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Exploring the Evolution and Recombination of Firms' Innovation Capabilities

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ABSTRACT

Objective: The study aims to elucidate whether and how firms evolve and recombine their innovation capabilities over time to adapt to market changes. To do so, Brazilian agricultural machinery manufacturers transitioning to Industry 4.0 were analyzed through the lens of four innovation capabilities (development, operations, transactions, and management). **Methods:** A longitudinal quantitative study was conducted with 29 companies, considering two periods: 2014 and 2018. The evolution and recombination of firms' capabilities were explored, respectively, through the Wilcoxon signed-rank test and the fuzzy-set qualitative comparative analysis (fsQCA). **Results:** The four capabilities evolved and were recombined. The evolution of business-driven capabilities (transactions and management) was more significant than the evolution of technology-driven capabilities (development and operations). In 2014 firms innovated by combining development, operations, and management capabilities (DC*OC*MC), and in 2018 by articulating transactions, operations, and management capabilities (TC*OC*MC). **Conclusions:** Firms changed their focus from technological innovations to business innovations over time. The study discusses the complementarities between these innovation types in the context of firms converting to Industry 4.0.

INTRODUCTION

Firms adapt to market changes, that is, to the advent of new technologies or new business opportunities, by innovating in products, production processes, ways of transact with customers and suppliers, or types of management (Dimakopoulo et al., 2024; Schumpeter, 1934). Firms create these novelties through their innovation capabilities, i.e., sets of organized activities through which the innovation process occurs (Daronco et al., 2023; Dosi et al., 2000; Saunilla & Ukko, 2012). Studies generally use two different approaches to explore firms' innovation capabilities: dimensional and processual. While the dimensional approach understands that each type of innovation is a consequence of a specific capability (Francis & Bessant, 2005; García et al., 2017; Guan & Ma, 2003), the processual approach considers that capabilities operate in sequence to produce different types of innovation (Patterson & Ambrosini, 2015; Teece, 2007; Warner & Wäger, 2019).

Independently of the approach utilized, the major part of the literature focuses on answering how firms combine their capabilities to innovate in a given period (Ali et al., 2024; Alpkan & Gemici, 2023; Csiki et al., 2023), remaining unknown whether and how firms recombine their capabilities over time. In addition, whether and how firms evolve their capabilities between periods is also a topic that is little addressed. Although a stream of research explores the evolution of firms' capabilities, these studies focus on capabilities geared toward technological innovations (new products or new production processes) (Figueiredo et al., 2020; Gräbner & Hornykewycz, 2022; Guo & Zheng, 2019), leading to little understanding about the evolution of capabilities oriented to business innovations (new ways of transaction with the market or new types of management).

The current Fourth Industrial Revolution, also known as Industry 4.0, instigates even more the filling of these research gaps. Industry 4.0 emerged at the beginning of the 2010 decade, creating intensive market changes through the advent of disruptive digital technologies, such as the internet of things, cloud computing, big data analytics, and artificial intelligence (Culot et al., 2020; Shen et al., 2023; Weking et al., 2019). Therefore, companies converting to Industry 4.0 are an appropriate context to explore whether and how firms evolve and recombine their capabilities to carry out innovations over time. In this regard, the present study aims to answer two pressing questions: 'How do firms adapting to Industry 4.0 evolve and recombine their innovation capabilities over time?'

To answer these questions, the theoretical framework of innovation capabilities proposed by Zawislak et al. (2012) was adopted. This framework encompasses many previous perspectives on the firm's innovation capabilities, merging dimensional and processual approaches, to provide a comprehensive understanding of the innovation process. The framework considers that every firm has four innovation capabilities: 'development', 'operations', 'transactions', and 'management.' While development and operations capabilities result in technological innovations, transactions and management capabilities result in business innovations. Development and transactions capabilities are change-driven, conducting the firm's technological and business changes. Operations and management capabilities are stability-driven, focusing on exploiting the technologies adopted and the business opportunities targeted (Pufal & Zawislak, 2021).

To observe the phenomenon, a longitudinal quantitative study was conducted with 29 Brazilian agricultural machinery manufacturers, considering two periods related to the rise of Industry 4.0: 2014 and 2018. Companies in this sector are making considerable efforts to convert to Industry 4.0 (Calvino et al., 2018; OECD, 2019; Smania et al., 2022), which characterizes them as an adequate sample to explore the phenomenon. For a proper analysis, only agricultural machinery manufacturers that are adapting to Industry 4.0 were selected for this study. Another important reason to approach companies in this sector is one of the consequences of their conversion to Industry 4.0: the high levels of productivity and sustainability provided to farmers (Mahda et al., 2022; Wolfert et al., 2017; Zambon et al., 2019). The increasing demand for food and the impact of climate change on growing conditions make this element crucial not only for the economy, but also for the future of mankind (Food and Agriculture Organization of the United Nations [FAO], 2017).

The Wilcoxon signed-rank test was applied to measure the evolution of innovation capabilities between periods. The results demonstrate that the four capabilities evolved, but the evolution of business-driven capabilities, transactions and management, was more significant. Subsequently, fuzzy-set qualitative comparative analysis (fsQCA) was used to identify the combinations of capabilities through which firms innovated in each period. The results show that the firms innovated in 2014 by combining development, operations, and management capabilities (DC*OC*MC), and in 2018 by articulating transactions, operations, and management capabilities (TC*OC*MC). The joint use of these two techniques is a methodological novelty of this study. The results of the two techniques converge, demonstrating that firms changed their capabilities, from a focus on technological innovations to a focus on business innovations, between the periods analyzed.

