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R&D Collaboration Strategies for Industry 4.0 Implementation: A Case Study in Brazil

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Abstract: Companies need to collaborate with partners to co-create digital solutions as part of Industry 4.0 implementation. The objective of this study is to investigate how collaborative partnerships contribute to the digital transformation of organizations. The research design is based on a case study investigation of a Brazilian manufacturing company. The findings indicate that the company is already generating results through its commitment to open innovation practices. The results indicate that business success depends more on how disruptive technologies are developed and utilized by engaged people to add value, rather than focusing on the adoption of new technologies.

Keywords*:* R&D Collaborations, Open Innovation, Digital Transformation, Competitive Advantage, Industry 4.0.

1. Introduction

The dynamic and competitive business environment in which most organizations operate emphasizes the need to foster both organizational transformation and innovation capabilities. Such capabilities are not developed in isolation, as highlighted by Chesbrough (2006). They are often dependent on innovative processes, ultimately resulting in the need to develop an open innovation strategy, due to the pressures of a competitive and volatile external environment that encompasses new technologies and more demanding customers (Chesbrough, 2003). The increasing speed of technological change and the intensification of international competitiveness has led to an increase in collaborative research and development (R&D) efforts, since organizations cannot solely rely on their own expertise and internal R&D to innovate. Moreover, the reliance on external technology inputs to the innovation process has accelerated due to the pace of developments associated with information and communication technology, biotechnology and other high-technology areas.

Industry 4.0, also known as the 4th Industrial Revolution, refers to an increase of digitalization processes throughout the manufacturing value chain. This is driven by the adoption and integration of digital technologies that are encompassed by the Industry 4.0 concept, such as: smart sensors, simulation, advanced and collaborative robotics, cloud computing, Internet of Things (IoT), 3D printing, machine learning, augmented and virtual reality, big data and advanced analytics (Oztemel & Gursev, 2018). Digital solutions result in a smart, agile, connected digital factory, which integrates different users, devices, machines and systems. This integration extends to customers, suppliers, and other partners, aiming to increase data agility, transparency, and the automation of production systems, boosting efficiency, productivity, and competitiveness (Durugbo, 2015; Thames & Schaefer, 2016, Appio et al., 2017; Capgemini, 2017; Camarinha-Matos et al., 2017, 2019). As a result, the innovation process becomes more interactive, dynamic, open and collaborative (Nambisan et al., 2017; Bogers et al., 2018). Therefore, managers need to find new ways to address organizational collaborations, since complementary partners can become co-creators of new digital solutions (Rayna & Striukova, 2015). Open Innovation (Chesbrough, 2003) can be adopted by industrial companies to drive forward digital innovation.

In the case of Brazil, large and medium-sized manufacturing companies have advanced towards adoption of Industry 4.0 technologies, including industry leaders such as Embraer, AmBev, Natura, Bosch Brazil, Renault-Nissan Brazil, and Electrolux Brazil (MDIC, 2017). However, digitalization is still a distant goal for most domestic companies (CNI, 2016). In countries where Industry 4.0 is more advanced, such as the United States, Germany, and China, it has already led to increased productivity and reduced operating costs, as well as to faster and more predictive decision-making.

Collaborations with the most diverse organizational actors are at the center of the digital innovation challenges (Camarinha-Matos et al., 2017, 2019). However, there are few studies that address strategic and managerial aspects of collaborative arrangements in manufacturing companies (Piccarozzi et al., 2018). As the relevance of Industry 4.0 for competitiveness grows, the stages of its practical implementation – and particularly the facilitating factors for its use – need to be studied in greater depth. The literature still lacks a detailed understanding of the social, strategic, and managerial aspects of digital transformation in manufacturing companies and how they engage external sources of new knowledge and technologies (Kiel et al., 2017; Kagerman, et al., 2013).

Moreover, existing research on digital innovation has largely been contained within specific disciplines (e.g., marketing, economics, information systems, strategy) and arguably, limited effort has been spent so far on adopting a more interdisciplinary view of the underlying issues (Nambisan et al., 2019). Studies on digital innovation that lie beyond the information systems domain have failed to incorporate such an expansive approach. This implies lost opportunities to develop more nuanced understanding of how digital technologies facilitate innovation process (Nambisan et al., 2019; Verhoef et al., 2019). There is also a lack of understanding of how companies can use effectively and consistently a wide range of digital technologies and how to gain competitive advantage from the use of such technologies (Koch & Windsperger, 2017).

Therefore, this paper addresses the research gaps outlined above by investigating how R&D collaborations with scientific and business partners contribute to the Digital Transformation (DT) of industrial companies towards Industry 4.0. The article is organized as follows. After the introduction there is a review of the literature on DT in manufacturing companies, as well as technology collaborations and their implications for innovation. This is followed by the details on the qualitative case study strategy used, including the data collection instruments and data analysis techniques employed. Thereafter, the case study of a Brazilian subsidiary of an international telecommunications manufacturing company headquartered in Japan is discussed. This is followed by conclusions, research limitations and future work.

2. Literature review

2.1 Digital Transformation in manufacturing companies

DT can be conceptualized as the use of digital technologies to create and improve market offerings, processes or even business models. Similarly, DT is the sociocultural process of adapting firms to the new organizational forms and capability sets needed to remain viable and relevant in a digital landscape (Saarikko et al., 2020). DT can be described as a "process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies" (Vial, 2019: 121). DT management refers to the practices, processes and organizational principles that underpin the effective orchestration of digital innovation (Nambisan et al., 2017). DT encompasses efficiency-driven digitalization of processes as well as digital innovations focused on enhancing existing physical products with digital capabilities (Yoo et al., 2012).

Technology drives DT at all organizational levels. The process includes both the exploitation of digital technologies to optimize existing processes and the exploration of digital innovation, which can potentially transform the business model (Mittag et al., 2016), that is, “the logic of how an organization creates, delivers and captures value” (Osterwalder and Pigneur, 2010, p. 14).

The Industry 4.0 concept arose from the incorporation of digital technologies into industrial activities (Kagerman et al., 2013; Xu et al., 2018). The use of digital technologies allows products, people, machines and devices to be monitored and tracked. These technologies enable companies to extract a large volume and diversity of data on manufacturing performance online, as well as other aspects outside the firm. Data comes from multiple sources, in different formats, structured or not, and there is a need to combine internal data with data from outside sources, such as the way customers are using a product, or more accurate data about when a manufacturing company will receive raw materials from its suppliers.

Many industries are already starting their journey toward DT by linking their business processes, from supply to aftermarket, to the Internet. Therefore, Industry 4.0 promotes total integration into a digital value chain (Fatorachian & Kazemi, 2018; Xu et al., 2018; Kagerman et al., 2013). Industry 4.0-related digital technologies are associated with the integration of the virtual and the physical worlds, transforming regular production systems into cyber-physical systems or CPS (Chen et al, 2017; Lu, 2017). The integration of the virtual and physical components enhances the functionalities of both and provides benefits to competitiveness such as increased productivity, reduction of operational costs and failures (Fetterman et al., 2018, Kagerman et al., 2013).

