information Systems Act, which aims to finance research & development & innovation (R&D&I) projects to support electronic automation, which is fundamental for Industry 4.0 development in the country [28]. These resources assisted Industry 4.0 implementation by enabling the engagement of external partners, such as an industrial automation private company, the CITS (International Center of Technology and Software), and the RAVI (an Institution for R&D located within a public university in Brazil). Omega is committed to the development of digital innovation projects with the support of the Information Systems Act. Since it is a Brazilian Federal Act, Omega’s digital projects are formalized and deliberate. In this regard, Omega must clearly demonstrate to government agencies why these projects are considered R&D&I projects and what are their implications to make Omega more competitive. Thus, in a near future, this factory intends to digitalize other stages of the production process with the use of smart sensors. This project is in the early stages of development and is being developed with the support of external partner RAVI.

At Sigma, there was no mention of the government Act to assist innovative practices. However, Sigma has partnerships with parastatal entities. At Theta, on the other hand, neither the

Governmental Act nor partnership with parastatal entities has been pursued to instigate digital innovation practices. However, the use of external partners was also found to be important, a fact emphasized by participant T-1: *“If it wasn’t for them [R&D external partners], our development would still be zero.”* For Sigma, it also considers their external partners as necessary for the development and operationalization of digital projects in the factory.

In all cases, the pathway toward factory digitalization has been a gradual, evolutionary journey. All cases are already realizing the incremental change generated by the use of digital solutions. Table V highlights the status of collaborations for the cases. It is clear that the companies collaborate more with scientific than with business partners. Neither Sigma nor Omega have business partners, and only Theta has been collaborating with its customers. This finding also characterizes the initial stage of these companies in their digital trajectory: they are beginning to explore the possibilities of a joint digital innovation for their factories, as most collaborative projects are still under development, and only a few projects are reported as completed.

Even though this article focuses on interorganizational collaborations, Table V also highlights intraorganizational collaboration, since it appears as an important feature in the interviewees’ perceptions. At Omega, while its digitalization process is primarily top-down, it has an open organizational structure to receive digital-driven ideas from its employees regardless of their hierarchical level. At Theta, the focus is on providing a transparent transition toward the Industry 4.0 context, and Sigma aims to develop its employees’ skills in multiple organizational areas, providing workshops and through a platform for intraorganizational information sharing.

As Table V shows the interviewees reported an increase in automation and operational efficiency, greater agility in production and decision making, and improvements in workforce quality. For interviewee O-3, “[Industry 4.0] is being implemented gradually, piece by piece [...] we start with a small cell [production stage] to prove the gains and then, once accepted by the production, expand to other areas.” In the case of Theta, one example of the process of “learning by doing” of new technologies is given by the emphasis on the importance of pilot projects by one of the interviewees: “in pilots we have [to make] the investment, but it is smaller. In the pilots, we apply in one line only [...]. The know-how is being acquired as we implement it. We are learning a lot in practice.” As digital initiatives need to be approved by the board of directors and operationalized in a timely manner, small projects are used as examples, allowing the board to perceive the value of digital projects, ultimately assisting them to approve Industry 4.0 initiatives of greater scope.

At both Sigma and Theta, some interviewees stated that their external collaborators were considered strategic partners, while other respondents perceive them only as facilitators to operationalize digital projects. Some interviewees also failed to make a distinction among partners for a joint digital R&D project, and digital technology suppliers that simply sell “off-the-shelf” Industry 4.0 solutions. The latter is not the focus of this research.

The interviews also revealed that the distinction between Industry 4.0 and ‘Industry 3.0’ technologies was not clear for some

