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ARTICLE
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Factors determining the path of digital technologies adoption of Brazilian industrial firms

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ABSTRACT

This paper aims to identify the main factors affecting the adoption of digital technologies for a panel of 299 Brazilian industrial firms surveyed in 2017 and 2019/20. A probabilistic model is used to estimate the likelihood of certain organizational, technological, and environmental characteristics of the firms affecting digital adoption in the two survey periods. The study reveals that digital adoption has advanced but still is at an infant stage in Brazil. The econometric results point out that current adoption, size, belonging to high digital intensity industries, being an exporter, and training the workforce have a significant positive effect on digital adoption. However, skills qualification has a negative effect, suggesting that qualification on previous technologies can be more a constraint than a pre-requisite for digitalization. One must interpret such findings against growth-adverse, investment-hostile economic framework conditions where firms can react in any given direction: move forward to survive, stay put to face uncertainty, and/or backtrack defensively.

KEYWORDS | Digital technologies; Technology adoption; Industrial firms; Brazil.

1. Introduction

Although the assessment of the adoption of digital-based technologies linked to Industry 4.0 by the Brazilian industry is a relatively unexplored topic, some systematic recent analyzes in this direction can be highlighted. Studies prepared by the National Confederation of Industry (CNI) address the punctual adoption of digital technologies by Brazilian manufacturing firms, based on the previous definition of lists of these technologies (CONFEDERAÇÃO NACIONAL DA INDÚSTRIA, 2016, 2018), advancing in the identification of some general conditions for their adoption (CONFEDERAÇÃO NACIONAL DA INDÚSTRIA, 2017, 2020a, b). Consulting companies have also approached this adoption from the point of view of their strategic relevance for companies and of the entrepreneurial "maturity" stage in the adoption of these technologies, based on restricted samples of companies (PRICEWATERHOUSE COOPERS BRASIL, 2016; MCKINSEY BRASIL, 2019; KPMG, 2021; CARMONA; AMATO NETO; ASCÚA, 2020).

In the academic sphere, some studies advance towards the systematization of the processes of adoption of digital-based technologies in manufacturing, associating them with the Brazilian reality (ARBIX et al., 2017), considering the benefits and barriers related to the adoption of Industry 4.0 technologies in Brazilian industrial companies (REIS, 2021). Other studies discusses the adoption of digital technologies in a sample of 90 companies associated with ABIMAQ, addressing the goals that companies want to achieve with the implementation of Industry 4.0 concepts, the customer expectations regarding the implementation of these concepts and the profile of the implementation level of four base technologies- Internet of Things, Cloud Services, Large Databases/Big Data and Structured Data Analytics (FRANK, 2018); or the adoption of digital technologies associated with (1) Smart Manufacturing, focused on the internal aspects of the factory; (2) Smart Working, focused on technologies that fulfill the function of helping the worker so that he becomes more productive; (3) Smart Supply Chain, focused on communication technologies and information integration in the supply chains; (4) Smart Products and Services, comprising products that offer additional services to the customer and collect information relevant to the company's manufacturing and engineering (FRANK; DALENOGAREB; AYAL, 2019). Others, like Dalenogare et al. (2018), using a survey conducted nationwide by the National Confederation of Industry, what explore the expected benefits for industrial Brazilian companies adopting specific technologies of the Industry 4.0, which are referred to operational performance and the development of new products. Recent studies prepared by the CGEE seek to identify promising niches and sectors of Brazilian industry for Industry 4.0, with a particular focus on the situation of Brazilian micro and small companies (CONFEDERAÇÃO NACIONAL DA INDÚSTRIA, 2020a) and advancing in the mapping of methodologies to align the needs of the industrial sector and critical technologies and enablers to meet these industrial demand, as well as in the assessment of maturity metrics that seek to identify the level of development of the company's capabilities to incorporate technologies associated with Industry 4.0 (CONFEDERAÇÃO NACIONAL DA INDÚSTRIA, 2020b).

Among all the recent studies on digitalization in Brazilian industry, this article aims to identify the role of technological, organizational, and environmental determinants on the observed evolution of digital adoption by Brazilian industrial firms using two different surveys, first in 2017 and the second along 2019/2020. When the first survey on digitalization was carried out, in 2017, the Brazilian economy was already in the downward side of the investment cycle. During the second survey, economic trends were even further negatively inclined. Such hostile environment could act as constraints to digital adoption, but also, it could push some firms to move digitalization forward as a survival defensive mechanism. The evolution of adoption compares the current generation adopted by a panel of the same 299 industrial firms that answered the first and the second survey. Organizational and environmental factors that determine the path of adoption came from variables included in the surveys. Additionally, we used information related to employment and STEM qualification RAIS. This kind of short-longitudinal analysis is unusual in the technology adoption literature and conforms the main contribution of the paper.