Industry 4.0 is widely viewed as the orchestrated application of three different sets of technologies (Oztemel and Gursev, 2020; Mittal *et al.*, 2019; Tao *et al.*, 2018; Tao *et al.*, 2019; Zhong *et al.*, 2017). The first set is related to the communication infrastructure, represented by the Internet of Things (IoT), Cloud computing, and machine-to-machine communication (M2M). The second set is related to cognition and is associated with the concepts of artificial intelligence and advanced analytics, encompassing machine learning and data mining techniques. The third set is related to autonomous behavior and flexibility of operations, and includes autonomous and collaborative robots, additive manufacturing, and augmented and virtual reality. There are technologies that may fall within two sets, such as smart sensors (Indri *et al.*, 2019), which connect to other devices and systems via IoT, and provide not only a measured value, but also infer the condition of the measured entity through intelligent algorithms. There are also technologies that have had their scope expanded. One example is simulation and its relation to the concept of the digital twin, in which a virtual representation of a physical system is constructed to simulate either its function or behavior (Schleich *et al.*, 2017; Tao *et al.*, 2019). Data collected from the physical system is used in its virtual representation, allowing for a simulation that may predict future conditions and help better plan operations, allocate resources, and avoid failures (Grieves and Vickers, 2017; Tao *et al.*, 2017; Tao et al., 2018).

The use of these technologies triggers a paradigm shift in organizations (Xu et al., 2018), allowing the connection of physical operations with computing infrastructures. The activities of extracting, analyzing and reporting data support the potential for greater value creation that is promised by Industry 4.0. It incorporates data science and analytical models to analyze real time production data from multiple sources such as production machines, systems, and processes, and an automated manufacturing system (Xu et al., 2018).

2.2 Technology collaborations and their implications for innovation

Competitive advantage heavily depends on how new technologies are developed, adopted, and applied by diverse organizational actors to create value (Soucasaux, 2017). The development of relational capabilities may be achieved with the establishment of partnerships with a focus on learning and improvement. In order to be able to efficiently orchestrate its network, a company should accumulate practical experience in conducting collaborative partnerships. This allows it to develop greater flexibility in terms of exchange of knowledge and competencies, and to extract value from internalized knowledge and competencies that emerge from innovation relations and associated resources (Costa & Porto, 2015). Digitalization is the first step for industrial manufacturers to enter a new interconnected technological level.

Technology collaboration is based on the capability to develop projects in which partners create and share technological and innovative resources to generate competitive advantages that are distinctive and difficult to imitate (Costa & Porto, 2015). It involves multiple organizations working together in a shared activity for a limited period of time (Jones & Lichtenstein, 2008). Collaboration has a key strategic role in the form of networks to create, modify, complement and expand new knowledge, innovations and technological resources, enabling a firm to compete in an uncertain and competitive environment (Eisenhardt & Martin, 2000; Costa & Porto, 2015), thus fostering the process of business innovation (Trantopoulos et al., 2017).

Collaborative Networks (CN) are often intensive in external information and facilitate the diffusion of information and knowledge sharing, and consequently the process of technological innovation (Powell et al., 1996). CNs leverage sociability and usability features of information technology to enable partnering that delivers competitive solutions, motivated by business, supply chain, market and technological developments that create uncertainty and pressure on independently operating firms (Durugbo, 2015). Appio et al (2017) contribute to the understanding of CN with a framework called Input-Process-Output (IPO). Inputs include both driving and enabling factors, which may influence the process of CN such as relational, structural and cognitive factors. The process includes management and governance issues, value alignment and reference models of collaborative networks. The outputs are expressed in terms of innovative outcomes and performance improvements. Moreover, in order to be successful, collaboration requires trust, an ability to learn and absorb new skills, awareness of the complexity of joint projects, and the ability to discern competition from collaboration (Powell et al., 1996).

Previous research has shown that external relationships with business and scientific partners have a positive impact on innovation performance (Simão et al., 2016). Business partnerships require new practices such as vertical and horizontal communication, incentives for knowledge acquisition and sharing among employees, as well as interactions to foster the introduction of innovations along the value chain. Collaborations with scientific partners may be important for companies that do not have well-qualified internal staff. These partners can provide access to various types of relevant knowledge that facilitate technological innovations in the companies, as well as opportunities to obtain technical training for company teams (Simão et al., 2016; Du et al., 2014). Consequently, when companies intend to make organizational changes, it is recommended to collaborate with partners (Simão et al., 2016).

Collaboration is gaining momentum in digitized environments. The advancement of automated and integrated processes and objects requires the development of competencies of employees who will be increasingly cognitive and analytical. These requirements are relevant to stimulate collaborative R&D for digital technologies (Camarinha-Matos et al., 2019; 2017; Appio et al., 2017).

2.3 Supply chain 4.0 and business partner relations

Today's industrial supply chain involves a series of discrete steps, ranging from marketing, new product development, manufacturing, and distribution, until the end product reaches the consumer's hands. Digitalization breaks down these "walls" and the supply chain becomes an integrated ecosystem that is transparent to all organizational actors. Digital technologies support factory integration with their customers and other business partners in value creation processes. This allows new business models within and between companies (Arnold et al., 2016). Similarly, recent research (Saarikko et al., 2020; Henfridsson et al., 2018; Nambisan et al., 2019) has highlighted how the unique properties of digital technologies enable new types of innovation and entrepreneurship that are different from the analog processes of the industrial era.

Digitalization has been transforming the network relationships of the business value chain (Veza et al., 2015). Integrated and connected plant planning and horizontal integration are supported by cloud computing (Arnold et al., 2016). Companies that adopt these systems to improve integration with business partners can improve their efficiency and reduce their inventory, via reliable planning and data exchange (Alicke et al. 2017). As companies use digital technologies throughout the supply chain, improved connectivity and traceability have impacted factory productivity (Alicke et al., 2017). In the so-called Supply Chain 4.0, collaboration can also reduce lead times by providing instant information along the chain, while providing an early warning system and the ability to quickly react to interruptions anywhere (Alicke et al., 2017). The increasing integration of companies and other external organizational actors creates the need for partnerships and interoperability standards (Veza et al., 2015). Coordination, cooperation, and collaboration processes are vital to deal with integration and interoperability in production processes (Sanchez, et al., 2020). Thus, companies aiming at digitalization need to seek strategic collaborations. In addition to significant changes in internal processes and practices, DT pushes innovation beyond firm boundaries into collaborative networks (Rocha et al., 2021; Westergren et al., 2019).

2.4 Collaboration with scientific partners to facilitate manufacturing digitalization

Scientific partners bring scientific knowledge to R&D projects and patentable innovations to be launched in the market. They also create a temporary incontestable market space, access to scientific equipment and research facilities (Simão et al., 2016). This type of partnership can accelerate the process of technological learning (Pitassi, 2012). Projects with scientific partners can leverage academic networks in which the scientists are involved (Philbin, 2008). Companies that search for information and knowledge for innovation may establish partnerships with science and technology institutions, specialized consultancies, universities, government development agencies, other companies in the same sector, and startups that develop new technologies (Du et al., 2014). This type of collaboration also allows access to key people, such as faculty and students to support the development of efficient innovation activities. 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 (Leten et al., 2013).