TABLE VI
VALIDATION OF EACH RESEARCH PROPOSITION

Proposition	Results	Highlights from the cases
P1: Social, managerial, and strategic antecedent factors are relevant to prepare the company for digitalization.	Supported in all case studies	<p>A. General aspects: 1. Outlined in item 4.1 which explained the antecedent factors to prepare companies for a digital factory, and more specifically to prepare them for collaborations that can support the journey; 2. Social Drivers as an important antecedent to build a Digital Mindset; 3. People perceived as the real digital change protagonists; 4. Establishing and communicating a digital strategy for everyone is crucial; 5. Bureaucracy as one of the major [managerial] challenges to operationalize digital practices. B. Case-specific aspects: 1. Omega: the provision of training for employees to understand the upcoming digital solutions and their applicability was identified as being critical for the digitalization. The need to “convince” the board of directors to approve digital projects, and the adoption of a digital mindset throughout the company was also emphasized as being critical for the digitalization; 2. Sigma: The creation of a digitalization committee aimed to verify the current stage of the company in order to track and discuss the development of digital projects. Some employees also act as “digital sponsors” to convince the board of directors to approve projects; 3. Theta: Increased transparency with employees in order to provide trainings and assess their skills regarding digitalization. Focus on having a clear line of communication between the entire organization.</p>
P2: Social, managerial, and strategic antecedent factors are relevant to motivate manufacturing to engage with external partners for digital innovation.	Supported in all case studies	<p>A. General aspects: 1. The companies have been motivating their workforce to engage with external partners; 2. Industry 4.0 perceived as a gradual and complex process of organizational change, requiring the companies to prepare their workforce to understand and perceive the value and the impact and consequences of digital solutions applicability in the factory, and in their work routine and dynamics; 3. In diagnosing the company in terms of internal capabilities and resources, companies are humble and resilient to recognize that they need to innovate urgent and digitally to be competitive in an unstable context and that this innovation is facilitated by engaging with external actors. B. Case-specific aspects: 1. Omega: The OIS, which is their plan for digital transformation, includes specific items related to the importance of external partnerships for digital solutions; 2. Sigma: Strategic plan provided by organization headquarters provide general guidelines and allow the organizations to flexibilize their initiatives, including the acceptance of external partnerships for digital solutions; 3. Theta: Employees are receiving training related to the importance of digital solutions and external partnerships. Events related to Industry 4.0 are also considered important to extend the organizations contacts with external institutions.</p>
P3: Digital technologies are enabling factors that assist collaborations with business partners.	Not supported in Omega. Partially supported in Sigma and Theta	<p>A. General aspects: 1. The companies display an incipient stage of development; 2. Companies could not determine whether technologies were enabling factors to collaborate with business partners, as they rely mainly on scientific partners at the moment. Two organizations displayed developments on this type of partnership. B. Case-specific aspects: 1. Omega: as it is still at an early stage in the path towards digitalization, the organization is not currently pursuing this type of partnership, and only mentioned that it aims for it on the future; 2. Sigma: the interviewees could not precise if digital technologies were enabling factors that assist collaborations or greater and stronger integration with customer or supplier data. The company aims to collect and monitor consumer data on how they are using the company's smart electronics in the future, making a viable way for Sigma to have real-time consumer interaction; 3. Theta: the interviewees could not determine whether digital technologies were enabling factors that assist collaborations. However, greater integration with customers data was already being developed, particularly with auto makers, with the goal of have partners with real-time data exchange, displaying more efficiency and accelerating the Supply Chain.</p>
P4: Collaborative R&D practices with scientific partners assist digital innovation in manufacturing	Supported in all case studies	<p>A. General aspects: 1. All cases had scientific partnerships to facilitate their journey towards digitalization (Table 5); 2. Interviewees affirmed that digital innovation would not be possible without external scientific partners; 3. All cases display a focus on R&D external scientific partners; 4. All companies displayed completed partnerships with scientific partners. B. Case-specific aspects: 1. Omega: accomplished a partnership with a startup that allowed the organization to increase the level of industrial automation. The factory also has partnerships with CITS (International Center of Technology and Software) and RAVI (Institution for R&D located within a public university in Brazil), and is also committed to the development of digital innovations with the support of Information Systems Act, which is accelerating their digital innovation trajectory; 2. Sigma: has developed partnerships with parastatal entities to foster its digital innovation. It has completed a partnership with a startup which allowed them to implement AR to their factory. Sigma also has partnerships in progress with universities, and startups; Theta: involved in partnerships with startups, one of which has allowed them to implement a real time monitoring system. Theta has prospected partnerships with universities to foster its digital innovation.</p>
P5: Collaborations with business and scientific partners, together, contribute to digital innovation in manufacturing.	Partially supported in all case studies	<p>A. General aspects: 1. All cases displayed scientific partnerships that facilitate their digitalization process (Table 5); 2. Nevertheless, business partnerships for digital innovation did not receive a similar emphasis; 3. Employees still have to increase their knowledge about digital transformation in order to successfully assess the importance of scientific and business partners for digital innovation. B. Case-specific aspects: 1. Omega: it was the only case that gave some emphasis to the importance of business partners; however, it is the only organization that did not have a plan for future partnerships with this type of partner. Omega demonstrated more developed partnerships with the scientific partners than the other two case studies; 2. Sigma: demonstrated the relevance of innovation as collaborative spaces that foster co-innovation practices and R&D for product and business processes, generating factory value from digital solutions. However, it has yet to establish partnerships with business partners to validate the importance of this type of partners for digital innovation; 3. Theta: Although it was the only case that completed a partnership with a business partner, some interviewees considered external collaboration as a facilitator of digital solution development rather than strategic. Interviewees also conflated R&D partners with mere digital solution providers, demonstrating that the actual benefit of these partnerships has yet to be better perceived.</p>