Besides this introduction, this paper has five other sections. The first reviews the literature on factors affecting technology diffusion and adoption. The second contextualizes Brazil's economic environment during the period under investigation. The third provides a comparative analysis of the two surveys for a set of technological, organizational, and market related features of firms. The fourth presents a model that estimates the probability of firms advancing from lower to higher digital technology generation between the two observed periods. The last section discusses the main results.

2. Determinants of technology adoption

Firms' decisions on technology adoption rely on information and perceptions about existing technology assets (*what do we have? where are we?*), and expectations about what the new solution can bring about (*which technologies are available now? when will they become available? what is to come?*). Perception refers to the individual's information, awareness, and comprehension about whether and how technologies are being used in their business environment (NUTLEY; DAVIES; WALTER, 2002). Moreover, it is considered that adoption is affected by technology-related factors: the compatibility, the adaptability, and the easiness of absorbing a new set of devices; the centrality of the new technology to the organization; and the complexity of requirements for adopting the new technology. This is so because decisions must consider the advantages and disadvantages of the required resource allocation, and the related potential economic benefits of adopting an innovation.

Two models address the factors affecting the decision-making concerning technology adoption: the Technology Acceptance Model (TAM) and the Technology-Organization-Environment (TOE)

(DAVIS, 1989; BAKER, 2012). TAM emphasizes on business leaders' perceptions, distinguishing perceived usefulness and perceived ease of use. The TOE model includes technological, organizational, and environmental or market related contexts as determinants of the decision-making process (TORNATZKY; FLEISCHER, 1990). *Technological aspects* are related to the current technological level of devices used by firms. The *organizational context* comprises firms' characteristics and resources, including size, managerial structure, competences, and competitive strategy, all of them strongly related to absorptive capacity in Zahra and George's (2002, p. 186) sense, this is, "[…] a set of organizational routines and processes by which firms acquire, assimilate, transform, and exploit knowledge to produce a dynamic organizational capability". The e*nvironmental context* includes the market structure of the industry a firm operates in, the economic context, and the regulatory environment. These models have been widely used in research interested in explaining the technology adoption by enterprises (OLIVEIRA; MARTINS 2011).

Empirical evidence confirms the importance of absorptive capacity and organizational capabilities and brings in further determinants of information and communication technologies (ICT) adoption. Fabiani, Schivardi and Trento (2005) found that the adoption of ICT in Italian manufacturing is positively associated with firm size, qualification of the labor force, and changes in organizational structures. Hollenstein (2004) observed similar results among Swiss firms, including positive effects of information spillovers between firms and competitive pressure. Bayo-Moriones and Lera-López (2007) found that size, foreign ownership, and a highly skilled workforce are all positively associated with ICT adoption in a sample of Spanish firms. Haller and Siedschlag (2011) suggested that Irish firms with more skilled workers operating in ICT-producing sectors had been relatively more successful in adopting and using ICT. In Indonesia, Arifin, Firmanzah and Wijanto (2016) noted that to be effective, firms need to invest in core competences required by the technology to be adopted. Finally, Martins et al. (2019) identified that what characterized the Brazilian leaders the most was their organizational structure and their capacity to recognize the complementary nature of digital practices. This capacity made them to be involved in constant learning to ensure the success of a broad implementation of digital solutions.

Departing from this conceptual framework, four propositions are put forward to guide the empirical analysis of the digital adoption by Brazilian firms in two moments of time. First one is the level of digitalization a firm is departing from. Absorptive capacity models foresee that moving forward is easier for lagging-behind firms, as they benefit from market conditions and the knowledge provided by the path tread by predecessors while still having a large space to evolve towards the technological frontier (GEROSKI, 2000). Conversely, firms using more advanced digital technologies at the initial period face less potential space to advance further in relation to a technology frontier. Thus, prior adoption of advanced digital technologies is negatively linked to subsequent adoption, while low levels of adoption may be positively linked to further progress, reflecting informational, competitive, or supply-side effects (BEN AOUN-PELTIER; VICENTE, 2012). These arguments support the following proposition: *the less advanced the level of digital adoption at the initial period, the higher the probability of moving forward in the next period.*

A second determinant factor is the firm size (GEROSKI, 2000): large firms have more resources to invest compared to their smaller peers. Also, they might be more motivated and able to innovate to pre-empt movements of rivals. A positive correlation between firm size and ICT adoption is found in several empirical studies (KARSHENAS; STONEMAN, 1995; TEO; TAN, 1998; THONG, 1999; FABIANI; SCHIVARDI; TRENTO, 2005; MORGAN; COLEBOURNE; THOMAS, 2006; ZOLAS et al., 2020; CARMONA; AMATO NETO; ASCÚA, 2020). Therefore, the second proposition is: *the larger the size, the higher the probability of a firm moving forward.*