Cross and Fellis (2016) highlight the implications of collaboration between manufacturing companies and university innovation research centers as scientific partners. The companies have developed, with the help of university researchers, intelligent products with embedded digital technologies. The benefits to each institution involved are significant in view of their different but complementary missions: the manufacturing company seeks to "pull" potential digital technology and the university seeks to "boost" research results.

Recognizing the practices that foster the success of these projects becomes an important theoretical contribution to the continuous development of the understanding of inter-organizational relations for business innovation. It is necessary to study and explore the development of new management capabilities, such as the capability to collaborate, in order to complement the predominant emphasis on technology.

2.5 Contribution of open innovation to the digital manufacturing innovation process

The open innovation (OI) approach can be understood as the antithesis of the traditional and closed innovation model, in which internal innovation activities lead to internally developed products and services that are then distributed by the firm (Chesbrough, 2012). OI is "the use of purposive inflows and outflows of knowledge to accelerate internal innovation and expand the markets for external use of innovation" (Chesbrough, 2006:1). Openness can be a powerful generative mechanism to stimulate significant levels of innovation (Chesbrough, 2012). OI practices may extend to suppliers, customers, partners, third parties, and the general community as a whole (Chesbrough et al., 2006). While OI practices have been successfully applied not only in high-tech settings, but also in traditional sectors (e.g.: incumbent firms), there is still a dearth of empirical research to clarify how OI practices are used in organizations in developing countries like Brazil (Ferrari et al., 2019).

OI may be classified into two main types: outside-in and inside-out (Enkel et. al., 2009). The outside-in part of OI involves opening up a company's innovation process to many kinds of external inputs and contributions. Inside-out OI requires organizations to allow unused and underutilized ideas to transfer outside the organization for others to use in their businesses and business models (Chesbrough, 2012). OI was first understood and implemented as a series of collaborations between two organizations to open up the internal innovation process. Later, the focus shifted to the use of this approach to orchestrate a significant number of players across multiple roles in the innovation process. Moreover, designing and managing innovation communities is likely to become increasingly important to the future of open innovation (Chesbrough, 2012).

Industry 4.0 implementation requires more than investments in technology. It requires investments in human resources development, organizational learning and relational and absorptive capabilities, as well as the facilitation of knowledge sharing between the areas of product development and production. Human and relational capital are critical factors for the success of the 4.0 industrial company (Schwab, 2016). Despite its central role, technology *per se* is only part of a complex DT puzzle that needs to be solved for firms to remain competitive in a digital world (Vial, 2019).

OI is closely intertwined with the current Digital Era (Hizam-Hanafiah & Soomro, 2021), as collaboration with external agents is increasing, resulting in more opportunities to create and share knowledge (Fayyaz et al., 2021). Collaborations with external partners are at the center of projects to co-create digital solutions (Rocha et al., 2021; Camarinha-Mattos et al., 2019). Firms are progressively participating in different forms of inter-collaborations to diversify into complementary knowledge-based resources and sustain their competitiveness (Hajiheydari et al., 2019). In sum, companies are increasingly adopting OI practices (Mubarak; Petraite, 2020; Chesbrough, 2012), so that value is no longer created by companies acting autonomously, but rather by firms acting together with external parties (Lardo et al. 2020). Hence, a collaboration-centered approach is appropriate to shed light on the complexity of DT in manufacturing with a focus on its managerial, strategic, and social aspects, which have not been sufficiently explored (Rocha et al., 2021; Burchardt; Maisch 2019).

The DT process needs to be a top management priority and a defining feature of the business strategy, as noted by Saarikko et al. (2020) in their recommendations on how companies can develop the necessary DT strategies and become digitally aware: start small and build "first-hand benefits"; form cross-functional teams; take responsibility for data ownership and ethics; and make the entire organization embrace and commit to the move to digital (Rocha et al., 2021). By becoming digitally aware, companies can gain a head start on their journey towards digitization. DT causes enterprises to rethink the very foundation of who and what they are. Saarikko et al. (2020) argue that the capability to stay relevant and competitive in the Digital Era, thus, requires digitally conscious business strategies that thread the needle between purposeful development and tumultuous disruption. Reassessing existing capabilities and how they are combined is one way to transition from functional silos to cross-functional teams that can accommodate the interdisciplinary nature of innovative products and services (Porter & Heppelmann, 2015; Vial, 2019).

3. Research Design

In order to address the research objective, an exploratory case study was undertaken in a manufacturing company, named here "Omega" for the purpose of anonymity. Omega started operations over 130 years ago in Japan. It is a global corporation with diversified solutions for communications network infrastructure. It has over 100 subsidiaries and modern R&D laboratories that develop new technologies and products. This study was carried out in its subsidiary located in the city of Curitiba, Brazil.

The company was selected because the telecommunications industry is one of the most mature in terms of awareness and application of digital technologies in Brazil (CNI, 2016; PWC, 2016). Another factor was that Omega's plant in Curitiba has already been operating initiatives in industrial digitalization for some time. The company was short-listed in previous consultations with Industry 4.0 experts to identify potential cases in Southern Brazil, as a typical case among the few plants that had already started collaborative projects for digital innovation. The analysis of the Omega case was conducted with the expectation of understanding the diversity of external partners for joint R&D in digital innovation as well as how these partnerships are managed and the degree of relevance of this diversity in the manufacturing digitalization trajectory of Omega.

A conceptual framework that summarizes the main theoretical constructs and their relationships, based on the literature review, is shown in Figure 1.

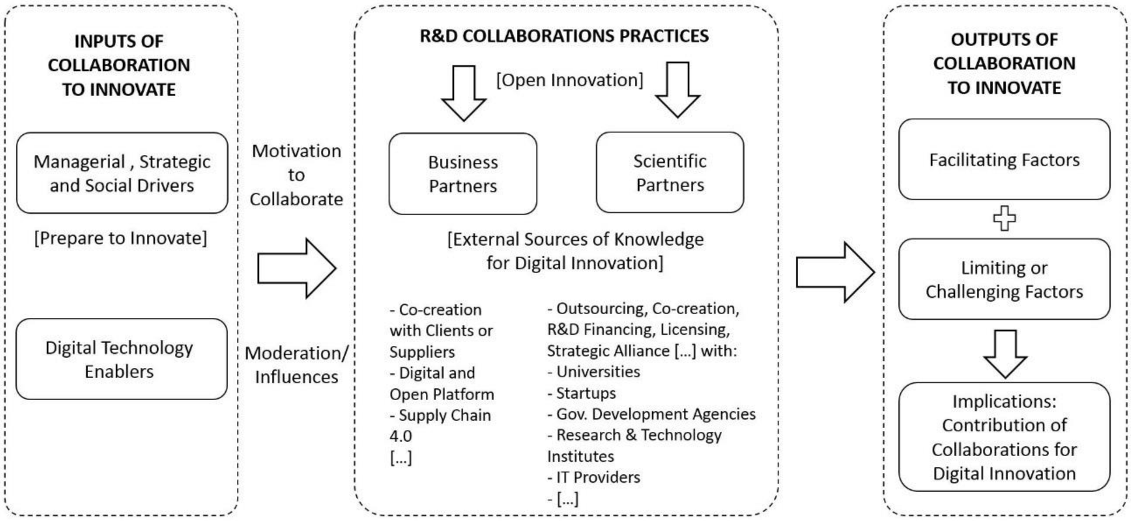

Fig. 1. Conceptual framework for digital transformation of industrial companies supported by open innovation

Five theoretical propositions were established prior to data collection and analysis for this case, based on the constructs of Figure 1. They are used for assessing the Omega case practices and are shown in Table 1. These propositions are statements about the likelihood of two or more concepts working together.