respondents. This misperception also characterized the initial trajectory of the case studies regarding Industry 4.0 awareness.

In contrast with the other cases, at Omega there was a consensus of external partners being considered strategic for the firm's awareness of digital solutions and their potential applicability. Therefore, established partners and potential technology providers were involved early on in promoting “tech day” events at Omega so that employees acquired knowledge and attended practical classes on how digital solutions are applied and implemented.

V. DISCUSSION

Table VI identifies whether each theoretical proposition from Table I was corroborated according to the main findings of each case. The findings indicate that organizations are at the beginning of their digital ecosystem development. However, these companies have already seen the first results in the form of an improved competitive advantage in their factories as they adopt open innovation practices. This demonstrates how the adoption of collaborative practices can help industrial companies accelerate the process of digital transformation.

As shown in Table VI, P1 and P2 were fully verified in all case studies, as interviewees detailed how the support from managerial, strategic, and social aspects are important for the digitalization in manufacturing firms. P4 was also supported by the evidence in all case studies, demonstrating the importance of scientific partners for joint R&D projects. However, P3 was not supported in Omega and only partially supported in Sigma and Theta. Finally, P5 was partially supported in all case studies, which demonstrate that they are still in the initial stages of development toward digital factory transformation.

More generally, intercollaboration is seen as a source of:

- 1) external inputs for the development of digital solutions and mutual learning from joint development;
- 2) complementary resources, since manufacturers need additional know-how and tools to develop all the digital solutions needed for their plants;
- 3) new ideas and points of view to support an open mindset among employees.

The cases indicate that it is more prudent and strategically advantageous to complement resources with external partners than to acquire new assets, such as hiring new employees.

Intercollaborative practices not only facilitate but also encourage factories to evolve in their digital journeys. Scientific partners play a particularly relevant role as sources of new technologies so that factories can learn and develop digital solutions, since they recognize that their knowledge is limited.

For the most part, the cases do not receive support from the government, except for Omega, which benefits from the Information Technology Act. Brazil has actions to promote technological innovation in the private sector, including tax incentives, scholarships to engage university researchers in innovation projects, and cooperation networks involving industry, R&D centers, and matching public funding. This has the potential to establish a digital innovation ecosystem to foster the country's industrial competitiveness. However, government support is lacking in these cases either due to insufficient knowledge about these public resources or because their organizational culture is not inclined to take advantage of them.

The cases demonstrated that they are still in an initial stage of development regarding the construction of an intercollaborative network. Therefore, Proposition 5 of this research was partially confirmed, given the dearth of business partners to assist in the digital manufacturing innovation process. Outside-in practices investigated are considered drivers and accelerators to operationalize digital projects. Without these practices, the digitalization trajectory would be more complex, expensive, and slow. Despite the lack of business partnerships, the cases consider the two groups of partners as factors that will take manufacturing to the next stage toward digital transformation.

The open innovation approach presents itself as appropriate to better understand what motivates factories to collaborate, and how ideation, testing, development, and application of digital projects take place in the factories. However, joint innovation is not a determining factor for industries to successfully engage in digital transformation. Together with technological factors, social, managerial, and strategic elements are fundamental for the operationalization of digital practices.