The third proposition relates technology adoption to capabilities. The skill level of the workforce would be a crucial factor affecting the technology absorptive capacity of companies (DOMS; DUNNE;

TROSKE, 1997). A high qualification profile of employees should contribute to the absorption of new procedures and inputs when such qualification induces learning and is sufficiently adaptable to new technologies (ARVANITIS, 2005; BRESNAHAN; BRYNJOLFSSON; HITT, 2002; FABIANI; SCHIVARDI; TRENTO, 2005; FALK, 2001). However, a high-level of formal education could pose a barrier to absorbing new technologies if rigidity to learn and adapt to new technologies is present and if existing qualification serves as barriers to leave behind routines related to previous technologies. Thus, adapting to new technologies would probably find a more amenable environment in organizations where learning and continuous innovation efforts are part of their culture. Undertaking R&D and workforce training, especially in the use of new equipment and machinery, would then be positively related to the adoption of new technologies (DELERA et al., 2020; PFEIFFER et al., 2016).

Although digital technologies are, from the adoption perspective, a process innovation, R&D activities constitute an essential source of learning, in Cohen's and Levinthal's sense. Performing R&D increases the firm's capacity to identify new opportunities and, more importantly, to mobilize the resources required to absorb new knowledge, even if such knowledge comes from external sources and is embedded into tangible and intangible devices. Moreover, technology absorption demands adapting to the new. So, learning through training is essential to adopting new technologies as employees must learn new procedures, identify, and solve unexpected problems, and properly explore what the new technologies can offer. These arguments support the third proposition: *the probability of moving forward in digital adoption is higher for firms that perform R&D and workers' training and have relatively high workforce qualification*.

The fourth determinant relates to the hypothesis that the firm sector and the competitive conditions and pressures they face may affect technology adoption. Also, higher, or lower diffusion rates depend on whether such technologies are an inherent and central for competition in an industry. The intensity of usage of digital technologies varies across industries. Transport Equipment, Telecommunications, Computers, and Electronics are digital prone, while Food, Beverages, and Tobacco or Mining are digitally lower intensive sectors (CALVINO et al., 2018). Competitive pressure represents an incentive to innovate and adopt new technology (ROBERTSON; GATIGNON, 1986), and concretely ICT as they contribute to strengthen firms' competitive performance (DASGUPTA et al., 1999; HOLLENSTEIN, 2004; KOWTHA; CHOON, 2001). Market competition may spark innovation and the adoption of new technologies in at least in two senses. First, the search for competitive leadership pushes firms towards adopting new technologies. Second, firms get 'contaminated' by the latest technologies adopted by their competitors, especially those competing in broader markets (local and, mostly, external ones). So, firms exposed to international competition should be more inclined to adopt digital technologies (HOLLENSTEIN, 2004; BAYO-MORIONES; LERA-LÓPEZ, 2007). Delera et al. (2020) suggest that, once controlling for firms' innovative behavior and structural characteristics, firms participating in global value chains are significantly more likely to adopt advanced digital technologies. These arguments support the fourth proposition: *export-oriented firms and firms that compete in industries with relative higher digital intensity have a higher probability of moving forward*.

3. The database

The database came from two firm-level surveys, the I-2027 and the I-2030[1]. The first was carried out during the second semester of 2017 and covered 753 firms; the second reached 1,003 firms between November 2019 and June 2020. Two common features mark these surveys. Firstly, firms had to respond about the adoption of digital

[1] I-2027 was carried out in a research project on the potential impacts of emerging technologies in the Brazilian industry (INSTITUTO EUVALDO LODI, 2018). Data collection was carried out by the Brazilian Industrial Board, CNI. The I-2030 survey is part of an on-going investigative work carried out by researchers from UFRJ, UNICAMP and UFF. The survey was implemented by the poll company Vox Populi.

technologies to relate with customers and suppliers and manage production. Secondly, as digital technologies have been around for quite some time and the rate of progress is very fast, firms were asked about what digital solutions were used to perform such business functions, regardless their technology generation.

The path of digital adoption is observed when firms advance from less to more sophisticated digital generations, which requires the understanding and the specification of "generations" of digital solutions. We distinguish four generations of digital solutions (namely, G1, G2, G3, and G4) employed in three business functions (relations with suppliers, relations with clients, and production management) (description in Appendix 1). G1 refers to relatively mature digital solutions usually used for specific purposes. For example, relations with suppliers and clients are carried out through manual or telephone transmissions. G2 refers to solutions with broader applications, allowing for more agile and flexible production processes. Some degree of integration between business functions, such as CAD-CAM, might occur without covering the entire scope of any given function, notwithstanding. The adoption of G2 technologies increases operational efficiency and the quality of products and processes. Transitioning from G1 to G2 does not require significant organizational changes and investments. G3 corresponds to interconnected technologies aimed at integrating different business functions. Firms using G3 technologies usually present a higher level of interaction between supplier and client relations being able to respond to changing supply and demand conditions on real-time. The transition from G2 to G3 requires significant investments in the standardization of data collection processes and management systems. G4 enables an integrated, interconnected, and digitally intelligent organization. G4 technologies are designed to pro-actively support decision-making with the intensive use of artificial intelligence and rely on advanced communication, robotization, sensing, and big data solutions. The increasing technological sophistication implies that moving from G3 to G4 would require equally sophisticated capabilities and substantial organizational changes.