Table 1: Propositions of the theoretical model.

Proposition	Main theoretical sources
P1: Social, managerial, and strategic antecedent factors are relevant to prepare the company for digitalization.	Yoo et al., 2012; Bogers et al., 2018; Galdo, 2016; Kiel et. al., 2017; Arnold et al., 2016; Hermann et al., 2016; Kagermann et al., 2013; Schwab, 2016; Berghaus; Back, 2016; Weber et al., 2017; Quattrociocchi et al., 2017; Porter & Heppelmann, 2015; Vial, 2019; Saarikko et al., 2020; Henfridsson et al., 2018; Rocha et al., 2021
P2: Social, managerial, and strategic antecedent factors are relevant to motivate the company to engage with external partners for digital innovation.	Costa; Porto, 2015; Tidd; Bessant, 2015; Faccin; Balestrin, 2015; Camarinha-Matos et al., 2019; 2017; Rocha et al., 2021
P3: Digital technologies are enabling factors that assist collaborations/ integration with business partners.	Camarinha-Matos et al., 2019; 2017; Hylving, 2015; Helfat e Raubitschek, 2018; Chesbrough 2003, 2006; Faccin; Balestrin, 2015; Pitassi, 2012; Simão et al., 2016; Du et. al., 2014; Alicke et al. 2017; Foidl; Felderer, 2016; Westergren et al., 2019;
P4: Collaborative R&D practices with scientific partners assist digital innovation in manufacturing	Camarinha-Matos et al., 2019; 2017; Simão et al., 2016; Du et. al., 2014; Chesbrough 2003, 2006, 2007; Rocha et al., 2021; Saarikko et al., 2019
P5: Collaborations with business and scientific partners, together, contribute to digital innovation in manufacturing.	Chesbrough; Crowther, 2006; Simão et al., 2016; Du et. al., 2014; Pitassi, 2012; Tidd; Bessant, 2015; Nambisan et al., 2017, 2019; Xu et al., 2018; Cross; Fellis, 2016; Mubarak & Petraite, 2020; Lardo et al. 2020; Hizam-Hanafiah & Soomro, 2021; Fayyaz et al., 2021

Data were collected between December 2018 and February 2019. The evidence is derived from primary sources, including the following: 1) semi-structured interviews with strategic and tactical level employees who participate in R&D collaborative projects for the purpose of business digitalization; 2) non-participant observations, for which field diaries were created to allow for data triangulation; and 3) a questionnaire with closed questions that complements the contents of the interviews. The resulting diversity of data is linked to the use of multiple sources of evidence, which leads to construct validity and results reliability, which are criteria of quality in research (Yin, 2014). Table 2 presents the profile of the interviewees from the Omega company.

Table 2: Profile of interviewees

Interviewee	Level	Current Position	Interview Length	Time in Company
I1	Tactical	Production Engineer	74 min	7 years, 3 mo.
I2	Strategic	Head of Department of Optical Cable Production	70 min	7 years, 8 mo.
I3	Strategic	Specialist in Automation Process Control and Traceability	67 min	11 years
I4	Tactical	Full Industrial Technology Analyst	50 min	6 years, 3 mo.
I5	Tactical	Industrial Application Engineer	60 min	8 years, 10 mo.

The non-participant observations were made in two specific time periods: 1) on the first day the researcher was guided by I1 in a three-hour tour of the facilities for an overview and collection of evidence of equipment, tools and software linked to digital technologies and their integration on the Omega factory floor; 2) on the second day, the researcher gathered evidence from one two-hour meeting of the interviewed members about the informal discussion of the digital projects status to understand their dynamics and content. The observations were recorded on field diaries.

The technique of content analysis by codification was used for data analysis (Bardin, 2000), supported by the *ATLAS.ti 8* software. The software also assisted in data triangulation. When using the content analysis technique, the study strictly followed the three phases put forth by Bardin (2000): 1) pre-analysis; 2) material exploration or coding and categorization of the corpus; and 3) treatment of results, inferences and interpretations. A total of 57 codes were established for the content analysis, comprising 14 codes that were created *a priori*, i.e., drawn from the literature review and the underlying theoretical framework, and 43 that emerged a *posteriori* from the coding of the transcribed interviews and the field diaries.

As the data were incrementally being input, their redundancy suggested that the saturation point had been reached. The 57 codes were used in 307 citations in interviews and field diaries. The comparison allowed the verification of data alignment, and no significant divergences of content were found. *ATLAS.ti 8* allowed the construction of networks that demonstrate the relationships between the main codes created in the software (see Figures 2 and 3). This analysis also allowed the elaboration of Tables 3 and 6 for a structured presentation of some main case results. Finally, data were compared to the propositions using a procedure called pattern matching (Trochim, 2000), a strategy for aligning data to theoretical propositions, so that the research can verify the existence or relevance of the propositions.

4. Results and analysis of the case study investigation

The first stage of the analysis was the compilation of the most frequent terms that appeared in the interviews and field diaries. It was observed that digital solutions are still triggering changes in terms of incremental improvements in production processes at the shop floor level, as also noted in broader studies by CNI (2016) and PWC (2016). It is noted that digitalization tends to affect process automation rather than products, as shown in Tables 3 and 6. Social factors and challenges related to management of new competencies are highlighted in the responses. Projects on collaborative R&D for digital innovation are also evident in the respondents' perceptions as a relevant factor for Omega's journey towards DT. Words connected with "partnership" were also pointed out as a relevant factor for the change towards a digital, connected, and intelligent manufacturing plant. The names of certain external partners in R&D for digital solutions, such as the acronyms in Portuguese "UFC Lab" (Laboratory of the Federal University of Ceará), "SENAI" (National Service of Industrial Training), "CITS" (International Center for Software Technology) were noted, as well as suppliers that develop digital solutions.

The Industry 4.0 concept is internally known at Omega as OSP – *Omega Smart Plant*. However, interviewee I5 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 for DT. The preparations involve technological infrastructure, awareness about what Industry 4.0 represents, as well as training employees to understand the upcoming digital solutions and their applicability, convincing the board of directors to approve digital projects and adopt a digital mindset throughout the company. It is possible to infer that the company is still at an initial stage in the process of manufacturing digitalization.

Omega has commenced its path towards digitalization recently. The Industry 4.0 concept first appeared in the firm in late 2016, as a result of research by its own engineers. A project for Industry 4.0 began in 2017. It consisted of a digital project for the plant, including goals, activities and schedules. The project design was completed in 2018, with the development of 4.0 guidelines, which included objectives and initiatives to be operationalized and attained within five years. Following those guidelines, Omega will try, in addition to other aspects, to leave behind its legacy system and enter a digital technology architecture characterized by IoT. It has been noted that one of the required factors to prepare for the digital era is to have a formal strategy for Industry 4.0 (Fatorachian & Kazemi, 2018; Kagerman et al., 2013).