THEORETICAL BACKGROUND

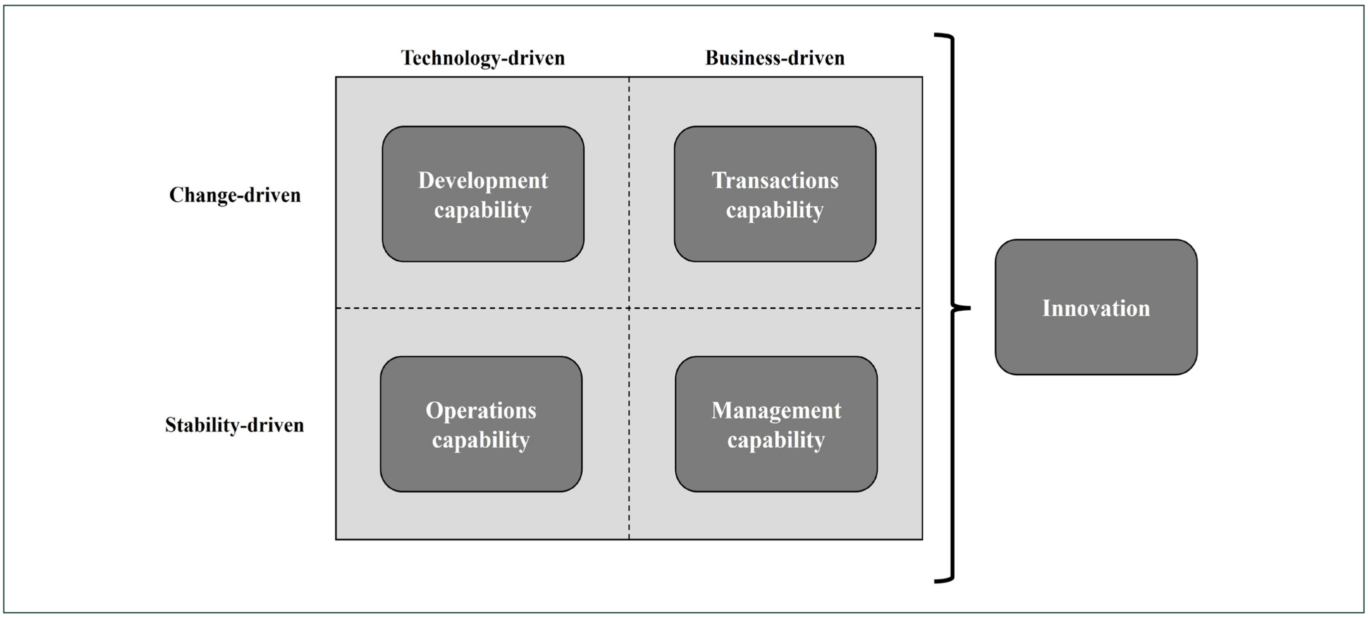
The firm innovation capabilities

Firm innovation capabilities were first defined by Richardson (1972) as sets of knowledge, experiences, routines, and skills through which firms obtain competitive advantages. This definition was refined and gained considerable strength in the literature on innovation through the work of Cohen and Levinthal (1990), Lall (1992), Teece et al. (1997), and many others. In summary, firms' innovation capabilities can be defined as sets of organized activities through which the innovation process occurs (Daronco et al., 2023; Dosi et al., 2000; Saunilla & Ukko, 2012). In general, studies employ two different approaches to explore these capabilities: dimensional and processual.

The dimensional approach considers that each type of innovation is the result of a specific type of capability. Its origins reside in the concept of technological capabilities put forward by Lall (1992), and hence, it was initially focused on technological innovations, only exploring capabilities that result in new products or new production processes (Leonard-Barton, 1992; Prahalad & Hammel, 1990). Over time, studies developed theoretical frameworks including capabilities that obtain business innovations: new ways of transact with customers and suppliers or new types of management (Francis & Bessant, 2005; García et al., 2017; Guan & Ma, 2003).

On the other hand, the processual approach understands that capabilities work in sequence to produce different types of innovation. Its essence is in the concept of absorptive capability presented by Cohen and Levinthal (1990): the firm ability to seek, absorb, and convert new knowledge into innovations (Oliveira & Silva, 2022; Patterson & Ambrosini, 2015), as well as in the concept of dynamic capabilities proposed by Teece et al. (1997). According to Teece (2007), firms have two types of capabilities: dynamic (subdivided into sensing, seizing, and reconfiguring capabilities), and ordinary capabilities. Sensing capabilities perceive market changes, seizing capabilities capture the opportunities that arise from these changes, and reconfiguring capabilities adapt ordinary capabilities to operate in a new context (Teece, 2007). Both dynamic and ordinary capabilities result in innovation, but only dynamic capabilities can sustain it in the long term (Warner & Wäger, 2019).

The present study employs the theoretical framework of innovation capabilities put forward by Zawislak et al. (2012), due to its efforts in merging the dimensional and processual approaches into an integrated perspective. For Zawislak et al. (2012), firms have four innovation capabilities: 'development', 'operations', 'transactions', and 'management.' Development and operations capabilities are technology-driven, respectively resulting in new products and new production processes, while transactions and management capabilities are business-driven, respectively resulting in new ways to transact with the market and new types of management. While development and transactions capabilities are change-driven, resembling dynamic capabilities, operations and management capabilities are stability-driven, similarly to ordinary capabilities (Pufal & Zawislak, 2021). Figure 1 illustrates the theoretical framework.



Source: Adapted from Pufal and Zawislak (2021).

Figure 1. Firm innovation capabilities framework.

The 'development capability' refers to the research and development (R&D) activities of the firm (Zawislak et al., 2012), and coordinates the technological change (Pufal & Zawislak, 2021). The development capability senses the advent of new technologies, seizes the opportunities that arise from it, and reconfigures itself to develop new products or to enhance the existing ones, adapting the firm to a new technological context (Alpkan & Gemici, 2023; Figueiredo, 2017; Peerally et al., 2022).

The 'operations capability' relates to the manufacturing activities of the firm (Zawislak et al., 2012), and stabilizes the technological change (Pufal & Zawislak, 2021). The operations capability uses the new technologies absorbed by the development capability to design new production processes or to modify the existing ones, seeking to improve both operational efficiency and flexibility, reduce manufacturing costs, and shorten lead times (Csiki et al., 2023; E. M. Silva et al., 2021; Fullerton et al., 2014; Moldner et al., 2020).

The 'transactions capability' corresponds to the trading activities of the firm (Zawislak et al., 2012), and coordinates the business change (Pufal & Zawislak, 2021). The transactions capability senses the emergence of new market needs, seizes the opportunities that arise from it, and reconfigures itself to create new or enhance the existing ways to commercialize products, modifying from their marketing to their sales (Ali et al., 2024; Nascimento & Zawislak, 2023), and to coordinate the supply chain, changing from its design to the negotiation techniques applied to suppliers (Golgeci & Gligor, 2017). Therefore, this capability adapts the firm to a new business context.

The 'management capability' encompasses the managerial activities of the firm (Zawislak et al., 2012), and stabilizes the business change (Pufal & Zawislak, 2021). The management capability uses the new business opportunities targeted by transactions capability to design new or modify the existing managerial processes, organizational structures, and business models, aiming to improve the firm's organizational efficiency (Anzola-Román et al., 2018; Brito & Sauan, 2016; Torres & Augusto, 2019).