VI. CONCLUSION

This article has investigated how R&D collaborations with scientific and business partners contribute to digital transformation in three Brazilian multinational industrial companies that have already commenced their respective journeys toward Industry 4.0. The analysis of the implementation of an R&D collaboration strategy between the company and external actors suggests that scientific partners played a crucial role to boost digital innovation practices in the factories in this article. The results of this article indicate that the collaboration network to promote digital innovation is at the center of Industry 4.0 and thus the innovation ecosystem needs to be considered as an important—though certainly not the only—enabler for industrial digital transformation.

It should be pointed out that the results are based only on the perceptions of participants from manufacturing companies directly involved in R&D collaborations for digital innovation since external actors were not included in the research. Furthermore, there are specific limitations inherent to the Brazilian

context. This article, as a matter of design, does not allow generalizations in the absence of further studies that encompass other manufacturing companies and other organizational actors involved in the Industry 4.0 concept, both in Brazil and in other countries.

As for the contribution to the literature, open innovation practices can facilitate the testing, development, and application of digital solutions for manufacturing enterprises. Industry 4.0 is probably the most disruptive concept for most industries, as it fosters not only the integration of people, machines, and information systems within a factory, but also integration between the company and its wider ecosystem, potentially involving customers, suppliers, startups, universities, and other R&D partners. The use of digital solutions is already increasing the need for innovation and introducing more complexity. Since Industry 4.0 can also bring factories to new limits in terms of innovation capacity and in-house capabilities, open innovation can be an effective approach to master innovation and stay competitive in today's fast-changing markets.

Open innovation is an approach based on the premises that knowledge and experience within an organization is necessarily limited and that internal work methodologies, processes, and even the mindset may impose limitations to (digital) innovation. The results demonstrated by the organizations contribute for these findings, emphasizing that the Brazilian cases lack internal capabilities and knowledge to develop Industry 4.0 skills and capabilities.

The findings of this article shed light on how and to what extent R&D collaborations can help in the digital business journey, clarifying the benefits of these collaborations, and thus contributing to the literature on external partnerships and their relationship with digital innovation. Thus, open innovation and intercollaborative strategies have been identified as promising approaches to deal with disruptive events, as shown by the cases. The collaborative perspective can strengthen the business environment in a context of market turbulence by supporting an agile combination of skills and by facilitating the sharing of data, information, ideas, and resources in times of crisis. The literature and the research findings highlighted the role of collaborations in the rapid response to the identification of business opportunities and threats in a volatile business environment. The development of collaborative relationships can increase resilience and facilitate effective contingency planning and risk sharing among partners.

A. Managerial and Practical Implications

This article contributed practical insights on the diversity and complexity of antecedent factors for digital readiness, the management of collaborations with diverse partners, and the challenges to sustain the effective orchestration of digital transformation in the cases under study. The analysis produced qualitative findings about the relevance of collaborations in the digital age as one of the main sources for creating value for manufacturing companies.

The findings also reveal a reciprocal relationship between open innovation practices and the use of digital technologies

in these cases. The respondents believe that open innovation facilitated or even accelerated the practices of digital innovation, and, simultaneously, the enhanced connectivity afforded by the use of digital technologies makes it easier to collaborate with actors outside the corporation for joint innovation. As the current digital context raises the need to seek and engage with external partnerships, the identification of practices that foster the success of these projects sheds light on the role of interorganizational relations for business innovation.

The research also emphasizes that if open innovation is a pathway without return and the tendency is for its growth in organizations, it is necessary to help the “innovation killers” of today to become innovation partners for the viability of digital innovation projects tomorrow. In the context of the cases, senior managers that are reluctant to take risks must develop a digital mindset that can embrace new skills and knowledge to help realize the digital transformation opportunities afforded by Industry 4.0.

The findings indicate that business innovation is not exclusively focused on technology, but on people’s engagement and attitudes, and in connecting them. If the factories do not mobilize internal and external human capital so that they realize the value of digital technologies, the promised gains of digitalization will hardly be realized. The priority in all cases is clearly the use of technological solutions to bring competitive advantages and add value to the company so that the use of digital solutions delivers results and is aligned with the business strategy.