As defined by its 4.0 guidelines, the company perceived the need to recruit new employees. In early 2018, the company hired technical specialists with experience in digitalization, particularly in IoT. This was necessary to operationalize Project 4.0 in the manufacturing plant, which includes, among other things, partnerships in digital technologies. Additionally, Omega is not only beginning to use some 4.0 solutions, but it is also selling connectivity solutions in the marketplace, as shown in Table 4.

Table 3: Company Status Regarding Digital Technologies

Digital Solutions Used/ Implemented	Solutions in Development/ Pilots/POCs	Ideation phase Solutions
• Smart Sensors in machines for performance data collection in the painting process (use of gateways) • Process automation via integration between PLCs and existing systems to reduce operator dependency) in the painting and tube processes • Palletizing with advanced autonomous robots • 3D Printer for prototyping • AGVs (Automated Guided Vehicle) to move materials on the factory floor • Optical fiber *Laser Way* - Omega product offered for the market	• Advanced Analytics (generation of a complete real-time monitoring dashboard of the entire production line for predictive maintenance and better decision-making) • Process automation via integration of programmable controllers (PLCs) with existing systems in other production processes	• Integration between different existing information systems • IoT architecture to generate environmental sustainability in the factory by enhancing the efficiency of utilities such as compressed air and water pipeline systems • RFID sensors use for product monitoring • Machine Learning • Augmented Reality • Collaborative Robots

During the interviews, the participants emphasized numerous challenges related to Industry 4.0 that they are trying to overcome. These challenges do not pertain only to the technological domains, but also include social and managerial aspects. This is aggravated by the economic crisis in Brazil and the lack of digital readiness that is prevalent in the market and particularly in Brazilian universities, as noted in Figure 2. More broadly, these conditions affect the prospects of manufacturing to become digitalized, highly connected, smart, and more competitive (CNI, 2016). Many organizations in the Brazilian market, such as technology suppliers and research and innovation centers are still unable to meet digitalization demands by the manufacturing sector, and therefore cannot develop solutions that meet Omega's goals. Such diverse challenges weaken Omega's readiness to engage in digital innovation and its intended uses. Depending on how the company manages its challenges, they may strengthen – or weaken – its disposition to collaborate with external organizations to jointly research, develop and apply digital solutions. The current Omega stage is typified by several challenges, as shown in Figure 2. The codes that are highlighted in red in Figures 2 and 3 are the most grounded, that is, the ones that received a higher number of quotations in the interviews.

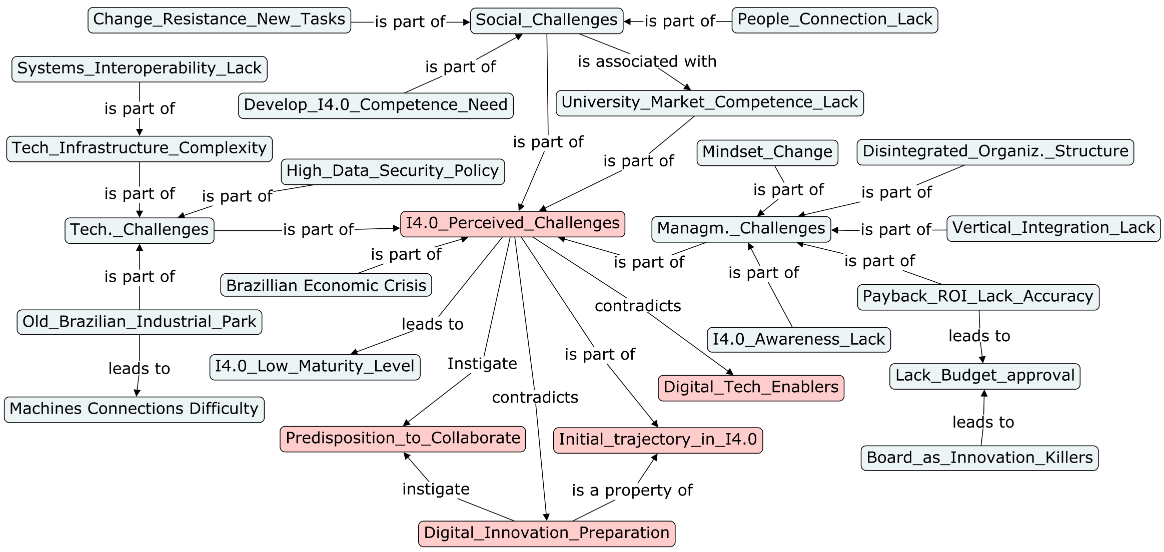

Fig. 2. Network of Industry 4.0 Challenges and Implications

Some of the challenges to digitalization observed in Omega also appear in a study that maps the challenges of manufacturing digitization in India. In that case, the major barriers are the fear of unemployment, lack of IT training for employees and top managers, poor IT infrastructure, and lack of comprehensive broadband availability and speed (Kumar et al., 2021).

The technological challenges to implement Industry 4.0 in the case study include: the complexity of technological architecture, such as difficulties to provide Wi-Fi signal throughout the plant; difficulty to implement interoperability among different information systems; a rigid data security policy that curtains the use of cloud computing; and an old industrial system, not only at Omega, but throughout Brazil, which poses connectivity problems when trying to match intelligent sensors with old machinery. The technological challenges that relate to interoperability or lack of interconnections between different information systems are also mentioned and discussed in previous studies (Veza et al., 2015; Herman et al., 2016; Wang et al., 2018; Burns et al 2019).

The managerial challenges include: a closed organizational structure with limited knowledge sharing and lack of integration among Omega's subsidiaries and between the subsidiary and its headquarters; lack of awareness about the Industry 4.0 concept and its advantages and challenges; lack of integration among internal departments, and particularly the poor integration of IT and business goals; difficulty to accurately demonstrate the real gains of digital projects, such as through payback and ROI calculations, which leads to a struggle in budget approval by the company's board of directors; and difficulty to change people's mindsets, particularly those at the strategic level, so that they understand the relevance of Industry 4.0 and act upon it. The lack of a digital mindset by the board of directors and delays in budget approval suggests their characterization as "innovation killers". Their resistance to change, errors and risks are perceived as an obstacle to possible gains of digital initiatives that could ensure the future of the organization. Among the social challenges, some are highlighted: the need to develop people's skills to understand and apply customized digital solutions for the company's needs, and the resistance among people from different hierarchical levels to change their attributions and responsibilities, which are already changing in face of the introduction of new technologies.

Table 4 presents, after the first and second cycles of coding (Saldaña, 2013), a ranking of the number of quotations regarding Omega respondents' perceptions and perceptions of the researchers' field diaries – represented by the "Grounded" column, for each of the codes directly linked to the perceived challenges of Industry 4.0 that are shown in Figure 2. Table 4 also shows the number of analytic links, i.e., links from each code in Figure 2 to other codes – represented by the "Density" column.