The main concern of the literature on innovation capabilities is how firms articulate their capabilities to innovate in a given period (Ali et al., 2024; Alpkan & Gemici, 2023; Csiki et al., 2023; Lall, 1992; García et al., 2017; Guan & Ma, 2003; Patterson & Ambrosini, 2015). This is not different for studies that apply Zawislak et al.'s (2012) framework. Alves et al. (2017) identified that innovation emerges from the articulation of development, transactions, and management capabilities. For the authors, the operations capability does not result in innovation, being only a minimal requirement for firms to compete in the market (Alves et al., 2017). However, Reichert et al. (2016) and Ruffoni and Reichert (2022) demonstrated that operations capability contributes to innovation when combined with the other capabilities. Furthermore, the relevance of each capability to innovation can be affected by sectoral characteristics. For example, the intensity of investments in R&D directly increases the importance of development capability (Ruffoni et al., 2018), while the proximity of firms to the final customer in the value chain directly leverages the relevance of transactions capability (Leo et al., 2022).

Since these studies only explore how firms combine their capabilities to innovate in a given period, it remains unknown whether and how firms recombine their capabilities over time. Market changes are constantly occurring, and therefore, firms might modify the way they use their capabilities to innovate (Zhang et al., 2023). The study by Collinson and Wang (2012) is one of the few in the research field that addresses this issue, and indicates that, over time, firms use different combinations of capabilities to innovate.

In contrast, the evolution of the firm's innovation capabilities between periods is a topic relatively well approached in the literature. However, studies in this regard generally only focus on the evolution of capabilities oriented to technological innovations (Figueiredo, 2017; Figueiredo et al., 2020; Gräbner & Hornykewycz, 2022; Guo & Zheng, 2019), with little attention being given to the evolution of capabilities geared to business innovations. Kumar and Yakhlef (2013), one of the few articles on this subject, elucidated the evolution of capabilities related to innovations in marketing, supply chain, and management.

The intensive market changes associated with the Fourth Industrial Revolution (Industry 4.0) offer an adequate context to understand whether and how firms evolve and recombine their innovation capabilities over time. The following section explores the adaptation of agricultural machinery manufacturers to Industry 4.0, a sector in which this transition has been intense.

Industry 4.0 in agricultural machinery manufacturers

Industrial revolutions are the consequence of both technological and business changes. Generally, four industrial revolutions are recognized (Liao et al., 2017). The first revolution (18th century) began due to the advent of steam-powered machines, and to the growth of the demand for products. The second revolution (19th century) occurred due to the emergence of electric-powered equipment, together with the demand for standardized products, leading to mass production. The third revolution (20th century) was a consequence of the rise of information technology and robotization, alongside the need to automate activities (Weking et al., 2019; Xu et al., 2018).

The current fourth revolution, also known as Industry 4.0, began in the 2010 decade (Kagermann et al., 2013). Its origins reside in the advent of a plethora of disruptive digital technologies (Rita & Silva, 2023; Rodrigues et al., 2021), standing out the internet of things, cloud computing, big data analytics, artificial intelligence, additive manufacturing (digital layered manufacturing/3D printers) and collaborative robots. Together with these technologies, emerges a demand for more personalized products (Culot et al., 2020; Dalenogare et al., 2018; Zheng et al., 2020). Consequently, the conversion of firms to Industry 4.0 is characterized by the application of these digital technologies to make the manufacture of customized products economically viable (Wang et al., 2017), or to increase the personalization of products by complementing them through the offering of customizable packages of digital services (Shen et al., 2023).

In this regard, the adaptation of firms to Industry 4.0 implies modifications not only in products, but also in production processes, ways of transacting with customers and suppliers, along with types of management (Frank et al., 2019; Meindl et al., 2021). Therefore, it can involve changes in the four capabilities of the theoretical framework proposed by Zawislak et al. (2012), potentially resulting in the four types of innovation. This perception is consistent with the perspective of the socio-technical systems (Emery & Trist, 1960) on Industry 4.0, according to which the transition of firms in this regard requires modifications not only in their technical system (the technological artifacts utilized), but also in their social system (the organization of the work involved) (Cimini et al., 2021; Manresa et al., 2024). The socio-technical perspective understands that changes in these systems result, respectively, in technological and business innovations (Damanpour & Evans, 1984). Since the two systems are intertwined, modifications in one affect the other, and thus, technological and business innovations are always related (Damanpour, 2020).

Recently, the Organization for Economic Cooperation and Development (OECD, 2019) created a taxonomy to classify economic sectors accordingly to their conversion level to Industry 4.0. The taxonomy classifies sectors into four levels of digital intensity (high, medium-high, medium-low, and low), which refers to the adoption rate of digital technologies related to Industry 4.0 by companies. The machinery and equipment sector, which includes agricultural machinery manufacturers (producers of tractors, planters, fertilizers, harvesters, silos, and so on), is considered of medium-high digital intensity, being one of the most digitalized sectors (Calvino et al., 2018).

The intensive transition of agricultural machinery manufacturers to Industry 4.0 is clearly perceived in the offering of equipment with embedded digital technologies to collect, transmit, and convert data related to their performance into accurate reports about productivity, need for maintenance and spare parts, fuel usage, CO_2 emissions, among others (Smania et al., 2022). This ends up promoting high levels of precision and sustainability in agriculture, leading to an important byproduct of Industry 4.0: Agriculture 4.0 (Mahda et al., 2022; Wolfert et al., 2017; Zambon et al., 2019). Given the increasing demand for food and the impact of climate change on growing conditions, Agriculture 4.0 represents more than efficiency gains for farmers, being a crucial transformation for the future of mankind (FAO, 2017).

The diffusion of Agriculture 4.0 is particularly relevant in Brazil, one of the main producers of food and agricultural commodities in the world (Vieira & Fishlow, 2017). This status was conquered through both public and private efforts. The public sector, through Brazilian Company for Agricultural Research (*Empresa Brasileira de Pesquisa Agrícola* [EMBRAPA]), serves as a key mechanism to develop, introduce, and diffuse innovations related to plating conditions among farmers (Vieira & Fishlow, 2017). On the private side, investments of agricultural machinery companies to develop and adapt equipment for the Brazilian soil and climate conditions also play an important role in achieving these high volumes of production. More recently, these investments are focusing on the development of equipment embedded with digital technologies related to Industry 4.0 (Bolfe et al., 2020; Mantovani et al., 2019; Smania et al., 2022).

In this regard, Brazilian agricultural machinery manufacturers are an adequate sample to explore the research question. The following section details the methodological procedures adopted to do so.

METHOD

To answer how firms adapting to Industry 4.0 evolve and recombine their innovation capabilities over time, a longitudinal quantitative study was carried out considering two periods: 2014 and 2018. Although the Fourth Industrial Revolution started in developed economies at the beginning of the 2010 decade (Kagermann et al., 2013; Liao et al., 2017; Xu et al., 2018), Brazil is an emerging economy, which are known to suffer from technological delays (Dutrénit et al., 2019; Wong & Goh, 2014).

Hence, the time interval between 2014 and 2018 is an adequate period to explore firms' conversion to Industry 4.0.