In sum, the cases helped to clarify that manufacturing digital transformation, despite having technology at its core, is a social transformation. It is done by people, with people, and for people. The path toward digital is driven by their interactions and connections in the form of collaborations. The orchestration of digital solutions enables this transformation to occur. Additionally, developing a digital mindset means creating a necessary foundation for leaders, directors, managers, analysts, and other employees to make digital innovation a reality both in the company’s routine and results.

B. Suggestions for Future Research

It is suggested, as future research, to consolidate and debate the qualitative research results in order to characterize and analyze the collaborations for digital innovation, and more specifically R&D intercollaboration. Such studies should investigate partnerships between manufacturing companies and other organizational actors that can positively impact the companies’ progress toward digital transformation, such as startups that develop digital solutions, universities, and public and private R&D centers. Furthermore, understanding this research field can be expanded by exploring the perceptions of other ecosystem actors. An even broader perspective that can provide further insights could be obtained by developing comparative case studies of digital innovation ecosystems between Brazilian manufacturing companies and their counterparts from developed countries that have a more mature digital industrial policy, such as Germany, Japan, and USA.

REFERENCES

- [1] H. Chesbrough, *Open Business Models: How to Thrive in the New Innovation Landscape*. Houston, TX, USA: Harvard Business School Press, 2006.
- [2] H. Chesbrough, *Open Innovation: The New Imperative for Creating and Profiting from Technology*. Houston, TX, USA: Harvard Business School Press, 2003.
- [3] Capgemini Consulting, “Industry 4.0 - The Capgemini consulting view: Sharpening the picture beyond the hype,” 2017.
- [4] M. Bogers, H. Chesbrough, and C. Moedas, “Open innovation: Research, practices, and policies,” *Calif. Manage. Rev.*, vol. 60, no. 2, pp. 5–16, Feb. 2018.
- [5] K. Schwab, *The Fourth Industrial Revolution*. New York, NY, USA: Crown Publishing Group, 2017.
- [6] PriceWaterhouse Coopers, “Indústria 4.0: Digitalização como vantagem competitiva no Brasil,” São Paulo: PwC Brasil, 2016.
- [7] H. Kagerman, W. Wahlster, and J. Helbig, “Recommendations for implementing the strategic initiative industry 4.0,” Frankfurt, Germany, 2013.
- [8] V. Rudtsch, J. Gausemeier, J. Gesing, T. Mittag, and S. Peter, “Pattern-based business model development for cyber-physical production systems,” *Procedia CIRP*, vol. 25, no. C, pp. 313–319, 2014.
- [9] L. M. Camarinha-Matos, R. Fornasier, and H. Afsarmanesh, “Collaborative networks as a core enabler of industry 4.0,” in *Collaboration in a Data-Rich World. PRO-VE 2017*, L. M. Camarinha-Matos, H. Afsarmanesh, and R. Fornasier, eds. Vicenza, ITA: Springer, 2017, pp. 3–17.