Table 4: Codes for Industry 4.0 Challenges

Codes	Grounded	Density
Initial Trajectory in I.4.0	70	7
Digital Tech Enablers	65	12
I.4.0 Perceived Challenges	59	10
Predisposition to Collaborate	55	3
Digital Innovation Preparation	46	7
Managerial Challenges	17	6
Technological Challenges	16	4
Social Challenges	15	5
University-Market Competence Lack	11	2
I.4.0 Low Maturity Level	4	2
Brazilian Economic Crisis	3	1

The interviewees stated that some of these socially related challenges induce a tendency to seek "outside elements" to accelerate the implementation of digital solutions in the company. Among these "outside elements" are partnerships with external organizations and the recruitment of people with proven experience in digitalization in other companies. The lack of internal capability and the lack of understanding of what is Industry 4.0 would appear to foster the need for outside-in OI practices (Chesbrough, 2003), that is, collaborations with external organizations with skills and knowledge which may complement Omega, or which it does not yet possess. Omega faces a specific challenge that relates to its status as a subsidiary of a Japanese multinational: it is perceived that traditional organizational culture interferes negatively in the change process. It has to "break the internal resistance of the Japanese model itself" (I2). At any rate, traditionalism seems to impair the move to digital adoption from occurring effectively in Omega. The challenges faced by this company corroborate and complement the industry-wide research findings by CNI (2016), and PWC (2016).

The company has been making use of managerial drivers, mainly strategic and social, considering that the professionals of the company have been dedicating themselves to the search for training, evolving in terms of understanding and use of digital solutions in the factory. It can also be observed that the personnel at the tactical level have been developing an "external mindset", by monitoring digital initiatives in other manufacturing companies and searching for successful application cases of digital solutions. The fact that Omega looks for these cases to learn about the applicability of Industry 4.0 characterizes it as being in the initial stage towards digitalization. The search for in-house professional capacity has raised the need for Omega to develop partnerships to gain more knowledge about these solutions, seeking actors who can assist it to become a connected or smart factory (Figure 2), similarly to what is reported in other cases (Thames & Schaefer, 2016; Capgemini, 2017; Camarinha-Matos, et al., 2019; 2017; Nambisan et al., 2019; 2017; Bogers et al., 2018).

The first production process of Omega that was fully automated and digitized at the time of data collection was the painting process, which is the first stage of the cable assembly line. This digitalization process was supported by resources derived from the tax exemptions of the Brazilian Information Systems Act (MDIC, 2019). The Act aims to finance research & development & innovation (R&D&I) projects in the areas of computing, electronics, and automation, which are fundamental for Industry 4.0 development in the country (CNI, 2016). These resources were directed to enable 4.0 initiatives with the support of external partners. The antecedent factors for digital innovation and their implications for collaborative factors are shown in Figure 3.

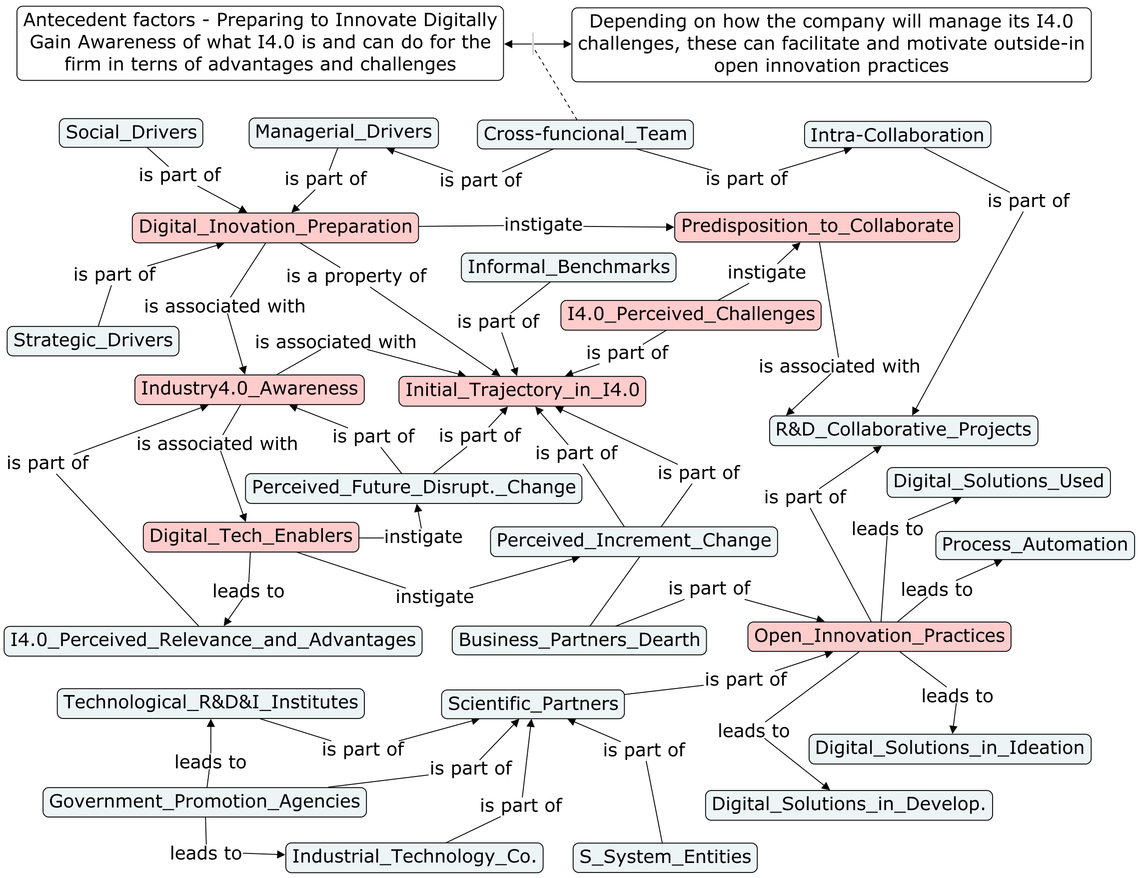

Fig. 3. Digital Innovation Preparation and its Implications for Collaborative innovation practices

Table 5 presents, for each of the codes shown in figure 3, their respective grounded and density numbers, ranked by the number of quotations from the perceptions of Omega respondents and annotations in the field diaries – represented by the "Grounded" column.