To identify whether and how firms evolved their innovation capabilities between these two periods, the Wilcoxon signed-rank test was applied. Subsequently, to identify whether and how firms recombined their innovation capabilities between periods, the fuzzy-set qualitative comparative analysis (fsQCA) was used. Both the Wilcoxon signed-rank test (MacFarland & Yates, 2016) and the fsQCA (Pappas & Woodside, 20211) are adequate techniques to examine small and intermediate samples (circa 30 observations). This study follows an emerging trend in management research in the use of the fsQCA to analyze longitudinal data (see Liu et al., 2022; Valéau et al., 2024), and brings a methodological novelty in combining the fsQCA with the Wilcoxon signed-rank test.

Data collection

Data related to 2014 were collected by a research group associated with Federal University of Rio Grande do Sul (*Universidade Federal do Rio Grande do Sul* [UFRGS]) for a previous study on innovation in manufacturing firms. A survey instrument was applied, with questions based on the framework of innovation capabilities proposed by Zawislak et al. (2012). The answers were measured with five-point Likert scales, varying from one (totally disagree) to five (totally agree). To contact companies, the Industries Federation of Rio Grande do Sul (*Federação das Indústrias do Estado do Rio Grande do Sul* [FIERGS]) catalog was used. This catalog encompasses 6,134 manufacturing companies, of which 187 are agricultural machinery manufacturers (producers of tractors, planters, harvesters, sprayers, grain dryers, silos, etc.). Data were collected by telephone, and only senior managers or owners were interviewed, due to their knowledge to properly answer the questions. Data collection resulted in a sample with 1,331 manufacturing companies (response rating of 21.7%), of which 62 were agricultural machinery manufacturers (response rating of 33.2%).

For the present study, we selected from these 62 agricultural machinery companies only those with evidence of conversion to Industry 4.0, i.e.: offer of equipment with embedded digital technologies (apps/software) to monitor the product performance and support the agricultural process; implementation of cloud computing platforms, big data analytics, or artificial intelligence in their activities; use of additive manufacturing equipment; and use of collaborative robots. The selection was based on magazines about digitalization in agribusiness, sectoral reports, news, companies' websites, and product catalogs. We identified 30 companies with evidence of adapting to Industry 4.0. Afterward, we collected data again in 2018 for only these 30 firms, using the same research instrument and collection protocol applied in 2014. Only one company did not respond to the questionnaire again, resulting in a sample of 29 firms. Taking into account the 187 agricultural machinery manufacturers in the FIERGS catalog, the sample obtained represents 15.5% of the sector.

All companies are located in the Brazilian state of Rio Grande do Sul, which concentrates important agricultural machinery manufacturers (Confederação Nacional da Indústria, 2024). Table 1 summarizes the characteristics of the sample (referring to 2014).

Table 1. Sample characteristics.

Characteristic	Category	No.	%
Size	Large	10	34%
	Medium	15	52%
	Small	4	14%
Age	Less than 10 years	2	7%
	From 10 to 20 years	8	28%
	From 21 to 30 years	8	28%
	From 31 to 40 years	2	7%
	From 41 to 50 years	3	10%
	From 51 to 60 years	4	14%
	More than 60 years	2	7%
Origin	Domestic	25	86%
	Foreigner	4	14%

Note. Developed by the authors.

The firm's size is based on the Bank of National Development (*Banco Nacional de Desenvolvimento* [BNDES], 2021) classification: small companies = annual revenue less than or equal to BR$ 4.8 million; medium companies = annual revenue greater than to BR$ 4.8 million, but less than or equal to BR$ 300 million and; large companies = annual revenue greater than BR$ 300 million.

Data analysis

The firm's innovation capabilities were addressed through the same items adopted by Reichert et al. (2016). Operations and management capabilities, respectively, consist of six and seven items. The development capability includes six items (also adopted by Alves et al., 2017; Oliveira et al., 2019; Pufal & Zawislak, 2021; Ruffoni et al., 2018), and transactions capability includes five items (also adopted by Oliveira et al., 2019). Almost all of these studies consider the firm's performance as the outcome of the innovation capabilities, evaluating it through the mean of three items: net profit, market share, and revenue (Alves et al., 2017; Oliveira et al., 2019; Reichert et al., 2016; Ruffoni et al., 2018). All studies cited here identified a Cronbach's alpha greater than 0.7 for each of the five constructs, indicating satisfactory reliability (Hair et al., 2009). The items are detailed in Table 2, in the Results section.

It is important to note that these previous studies use firm's performance as outcome, and not its innovative performance. Generally, innovative performance is measured by revenue related to new products or the number of registered patents (Bending et al., 2024; Hagedoorn & Cloodt, 2003). However, this tends to restrict innovation to product innovation, once the other types of innovation — new production processes, new ways of transacting with customer and suppliers, and new types of management — are hard to measure in similar terms. In parallel, some studies adopt the 'revealed capability' approach, considering that the firm's capabilities are a direct characterization of its innovative performance (Figueiredo, 2017; Figueiredo et al., 2020). The aforementioned studies that adopt the framework presented by Zawislak et al. (2012) try to build a bridge between these two perspectives. Taking innovation as anything new that creates value (Schumpeter, 1934), it is understood that, if a capability has a causal effect on firm performance, then this capability is producing innovations.

Data analysis was conducted in two stages. The first stage analyzed whether and how firms evolved their innovation capabilities over time. This was operationalized by measuring the differences in the capabilities between the periods considered. To choose a proper technique to do so, two normality tests, Kolmogorov-Smirnov and Shapiro-Wilk, were carried out. Practically, all items in both periods exhibit a significant difference from a normal distribution with both tests (below 0.05). Therefore, nonparametric statistical tests are recommended to evaluate the differences between the periods (Hair et al., 2009).

Since this study compares data from different periods, but that refer to the same companies, the Wilcoxon signed-rank test was chosen because of its suitability to analyze related samples (MacFarland & Yates, 2016). This test is the nonparametric equivalent of the dependent t-test, measuring the differences between variables based on their medians (instead of their means) (Field, 2009). Similar tests, such as Wilcoxon rank-sum and Mann-Whitney, were discarded because they are nonparametric equivalents to the independent t-test, and thus, are geared to explore unrelated samples (Field, 2009). All analyses of the first stage were performed using SPSS software.

The second stage of the data analysis examined whether and how firms recombined their innovation capabilities over time. This was done by employing the fsQCA to identify the combinations of capabilities through which firms obtained high performance in each of the periods considered. The fsQCA follows a set-theoretic approach to identify combinations of conditions that result in a given outcome (Ragin, 2000). Consequently, data must be converted into membership scores, ranging from 0.05 (non-membership) to 0.95 (full-membership), a process known as calibration (Pappas & Woodside, 2021).