- [10] C. Burchardt and B. Maisch, “Digitalization needs a cultural change – examples of applying agility and open innovation to drive the digital transformation,” *Procedia CIRP*, vol. 84, pp. 112–117, 2019.
- [11] L. Barroso Simao, R. Gouveia Rodrigues, and M. J. Madeira, “External relationships in the organizational innovation,” *RAI Rev. Administ. e Inovação*, vol. 13, no. 3, pp. 156–165, Jul. 2016.
- [12] I. Bucker, M. Hermann, T. Pentek, and B. Otto, “Towards a methodology for industrie 4.0 transformation,” in *Business Information Systems. BIS 2016*. in *Lecture Notes in Business Information Processing*, vol. 255, W. Abramowicz, R. Alt, and B. Franczyk, eds. Berlin, Germany: Springer, 2016, pp. 209–221.
- [13] B. Bunse, H. Kagermann, and W. Wahlster, “Foreword,” in *Industrie 4.0: Smart Manufacturing For the Future*, W. MacDougall, ed. Berlin, Germany: GTAI - Germany Trade and Invest, 2014, pp. 1–40.
- [14] T. Rayna and L. Striukova, “Open innovation 2.0: Is co-creation the ultimate challenge?”, *Int. J. Technol. Manage.*, vol. 69, no. 1, pp. 38–55, 2015.
- [15] I. Veza, M. Mladineo, and N. Gjeldum, “Managing innovative production network of smart factories,” *IFAC-PapersOnLine*, vol. 48, no. 3, pp. 555–560, 2015.
- [16] J. West and M. Bogers, “Leveraging external sources of innovation: A review of research on open innovation,” *J. Prod. Innov. Manage.*, vol. 31, no. 4, pp. 814–831, Jul. 2014.
- [17] A. F. de Paulo, L. C. Carvalho, M. T. G. V. Costa, J. E. F. Lopes, and S. V. R. Galina, “Mapping open innovation: A bibliometric review to compare developed and emerging countries,” *Global Bus. Rev.*, vol. 18, no. 2, pp. 291–307, Apr. 2017.
- [18] J. West and M. Bogers, “Leveraging external sources of innovation: A review of research on open innovation,” *J. Prod. Innov. Manage.*, vol. 31, no. 4, pp. 814–831, Jul. 2014.
- [19] X. Fu, J. Li, H. Xiong, and H. Chesbrough, “Open innovation as a response to constraints and risks: Evidence from china,” *Asian Econ. Pap.*, vol. 13, no. 3, pp. 30–58, Oct. 2014.
- [20] A. Ovanessoff, E. Plastino, and F. Faleiro, “Why Brazil must learn to trust in collaborative innovation,” *Accenture*, pp. 1–20, 2015.
- [21] S. Nambisan, K. Lytyinen, A. Majchrzak, and M. Song, “Digital innovation management: Reinventing innovation management research in a digital world,” *MIS Q.*, vol. 41, no. 1, pp. 223–238, Jan. 2017.
- [22] K. Matzler, S. Friedrich von den Eichen, M. Anschober, and T. Kohler, “The crusade of digital disruption,” *J. Bus. Strategy*, vol. 39, no. 6, pp. 13–20, Nov. 2018.
- [23] Y. Liao, F. Deschamps, E. de, F. R. Loures, and L. F. P. Ramos, “Past, present and future of industry 4.0 – A systematic literature review and research agenda proposal,” *Int. J. Prod. Res.*, vol. 55, no. 12, pp. 3609–3629, 2017.
- [24] H. Fatorachian and H. Kazemi, “A critical investigation of industry 4.0 in manufacturing: Theoretical operationalisation framework,” *Prod. Planning. Control*, vol. 29, no. 8, pp. 633–644, Jun. 2018.