Table 5: Codes for Preparation for Digital Innovation

Codes	Grounded	Density
Industry 4.0 Awareness	41	5
I.4.0 Perceiv. Relev. Advantages	40	7
Open Innovation Practices	39	8
Social Drivers	34	5
Managerial Drivers	34	4
Strategic Drivers	33	4
R&D Collaborative Projects	28	3
Business Partners Dearth	25	2
Process Automation	20	2
Perceived Incremental Change	19	2
Scientific Partners	18	9
Technological R&D Institutes	17	2
Industrial Technological Co.	17	2
Dig. Solution in Develop.	16	1
Gov. Promotion Agencies	13	3
Dig. Solution Used	11	1
Dig. Solution in Ideation	10	2
Informal Benchmarks	10	1
Cross-functional Team	9	3
Perceiv. Fut. Disruptive Change	9	2
S System Entities	9	1
Intra-Collaboration	8	2

Omega is committed to developing digital innovation projects and this is supported by the provisions of the Brazilian Information Systems Act. These projects are jointly operationalized through the assistance of the partners' competences. Since it is a federal Act, Omega's digital projects are formalized and deliberate. As a future perspective, Omega aims to have a fully automated factory, dispensing with manual operators. Thus, in a "near future" the factory intends to digitize the other stages of the production process. Furthermore, Omega aims to make use of smart sensors to measure efficiency levels of all machines. This project is under development with the support of *UFC Lab.*

Digital solutions are currently being applied in Omega and can be regarded as a form of incremental change. For I3: "[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 it is accepted by the production, it is implemented in other areas". Hence, digital initiatives begin to be operationalized in a specific and timely manner, so that small improvements are initially achievable. It is from these that the company's board begins to recognize successful cases of digitalization, and thus, may be motivated to approve further Industry 4.0 initiatives with greater scope. By following the "step-by-step" procedure, Omega has so far digitized and automated the first stage of the production line: cable painting. The next stage was already finished, but its full implementation was hampered by problems with the connection to the wi-fi network.

Some interviewees failed to discern partners or potential partners for joint R&D, and instead identified Industry 4.0 technology suppliers that simply sell "off-the-shelf 4.0 solutions" rather than full collaborations. Another issue raised by the respondents was the lack of knowledge about the differences between Industry 4.0 and Industry 3.0 technologies, which reflected on the initial trajectory of the company regarding Industry 4.0. However, both established partners and potential technology providers have their relevancy in presenting and promoting "Tech Day" events at Omega. This allows employees access to knowledge and practical classes on digital solutions and applications. Therefore, these external actors are considered strategic for Omega's awareness of new digital solutions and their potential applicability. Table 6 shows the status of scientific partners, linking each one with the digital solutions and their respective applicability.

Table 6: Omega's Status in Open Innovation practices for Digital Innovation

Partnerships	Digital Solutions	Solution Applicability
CITS – Institute of Science and Technology focused on software development	Integration between Information Systems and Machines (continuity and development of the solution initiated by a private companies)	Industrial Automation (Manufacturing Process Painting Step Completed and Tube Step)
RAVI (Institution for R&D acting jointly with UFC University)	Communication of Different Information Systems	Industrial Automation (Manufacturing Process Painting Step Completed
	Creation of data collection system from the factory floor to generate a global dashboard	Real-time information for better decision making
Government Promotion Agency via Brazilian Information Systems Act that provides resources for R&D collaborative projects in Industry 4.0	[practically all the Digital projects are being realized through this Act assistance]	Applications developed in partnership with RAVI, CITS and a private company
SENAI PR & SENAI SP (National Industrial Learning Service parastatals)	Offering projects in their laboratories inviting companies like Omega to contribute to the construction of a "Factory 4.0". Omega provides cabling, routing, connection of machines	These projects are a way for Omega to release and offer its connectivity solutions to interested actors
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	Initiative to automate production process via connected tablets (the idea was later operationalized through RAVI)	Automated / Digital Checklists

Table 6 shows that one R&D collaborative project was fully completed with one external partner. The use of digital solutions does not yet appear to moderate closer relationships or integrations with customers and suppliers, meaning that Supply Chain 4.0 – which is one of the gains promised by Industry 4.0 (Xu et al., 2018; Kagerman et al., 2013) – has not been implemented by this company. However, such integration will be desirable in the future when Omega is more mature regarding the absorption of the Industry 4.0 concept. Omega has few partnerships for digital innovation, despite of its intention and investment in building a more solid "digital ecosystem". All respondents believe that this aspect needs to be improved over time. For Omega, R&D collaborations are, at least, facilitators and even accelerating factors for Omega's journey towards manufacturing digitalization. This finding corroborates research by Muller et al. (2018) and Camarinha-Matos et al. (2019; 2017).

Omega has with CITS and the UFC Lab historical and long-term partnerships. CITS, International Center of Technology and Software, is an integrated institution of education, research, development, and business in the IT field, committed to results and creating products and services for clients and partners. CITS offers R, D&I services, and manufacturing automation solutions to generate greater integration of older machines with information systems (IS). The UFC university lab is a research-driven entity that assists in the integration between different information systems. As shown in Table 6, partnerships for the purposes of digital innovation applied in manufacturing were under way, although most of them were in early stages of development at the time of data collection. Partnerships with universities, such as UFC, and specialized consultancies, such as CITS, are under continuous prospection.

Although this study is focused on inter-organizational collaborations, Table 6 also highlights intra-organizational collaborations that emerged from the interviews. Omega has an open organizational structure to receive digital-driven ideas from its employees regardless of their hierarchical level. Table 6 also reveals the influence of the partnership with FIEP (Federation of Industries of the Paraná State), a parastatal entity that supports manufacturing companies, particularly with one of its branches, SENAI (National Service of Industrial Training) of the states of Paraná (PR) and São Paulo (SP). Although this is not an external R&D collaboration, this partnership is important for Omega to showcase its connectivity solutions in SENAI for other manufacturing companies and other actors. In sum, Omega is beginning to build a digital ecosystem. Nevertheless, the company has already developed some competitive advantages in manufacturing, using open innovation practices, which has proved to be a relevant approach to understand how manufacturing firms can accelerate their journey towards DT.

5. Discussion

This section compares the main findings of the Omega case with the five propositions that were derived from the literature, as shown in Table 2. Propositions P1 and P2 are confirmed by Omega's case. Social, managerial, and strategic factors are present in the company's efforts to structure itself for the DT process. These antecedent factors and implications are outlined in Figure 3. It can be inferred that the need to leverage digital solutions to renew the way Omega does business is driving the company to reassess its existing capabilities, structures, and mindset to identify which technologies are relevant and appropriate, and how they will be applied in business processes and products. This finding is in line with evidence from recent research (Saarikko et al., 2020). Omega's preparation process for industrial digitalization makes it clear that Industry 4.0 does not happen quickly. It is a gradual, complex organizational change, as the company needs to prepare people to become aware of the value and impact of digital innovation on the factory and on their jobs. The case indicates that the trajectory towards digitalization needs to be customized to meet the needs and pains of each manufacturing context. Given the diversity of antecedent factors (Fig. 3), the operationalization of digital practices is multifaceted and depends as much on digital technological infrastructure as on change management.

P4 is also confirmed in Omega's case. The CITS research and technological innovation center and the UFC university lab are scientific partners that support the innovation process in large companies (Du et al., 2014; Simão et al., 2016; Philbin, 2008). For Wang and Islam (2017), these partners can be considered as "non-industrial entities" in Omega`s context of open innovation practices. During an innovation project, the manufacturing firm has various requirements, such as knowledge, technology, inspections, management, consultation, and material supply. Hence, the inputs from the external parties need to be in line with the actual requirements at different stages of the open innovation process. The open innovation roles for a non-industrial entity include, among other aspects, technology R&D, joint planning, testing, and industry standards development, among others. Those entities may include universities, research and development institutions, industrial associations, among others such as consulting firms, law firms, IP management entities, and governmental agencies (Wang & Islam, 2017). These findings are in line with other recent studies. Technological infrastructure and new market offerings are increasingly being developed through collaborative networks or innovation ecosystems, further reinforcing the sociocultural nature of DT (Rocha et al., 2021; Camarinha-Matos et al., 2019; Saarikko et al., 2019).