To transform the data into membership scores, anchor points must be defined (Ragin, 2008). Regarding five-point Likert scales, studies adopt different approaches to do so, such as: direct correspondence (e.g., 1 = 0.05; 3 = 0.50; 5 = 0.95) (Leischnig & Kasper-Brauer, 2015); percentiles (e.g., 20th = 0.05; 40th = 0.35; 60th = 0.65; 80th = 0.95) (Sjödin et al., 2016); and descriptive statistics (e.g., mean − standard deviation = 0.05; mean = 0.50; mean + standard deviation = 0.95) (F. Silva et al., 2019). To standardize the analysis criteria, the data were calibrated with the same approach and anchor points in both periods. The direct correspondence approach was applied and, since the values obtained in 2014 are lower than those obtained in 2018, anchor points that represent a middle ground between the periods were considered (2 = 0.05; 3.50 = 0.50; 5 = 0.95) (Pappas & Woodside, 2021). The fsQCA 2.0 software was used to calibrate the data and identify combinations of capabilities for high performance.

RESULTS

Evolution of innovation capabilities

Table 2 presents the results of the Wilcoxon signed-rank test, showing the median of each item in each period, the positive ranks (number of observations in which the median of 2018 is superior to the median of 2014), the negative ranks (number of observations in which the median of 2014 is superior), and the ties (number of observations in which the medians are equal). Table 2 also presents the z-score and the p-value, which, respectively, assess the differences between the medians and the significance of these differences (Field, 2009; MacFarland & Yates, 2016). To complement the analysis, Table 2 also provides the mean of each item in 2014 and 2018, as well as the differences between these means.

Table 2. Wilcoxon signed-rank test.

Item — Does your firm:	Median 2014	Median 2018	Positive ranks (2018>2014)	Negative ranks (2018<2014)	Ties (2018=2014)	z-score	p-value (2 tailed)	Mean 2014	Mean 2018	Mean 2018 – Mean 2014
Design its own products	4	4	16	6	7	-1.900[b]	0.057*	3.59	4.17	0.59
Monitor the latest tendencies in technology in the industry	4	4	15	4	10	-2.583[b]	0.010***	3.69	4.34	0.66
Use formal project management methods (e.g., stage gate, PMBOX, innovation funnel)	3	4	17	5	7	-2.616[b]	0.009***	3.31	4.07	0.76
Adapt the technology in use for its own needs	4	4	10	4	15	-1.732[b]	0.083*	3.61	3.93	0.32
Prototype its own products	4	4	15	8	6	-2.329[b]	0.020**	3.69	4.38	0.69
Launch its own products	5	4	11	11	7	-0.365[b]	0.715	4.07	4.17	0.10
Development capability[1]	**3.83**	**4.33**	**17**	**10**	**2**	**-1.731[b]**	**0.083***	**3.66**	**4.18**	**0.51**
Keep statistical control of the process	3	4	15	5	9	-2.334[b]	0.020**	3.59	4.14	0.55
Use leading edge technology within the sector	4	4	14	2	13	-2.482[b]	0.013**	3.59	4.10	0.52
Maintain adequate stock levels of materials for the process	4	4	12	4	13	-1.469[b]	0.142	3.93	4.24	0.31
Carry out the productive process as scheduled	4	4	10	8	11	-1.177[b]	0.239	3.90	4.10	0.21
Establish a productive routine that does not generate rework	4	4	14	6	9	-2.057[b]	0.040**	3.93	4.31	0.38
Manage to expand the installed capacity whenever necessary	4	4	15	3	11	-2.707[b]	0.007***	3.59	4.28	0.69
Operations capability[1]	**3.67**	**4.33**	**19**	**5**	**5**	**-2.296[b]**	**0.022****	**3.75**	**4.20**	**0.44**
Conduct formal research to monitor the market	3	4	17	7	5	-2.487[b]	0.013**	3.24	4.10	0.86
Impose its prices on the market	3	4	15	8	6	-1.807[b]	0.071*	3.38	3.86	0.48
Impose its negotiating terms on its customers	3	5	21	0	8	-4.081[b]	0.000***	3.31	4.62	1.31
Conduct research to measure its customers satisfaction	3	5	20	1	8	-3.897[b]	0.000***	3.24	4.69	1.45
Use formal criteria to select suppliers	4	4	17	4	8	-2.758[b]	0.006***	3.52	4.28	0.76
Transactions capability[1]	**3.60**	**4.40**	**24**	**4**	**1**	**-3.926[b]**	**0.001*****	**3.34**	**4.31**	**0.97**
Formalize production planning and control procedures	3	4	18	2	9	-3.569[b]	0.000***	3.17	4.31	1.14
Formally define its strategic aims annually	4	4	18	4	7	-3.150[b]	0.002***	3.59	4.34	0.76
Use information technology to integrate all of its areas	3	5	19	3	7	-3.596[b]	0.000***	3.34	4.38	1.03
Standardize and document the work procedures	4	4	17	3	9	-3.189[b]	0.001***	3.59	4.24	0.66
Update its management tools and techniques	3	5	18	3	8	-3.338[b]	0.001***	3.57	4.45	0.88
Maintain adequately trained personnel for company function (training)	4	5	17	3	9	-3.320[b]	0.001***	3.90	4.59	0.69
Use modern financial management practices	4	4	20	3	6	-3.061[b]	0.002***	3.57	4.28	0.70
Management capability[1]	**3.71**	**4.43**	**25**	**4**	**0**	**-3.841[b]**	**0.000*****	**3.54**	**4.37**	**0.83**
Had growth in net profits over the last three years	3	4	16	5	8	-2.623[b]	0.009***	3.48	4.21	0.72
Had growth in market share over the last three years	4	4	13	5	11	-2.304[b]	0.021**	3.79	4.31	0.52
Had growth in revenue over the last three years	4	4	14	6	9	-1.939[b]	0.052*	3.57	4.10	0.53
Performance[1]	**3.67**	**4.33**	**20**	**8**	**1**	**-2.639[b]**	**0.009*****	**3.61**	**4.21**	**0.60**

Note. [1] The values refer to the mean of the items associated with the construct; [b] based on negative ranks; *** difference is significant at 1%; ** difference is significant at 5%; * difference is significant at 10%.

The results show that the medians are consistently higher in 2018 than in 2014, once the z-scores of all items are based on negative ranks (Field, 2009). Therefore, agricultural machinery manufacturers evolved their four innovation capabilities from 2014 to 2018, and also achieved better performance.

The evolution of the development capability was the less significant of the four capabilities (z-score = -1.731; p-value < 0.10). Specifically, the main evolutions occurred in the monitoring of technological trends, the formalization of project management methods, and the prototyping of products. In parallel, little representative enhancements happened in activities to design products, and in the adaptation of technologies for its own use. No improvement was observed in procedures to launch new products.