- [25] L. D.. Xu, E. L. Xu, and L. Li, "Industry 4.0: State of the art and future trends," *Int. J. Prod. Res.*, vol. 56, no. 8, pp. 2941–2962, Apr. 2018.
- [26] L. Zhou, A. Y. L. Chong, and E. W. T. Ngai, "Supply chain management in the era of the Internet of Things," *Int. J. Prod. Econ.*, vol. 159, pp. 1–3, Jan. 2015.
- [27] K. Trantopoulos, G. von Krogh, M. W. Wallin, and M. Woerter, "External knowledge and information technology: Implications for process innovation performance," *MIS Q.*, vol. 41, no. 1, pp. 287–300, Jan. 2017.
- [28] CNI – Confederação Nacional da Indústria, "Desafios para indústria 4.0 no Brasil," Brasília: CNI, 2016.
- [29] J. M. Müller, O. Buliga, and K.-I. Voigt, "Fortune favors the prepared: How SMEs approach business model innovations in industry 4.0," *Technol. Forecast. Soc. Change*, vol. 132, pp. 2–17, Jul. 2018.
- [30] B. Quattrociocchi, M. Calabrese, X. Hysa, and E. Wankowicz, "Technology and innovation for networks," *J. Organ. Transform. Soc. Chang.*, vol. 14, no. 1, pp. 4–20, Jan. 2017.
- [31] P. Costa and G. Porto, "Capacidade dinâmica de cooperação nas multinacionais brasileiras e seus fatores gerenciais determinantes," *Rev. Eletrônica Negócios Int.*, vol. 10, no. 1, pp. 57–69, 2015.
- [32] C. Jones and B. Lichtenstein, "Temporary inter-organizational projects: How temporal and social embeddedness enhance coordination and manage uncertainty," in *The Oxford Handbook of Inter-Organizational Relations*, S. Cropper, C. Huxham, M. Ebers, and P. Smith Ring, eds. Oxford, U.K.: Oxford Univ. Press, 2018, pp. 231–255.
- [33] K. M. Eisenhardt and J. A. Martin, "Dynamic capabilities: What are they?," *Strategic Manage. J.*, vol. 21, no. 10–11, pp. 1105–1121, Oct. 2000.
- [34] H. Chesbrough and M. Bogers, "Explicating open innovation: Clarifying an emerging paradigm for understanding industrial innovation," in *New Frontiers in Open Innovation*, H. Chesbrough, W. Vanhaverbeke, and J. West, ed.s. Oxford, U.K.: Oxford Univ. Press, 2014, pp. 3–28.
- [35] H. Chesbrough, "Open innovation: Where we've been and where we're going," *Res. Manage.*, vol. 55, no. 4, pp. 20–27, Jul. 2012.
- [36] V. van de Vrande, J. P. J. de Jong, W. Vanhaverbeke, and M. de Rochemont, "Open innovation in SMEs: Trends, motives and management challenges," *Technovation*, vol. 29, no. 6–7, pp. 423–437, Jun. 2009.
- [37] M. Praest Knudsen and T. Bøtker Mortensen, "Some immediate – but negative – effects of openness on product development performance," *Technovation*, vol. 31, no. 1, pp. 54–64, Jan. 2011.
- [38] K. Faccin and A. Balestrin, "Práticas colaborativas em P&D: Um estudo na indústria brasileira de semicondutores," *Rev. Adm. Mackenzie*, vol. 16, no. 6, pp. 190–219, Dec. 2015.
- [39] J. Du, B. Leten, and W. Vanhaverbeke, "Managing open innovation projects with science-based and market-based partners," *Res. Policy*, vol. 43, no. 5, pp. 828–840, Jun. 2014.
- [40] C. Pitassi, "A virtualidade nas estratégias de inovação aberta: Proposta de articulação conceitual," *Rev. Adm. Pública*, vol. 46, no. 2, pp. 619–641, Apr. 2012.
- [41] B. Leten, W. Vanhaverbeke, N. Roijakkers, A. Clerix, and J. Van Helleputte, "IP models to orchestrate innovation ecosystems: IMEC, a public research institute in nano-electronics," *Calif. Manage. Rev.*, vol. 55, no. 4, pp. 51–64, Jul. 2013.
- [42] L. A. L. Brito, E. P. Z. Brito, and L. H. Hashiba, "What type of cooperation with suppliers and customers leads to superior performance?," *J. Bus. Res.*, vol. 67, no. 5, pp. 952–959, May 2014.
- [43] U. H. Westergren and J. Holmström, "Exploring preconditions for open innovation: Value networks in industrial firms," *Inf. Org.*, vol. 22, no. 4, pp. 209–226, Oct. 2012.
- [44] R. Conti, A. Gambardella, and E. Novelli, "Research on markets for inventions and implications for R&D allocation strategies," *Acad. Manage. Ann.*, vol. 7, no. 1, pp. 717–774, Jun. 2013.
- [45] G. George, J. Howard-Grenville, A. Joshi, and L. Tihanyi, "Understanding and tackling societal grand challenges through management research," *Acad. Manage. J.*, vol. 59, no. 6, pp. 1880–1895, Dec. 2016.
- [46] M. Bogers, A. Burcharth, and H. Chesbrough, "Open innovation in brazil: Exploring opportunities and challenges," *Int. J. Innov.*, vol. 7, no. 2, pp. 178–191, Mar. 2019.
- [47] G. Schuh, R. Anderl, J. Gausemeier, J., M. ten Hompel, W. Wahlster, Eds., "Industrie 4.0 maturity index. Managing the digital transformation of companies," Munich, Germany: Herbert Utz Verlag, 2017.
- [48] Y. Yoo, R. J. Boland, K. Lyytinen, and A. Majchrzak, "Organizing for innovation in the digitized world," *Org. Sci.*, vol. 23, no. 5, pp. 1398–1408, Oct. 2012.
- [49] L. Bardin, *Análise De Conteúdo*, Lisboa: Edições, vol. 70, 2011.