P3 was only partially validated in the Omega case. Even though the company displays a propensity toward openness, it has not yet taken advantage of the opportunities that digitalization offers to radically change the notion of openness in terms of degree, scale and scope, as proposed by Nambisan et al. (2019). As much as Omega is aware of the importance of establishing business partnerships to create an integrated supply chain through the use of digital solutions, it does not yet make use of these solutions to support business partnerships. Omega is in a stage in which collaborations are established to master the use of digital technologies, rather than focusing on the use of digitalization to foster and transform partnerships. Similarly, P5 was partially confirmed. Omega relies on scientific partners for assistance on digital innovation in manufacturing, mostly on digital innovation projects that are under development (Table 6), but the reinforcement effect of both business and scientific partnerships was not observed.

6. Conclusion

This paper analyzed how R&D collaborations with scientific and business partners contribute to the DT of a Brazilian subsidiary of a multinational industrial company that has begun the implementation of Industry 4.0. The findings are summarized in Figures 2 and 3, and in Tables 3, 4, 5 and 6. The case study presents the development of a collaborative R&D strategy with external actors, facilitated by incentives from the Brazilian Information Systems Act. Such a supporting strategy appears as an accelerating factor for manufacturing companies to move towards digitalization in this specific context.

The study contributes to organizational practice by showing how the use of digital technologies can drive new forms of innovation initiatives and projects that cross traditional industry boundaries and integrate digital and non-digital resources in innovation ecosystems. Moreover, this study sheds light on how a large incumbent corporation has been trying to redefine itself and restructure its innovation practices to meet the pressures for digitalization. The case study also shows that the adoption of DT requires companies to identify which technologies are relevant to their strategic needs and prioritize how they will be applied in business processes and offerings. The infusion of digital technologies in the case has changed how uncertainty is approached in innovation processes and outcomes, as well as the importance of building a new mindset among people and organizations about the development of innovative projects. Most importantly, this investigation showed that developing digital consciousness and embracing DT requires considering not only technological aspects, but also social, cultural and managerial factors, and firmly grounding them in organizational strategy and practice.

The results of this case also highlight that digital innovation practices and projects have implications at broader regional levels, with the potential to better target policy makers and other stakeholders. DT has compelled government agencies to rethink laws, regulations, and policies related to a wide range of issues including intellectual property rights, data privacy and security, consumer rights, work force skills and training, innovation financing, and incubator programs (Nambisan et al., 2019). It becomes evident that Brazilian policy makers as well as industry leaders need to be aware of the challenges and bottlenecks to digitalization, and to face them so that the use of the Industry 4.0 concept is effective.

Collaborative networks to promote digital innovation are at the center of Industry 4.0 and thus the innovation ecosystem needs to be considered as one of the most important enablers for industrial digitalization. The findings also indicate that, as the adoption of open innovation practices grows, the “innovation killers” of today become active supporters of digital innovation projects. Therefore, senior managers need to adopt a digital mindset and engage in collaboration partnerships to implement digital solutions and smart factories.

This study also contributes to the literature on how open innovation practices facilitate the testing, development, and application of digital solutions in manufacturing firms. Advancements in digital technologies and their applications offer significant opportunities to enhance innovation processes, to instigate collaborative innovation and increase competitiveness. Additionally, the results of this study indicate that business success depends more on how digital technologies are adapted, developed and applied to add value, rather than simply adopting the new technologies, as Bogers et al. (2018), Camarinha-Matos et al. (2019; 2017) and Schwab (2017) have pointed out.

This paper supports the understanding of the main DT challenges, bringing empirical evidence to a topic that is still emerging and requires deeper contextual investigation. It highlights the importance of understanding the micro-level social and human aspects of DT. The case suggests that managing change in people's mindsets poses highly subjective and complex challenges. In addition, it shows that value creation in the digital age depends heavily on the development of relational and absorptive capacity by the organization to create a culture of openness to innovation. The DT literature has emphasized a shift in the nature of value proposition, from internal organizational boundaries towards shared value created by collaborative networks (Nambisan et al., 2019; McIntyre & Srinivasan, 2017). Some digital practices highlighted in Omega – such as "designing digital strategies", "promoting digital mindsets", "making everyone aware of what are the benefits of digitalization", and "skills management for the Digital" – highlight an essential context for the study of strategic change and change management. This paper contributes to existing knowledge by raising issues that are key to digital readiness in a manufacturing context.

The research limitations in this case are inherently related to its basis on the perceptions of participants who are directly involved in R&D collaborations for digital innovation in a single manufacturing company in Brazil. On the other hand, Omega may be considered a typical case in the sense that it is representative of a group of similar organizations that are actively moving into digitalization in the Brazilian context, as noted before. In addition, it should be noted that Brazil, as one of the world's largest economies, should be a fertile ground for research on collaborative innovation between companies and various types of partners, together with the importance of government support in this field (Negri, 2018), and domestic potential for the development of diverse technologies (Ferrari et al., 2019). In that sense, the choice of a Brazilian case contributes to the still limited number of empirical studies that address OI and DT in the local context. Generalizations will become possible after the development of further studies of other manufacturing companies and other scientific and business actors directly involved with Industry 4.0.

New research avenues may stem from an interdisciplinary research agenda that has been advanced in this paper by its focus on the relationships between openness and digitalization. This broad theme may inform future research efforts on the potential of interdisciplinary and cross-level research to the further understanding of innovation practices in an increasingly digital context. Future research could empirically explore how the use of digital technologies facilitates or accelerates open innovation practices such as co-creation, crowdfunding and crowdsourcing. It should be noted that prior research has emphasized the implications of innovation openness at distinct levels: individual, organizational, or societal (Nambisan et al., 2019). However, openness questions that cross multiple levels of analysis have been mostly neglected (Bogers et al., 2017). Such questions may lead to a more nuanced understanding of how openness factors that promote innovation at one level might prove to be a hindrance at another. Connecting issues across multiple levels of analysis may also inform policies to support innovation initiatives with broader strategic, economic and social impacts.

Future research may also expand the results of this study to characterize and analyze R&D collaborations for digital innovation in other manufacturing companies and with other organizational actors that impact the factories' journey towards DT. Additionally, comparative studies between manufacturing companies in Brazil or other developing countries and firms from developed countries that have established digital industrial policies could shed light on differences of their digital innovation ecosystems. Moreover, it is suggested that research on how best practices of these developed countries can contribute to the strengthening of manufacturing companies in developing countries. Another possibility is a follow-up on this case, applying the same research instruments in 2-3 years to verify the evolution process of R&D collaborations and their outputs. More broadly, other research questions can be suggested for future studies: 1) How does digitalization-enabled openness promote collaborative innovation among individuals, firms, and at the city/region levels? 2) What are the ensuing organizational and public policy implications? and 3) How can digitalization facilitate inter-collaboration involving different external actors to resolve complex societal level challenges?

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