The operations capability presented a more significant evolution than the development capability (z-score = -2.296; p-value < 0.05). The main evolutions took place in activities oriented to create new production processes, i.e., conduction of statistical control, use of leading-edge technology, and expansion of the production capacity. On the other hand, activities geared to execute the current production process exhibited a weak evolution: only the establishment of productive routines was enhanced, while there were no improvements in stock management and production scheduling.

The evolution of transactions capability was the most significant of the four capabilities (z-score = -3.926; p-value < 0.01). Practically all activities associated with this capability evolved consistently: conduction of formal market research, execution of research to monitor customer satisfaction, imposition of negotiation terms on customers, and use of formal criteria to select suppliers. Only procedures related to the imposition of prices in the market were little enhanced.

The management capability also demonstrated a significant evolution (z-score = -3.841; p-value < 0.01). Firms improved their entire management system, since all activities associated with this capability presented considerable enhancements: production planning and control, formulation of strategic objectives, integration of managerial processes through information technology, standardization of work procedures, use of updated management tools, adequacy between training and job functions, and application of modern financial management techniques.

Firms also exhibited a significant growth in their performance between 2014 and 2018 (z-score = -2.639; p-value < 0.01). This occurred mainly in net profits, followed by market share, and, at last, in revenue. This suggests that the evolutions carried out in the innovation capabilities brought benefits to firms. To verify the causal effects of innovation capabilities on firms' performance, as well as to identify whether and how firms recombined their innovation capabilities between periods, the following section presents the results obtained with the fsQCA.

Recombination of innovation capabilities

The fsQCA consists of two analyses: necessity and sufficiency. While the necessity analysis identifies the individual conditions that must be present for the outcome to occur, the sufficiency analysis identifies combinations of conditions that result in the outcome (Ragin, 2008). Both analyses are evaluated through consistency and coverage indicators, which range from zero (low) to one (high). 'Consistency' measures the extent to which an individual condition/combination of conditions contributes to the desired outcome, resembling the statistical correlation (Hsiao et al., 2015). 'Coverage' measures the percentage of cases in which an individual condition/combination of conditions is associated with the outcome, similar to R^2 (Hsiao et al., 2015). Table 3 presents the necessity analysis.

Table 3. Necessity analysis.

Period:	2014		2018	
Outcome:	High performance		High performance	
Condition	Consistency	Coverage	Consistency	Coverage
Development capability [DC]	0.82*	0.79	0.86*	0.83
~Development capability [~DC]	0.50	0.66	0.31	0.97
Operations capability [OC]	0.84*	0.79	0.89*	0.85
~Operations capability [~OC]	0.52	0.70	0.30	0.95
Transactions capability [TC]	0.66	0.80	0.92**	0.85
~Transactions capability [~TC]	0.66	0.68	0.24	0.90
Management capability [MC]	0.78	0.84	0.92**	0.83
~Management capability [~MC]	0.61	0.71	0.23	0.98

Note. ** Necessary condition (consistency >= 0.90); * almost always necessary condition (consistency >= 0.80).

A condition is deemed 'necessary' or 'almost always necessary' when its consistency is, respectively, greater than 0.900 or 0.800 (Ragin, 2000; Santos & Gonçalves, 2019). Thus, development and operations capabilities are almost always necessary for high performance in both periods, while transactions and management capabilities are only necessary in 2018.

The sufficiency analysis consists of building and reducing the truth table. The truth table lists all possible combinations of conditions for the desired outcome, informing the number of observations associated with each combination (frequency), and the degree to which the observations are associated with the combinations (raw consistency) (Ragin, 2008). The truth table must be reduced by removing combinations with low frequency and raw consistency. For both periods, the truth table was reduced by excluding combinations with a frequency below or equal to one case, and with a raw consistency below 0.80 (Pappas & Woodside, 2021).

Afterward, fsQCA generates three solutions: complex, intermediate, and parsimonious. According to Ragin (2008), the solutions differentiate from each other in the inclusion of counterfactuals. The complex solution includes all counterfactuals, the intermediate solution consider only those that are plausible, and the parsimonious solution does not consider any counterfactual. Consequently, while the complex solution can be difficult to interpret, the parsimonious solution can be too simplistic. Hence, it is recommended for researchers to consider only the intermediate solution (Ragin, 2008). Additionally, Pappas and Woodside (2021) suggest comparing the intermediate and parsimonious solutions to identify peripheral conditions, i.e., those present only in the intermediate solution (Huang et al., 2023). However, the results of both solutions are the same, and thus, there are no peripheral conditions to report. Table 4 presents the sufficiency analysis.

Table 4. Sufficiency analysis.

Period: Outcome: Condition	2014 High performance Combination	2018 High performance Combination
Development capability [DC]	●	
Operations capability [OC]	●	●
Transactions capability [TC]		●
Management capability [MC]	●	●
Solution consistency	0.88	0.87
Solution coverage	0.70	0.81
Configuration consistency	0.88	0.87
Raw coverage	0.70	0.81
Unique coverage	0.70	0.81

Note.● = Causal condition must be present for the outcome to occur; ○ = causal condition must be absent for the outcome to occur; blank = causal condition is indifferent for the outcome to occur.

The solution generated by the sufficiency analysis can include one or multiple combinations of conditions that result in the same outcome (equifinality) (Ragin, 2008). For each period analyzed, the solution indicates that there is only one combination of conditions that can result in high performance. Both solutions are valid, presenting scores for consistency (0.88 and 0.87) above 0.75, and for coverage (0.70 and 0.81) above 0.25 (Woodside, 2013). Measures of configuration consistency, raw coverage, and unique coverage refer to each combination of conditions included in a solution (Ragin, 2008). However, since only one combination can obtain high performance in each period, the values of these indicators are equal to the values of the solution consistency and solution coverage.

The results of the sufficiency analysis indicate that firms achieved high performance in 2014 by combining development, operations, and management capabilities (DC*OC*MC), and in 2018 by articulating transactions, operations, and management capabilities (TC*OC*MC). Therefore, agricultural machinery manufacturers recombined their innovation capabilities from 2014 to 2018, substituting the development capability by transactions capability. The next section discusses the results.

DISCUSSIONS

The Wilcoxon signed-rank test (Table 2) demonstrated that agricultural machinery manufacturers evolved their four innovation capabilities and obtained increases in their performance between 2014 and 2018. However, business-driven capabilities (transactions and management) presented more significant evolutions than technology-driven capabilities (development and operations).

The evolution of technology-driven capabilities can be considered weak. Since these two capabilities are intertwined (the development capability conducts the technological change, while the operations capability stabilizes it) (Pufal & Zawislak, 2021), it can be assumed that the few enhancements in the development capability led to the little improvements in the operations capability. The weak evolution of development capability can be explained by the characteristic technological delay of emerging economies, which ends up restricting the technological change of firms (Dutrénit et al., 2019; Wong & Goh, 2014). Generally, this delay is overcome by building open-innovation processes with institutions (Guo & Zheng, 2019) or, in the case of subsidiaries, by establishing knowledge transfer mechanisms with headquarters abroad (Figueiredo et al., 2020). However, most companies reported (23 of 29) that they had little interaction with science and technology institutions in 2014, demonstrating weak open innovation processes in the first period considered. Furthermore, most of the firms have a domestic origin (25 of 29, see Table 1), and thus, do not count on headquarters abroad to support the absorption of new technologies.

Despite that, the operations capability was able to enhance activities related to the creation of production processes: conduction of statistical control, expansion of production capacity, and even the use of leading-edge technologies. According to Figueiredo (2017), although the different dimensions of the firm's technological capability are associated, their evolution displays a certain degree of heterogeneity, because each dimension performs a specific function (Figueiredo, 2017; Figueiredo et al., 2020). In other words, the operations capability is able of enhancing the exploitation of technologies already absorbed to create new production processes, even if the development capability does not absorb new technologies.

Regarding business-driven capabilities, the firms showed a strong evolution in both transactions and management capabilities. Like technology-driven capabilities, these two capabilities are also intertwined (transactions capability conducts the business change, while the management capability stabilizes it) (Pufal & Zawislak, 2021). Consequently, it can also be assumed that the enhancements in transactions capability led to the improvements in management capability. In line with this, Kumar and Yakhlef (2013), one of the few studies addressing the evolution of business-driven capabilities, identified that the evolution of marketing and supply chain capabilities occurred alongside the evolution of internal management capabilities, also suggesting some degree of association between these evolutions.

The results obtained with the fsQCA indicate that agricultural machinery manufacturers recombined their innovation capabilities between 2014 and 2018. It is perceived that business-driven capabilities gained more strength than technology-driven capabilities between the periods analyzed, reinforcing the results of the Wilcoxon signed-rank test. The necessity analysis (Table 3) demonstrates that technology-driven capabilities were maintained as almost always necessary conditions for high performance in both periods, while business-driven capabilities varied from non-necessary, in 2014, to necessary, in 2018. Additionally, the sufficiency analysis (Table 4) shows that firms achieved high-performance in 2014 using a combination with two technology-driven capabilities (DC*OC*MC), and in 2018 using a combination with two business-driven capabilities (TC*OC*MC).

The DC*OC*MC combination, due to the presence of the development capability, suggests that firms focused on technological changes in 2014. While the development capability was absorbing new technologies to develop new products, the operations capability was using these technologies to create new production processes. In this context, the management capability was exploiting already absorbed business opportunities to enhance managerial processes. It is reasonable to assume that the role of the management capability was to support the technological change. According to previous studies, enhancements in business models, organizational structures, and managerial processes can set the pieces for the introduction of new products in existing markets, as well as facilitate the implementation of new technologies in production (Anzola-Román et al., 2018; Torres & Augusto, 2019).

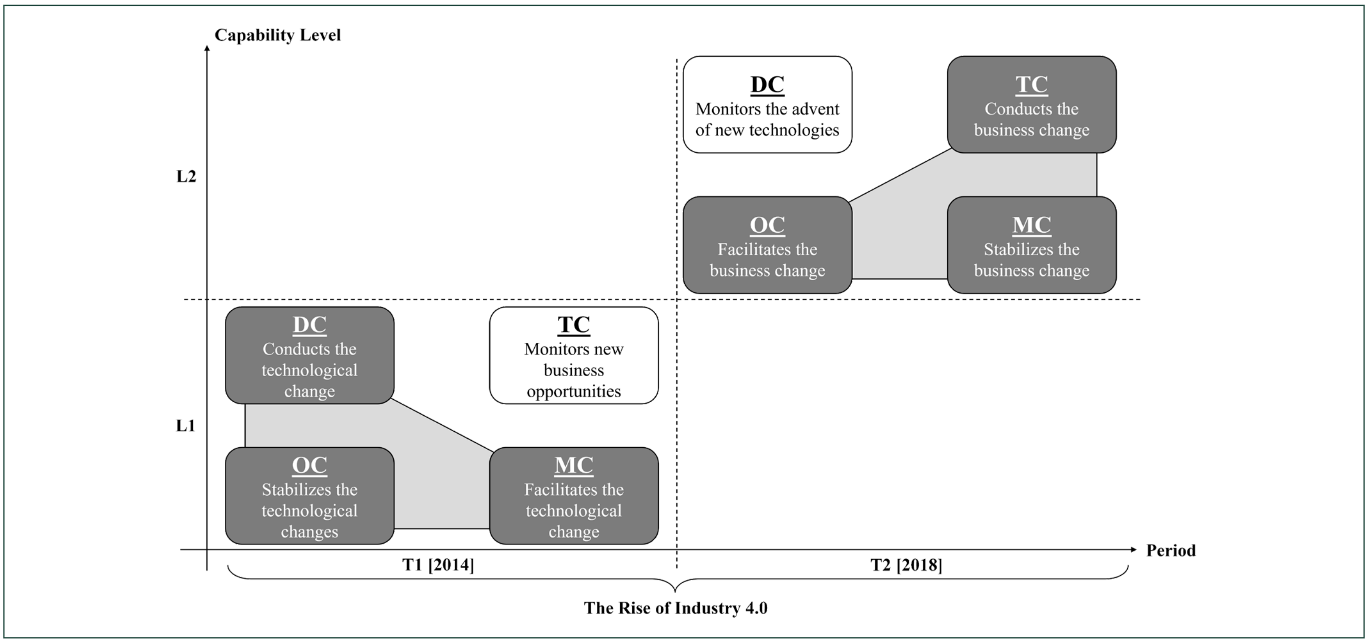
The TC*OC*MC combination, given the presence of transactions capability, indicates that the firms concentrated on business changes in 2018. The transactions capability was absorbing new business opportunities to create new ways to commercialize existing products and coordinate the supply chain, while the management capability was using these opportunities to create new managerial processes. In this scenario, the operations capability was exploiting already absorbed technologies to improve production processes. It can be assumed that the operations capability was assisting the business change. For Moldner et al. (2020), improvements in production processes can foster business innovations. More efficient and flexible manufacturing operations facilitate increasing the scale of production (Reichert et al., 2016) and the improvement of negotiation methods applied to customers due to high product quality, delivery of products on time, and short lead times (Ruffoni & Reichert, 2022). This allows the firm to expand its customer portfolio and enter new markets. Furthermore, the implementation of practices for excellence in production, such as lean manufacturing, is extendable to management areas (Fullerton et al., 2014).

Hence, a complement to Pufal and Zawislak (2021) is that operations and management capabilities not only stabilize, respectively, the technological and business changes. The operations capability can also contribute to the business change, while the management capability can also favor the technological change.

The recombination of innovation capabilities, substituting the development capability by transactions capability, is consistent with the findings of Collinson and Wang (2012). The authors identified that firms alternated the use of three capabilities (product design, production, and marketing) to obtain innovations over time. Therefore, although firms discontinue the use of an innovation capability in a given period, they can resume it later (Collinson & Wang, 2012). Considering that Zawislak et al.'s (2012) framework understands that all firms have the four innovation capabilities (Pufal & Zawislak, 2021), the fact that a capability is absent from a combination for high-performance does not mean that firms do not use it to a certain degree. It can be supposed that firms used the transactions capability in

2014 and the development capability in 2018 only to monitor, respectively, business opportunities and new technologies, without directly involving them in the innovation process.

Since the Wilcoxon signed-rank test indicates that the performance of agricultural machinery manufacturers increased between 2014 and 2018, the evolution and recombination of capabilities can be taken as beneficial for firms. Figure 2 resumes the discussion, illustrating the evolution and recombination of capabilities in the rise of Industry 4.0.



Source: Developed by the authors.

Figure 2. The evolution and recombination of innovation capabilities of agricultural machinery manufacturers in the rise of Industry 4.0.

The context of adaptation to Industry 4.0 of the firms analyzed can provide explanations for the observed evolution and recombination of capabilities. Since the Fourth Industrial Revolution is an environment of uncertainty and turbulence (Liao et al., 2017; Weking et al., 2019; Xu et al., 2018), firms need to carry out intense changes in their capabilities to adequately respond to radical shifts and, consequently, to become able to innovate (Zhang et al., 2023).

It is possible that the evolution of capabilities was caused by the absorption of disruptive digital technologies related to Industry 4.0, through the DC*OC*MC combination in 2014. Technologies such as the internet of things, cloud computing, big data analytics, and artificial intelligence (Culot et al., 2020; Dalenogare et al., 2018; Zheng et al., 2020) enable a quick collection and conversion of large amounts of data into useful information for the firm (Meindl et al., 2021). Generation of information is related to generation of knowledge, which is the main building block of capabilities (Daronco et al., 2023; Dosi et al., 2000). Consequently, these building blocks could have contributed for firms to evolve their capabilities.

Regarding the recombination of capabilities, it reflects the very nature of the innovation process: from product development (DC*OC*MC) to product commercialization (TC*OC*MC). In the context of transition to Industry 4.0, it can be said that firms first focused on develop products with digital technologies embedded, to later concentrate on how to commercialize them. The perspective of socio-technical systems on Industry 4.0 can offer a comprehensive explanation for the recombination of capabilities. Through the lens of this approach, in 2014, firms used the DC*OC*MC combination to modify their technical system by incorporating digital technologies into products, production processes, and managerial procedures. In other words, firms were conducting their digitalization (Manresa et al., 2024). In 2018, firms used the TC*OC*MC combination to change their social system by reorganizing the work around the new technical system established years before, creating new forms of organizing commercial, managerial, and production activities. That is, firms paired their social and technical systems, which is fundamental for them to extract the full potential of new technologies and thrive (Cimini et al., 2021).

CONCLUSION

The study achieved its objective of identifying how firms adapting to Industry 4.0 evolve and recombine their innovation capabilities over time. A four-innovation capabilities framework (development, operations, transactions, and management) was considered, and agricultural machinery manufacturers were explored, a sector in which the transition to Industry 4.0 has been intense. Using longitudinal data related to two periods, 2014 and 2018, it was identified that firms evolved and recombined their innovation capabilities. The results demonstrated that firms' focus varied from technological change to business change. Besides a more intense evolution of business-driven capabilities, the recombination of capabilities consisted of modifying an arrangement based on two technology-driven capabilities (DC*OC*MC) to an arrangement based on two business-driven capabilities (TC*OC*MC). Since increases in performance were also observed, the changes carried out in the capabilities can be considered beneficial.

The article offers academic, methodological, and practical contributions. In terms of academic contributions, the study contributes to cover two important research gaps in the literature on innovation: how firms evolve and recombine their innovation capabilities over time, considering both technological and business capabilities. Regarding methodological contributions, the article follows the recent trend of applying the fsQCA to explore longitudinal data, supporting its consolidation. Additionally, it also brings a methodological novelty in combining the fsQCA with the Wilcoxon signed-rank test. The combination of these two techniques enabled the analysis of how the modification of individual conditions over time (Wilcoxon signed-rank test) relates with modifications in combinations of these conditions (fsQCA).

In terms of practical contributions, the study demonstrates that all four capabilities contribute to innovation, even if, at a given moment, one or more of them are not necessary. In this regard, companies must develop their four capabilities and be flexible in articulating them according to the circumstances. Managers must keep in mind that, although a combination of capabilities results in innovation in a given period, this might not persist over time. Another practical contribution is the reinforcement of previous evidence that the conversion of companies to Industry 4.0 requires both technological and business changes. In addition to digitalize their products and processes, companies also need to modify their marketing and supply chain strategies, business models, and organizational structures.

As in all research, this study also has limitations. First, the generalization of the results is restricted, since the sample utilized is small and only includes companies operating in the agricultural machinery industry. Additionally, the capability approach restricts the perception of performance to internal factors of the firm, ignoring external elements, such as the influence of institutions and public policy. More specifically, the perspective of 'revealed capability' neglects traditional innovation indicators. Some researchers may argue that the causality between innovative activities (represented through capabilities) and performance does not exactly reflect the development of new products, production processes, ways of transacting, and types of management. These limitations can be overcome in future research by, respectively: using larger samples and examining companies from different industries; addressing the impact of external factors on the evolution and recombination of innovation capabilities; and using both the 'revealed capability' approach and traditional innovation indicators to characterize firms' adaptation to Industry 4.0.

Finally, to advance the research field, future studies can deepen important topics raised here. First, although the article characterizes the evolution and recombination of innovation capabilities in firms transitioning to Industry 4.0, it does not evaluate the effects of Industry 4.0 on capabilities. Future research can explore this issue, measuring and detailing how Industry 4.0 affects capabilities. Second, future research can also better elucidate the links between innovation capabilities and socio-technical systems, clarifying how changes in each system correspond to changes in technological and business capabilities. Third, future studies can address to what extent firms are flexible to modify their combinations of innovation capabilities over time, expanding innovation research by exploring not only the capabilities of firms, but also their flexibility to rearrange capabilities over time.

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