The panel comprises 299 firms and four variables from the surveys: the sectoral digital intensiveness (CALVINO et al., 2018), the engagement in R&D, labor training and sales to foreign markets. Two additional variables were included from the Annual Social Information Database (RAIS): number of employees, used as a proxy of firm size, and, as a proxy of capabilities, the ratio of employees' formal education in STEM (Science Technology, Engineering, and Mathematics) related disciplines to total employees of a firm, weighted by each sector of origin of firms.

The distribution of firms by variable is shown in Table 1. Although the panel is not statistically representative of the diversity of the Brazilian manufacturing industry, the forthcoming analysis can provide strategic insights about the factors behind of the adoption trends followed by firms between 2017 and 2019/20. The panel is composed chiefly of medium-small (35.8%) and medium-large (20.1%) firms, although almost a third is of large companies (28.4%). Most companies operate in medium-low (40.1%) and medium-high (33.8%) digital intensity industries. As for the STEM qualification of the labor force, no clear pattern has been found. More than half of the surveyed companies perform R&D activities (58.2%) and carry out training programs (60.9%). As for trade performance, almost half of the firms have export sales (42.5%).

4. A longitudinal analysis of digitalization in Brazilian firms

4.1 The evolution of digitalization by business functions

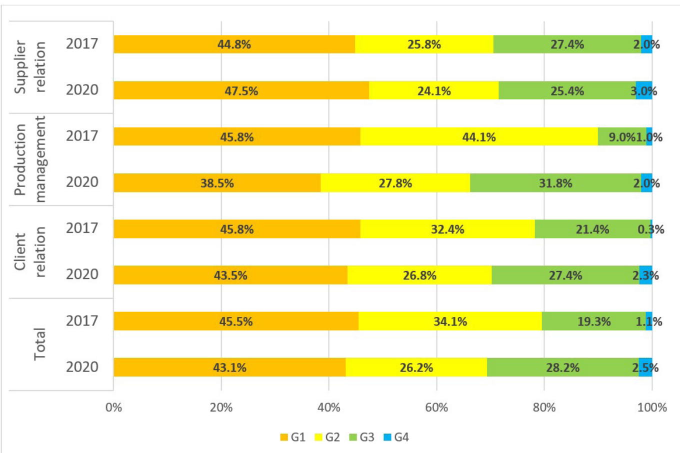
In 2017 and 2019/20, most firms employed G1 solutions, regardless the business functions (Figure 1). When the three functions are bundled, the adoption of G1 solutions slightly decreases from 45.5% to 43.1% of the panel. The usage of G2 solutions also fell but more

TABLE 1
Panel characterization

Size	**Number**	**Share (%)**	**STEM Qualification**	**Number**	**Share (%)**
< 50 employees	47	15.7	Low	85	28.4
50-100 employees	107	35.8	Medium-low	57	19.1
>100 employees	60	20.1	Medium-high	78	26.1
Large	85	28.4	High	59	19.7
			N/A	20	6.7
Digital Intensity	**Number**	**Share (%)**	**Perform R&D**	**Number**	**Share (%)**
Low	53	17.7	Yes	174	58.2
Medium – Low	120	40.1	No	125	41.8
Medium – High	101	33.8			
High	25	8.4			
Perform exports	**Number**	**Share (%)**	**Perform Training**	**Number**	**Share (%)**
Yes	127	42.5	Yes	182	60.9
No	172	57.5	No	117	39.1
Total = 299					

Note: N/A = firms with no available data.
Source: Own elaboration based on the I-2027 and the I-2030 surveys, and RAIS (BRASIL, 2021).

FIGURE 1
Share of firms employing each generation of digital technology to perform each business function, 2017 vs 2019/20



Source: Own elaboration based on data from the I-2027 and I-2030 surveys.

significantly: from 34.1% to 26.2%. Conversely, the share of firms using G3 solutions to perform all business functions increased visibly, from 19.3% to 28.2% in 2019/20. Concerning G4, it also increased from 1.1% to 2.5%. These figures suggest that some level of progress has occurred. However, G1 or G2 solutions remain predominant for two-thirds of all business functions.

Observing changes by business functions, no significant changes occurred in the adoption of digital technologies to conduct supplier relations, despite a slight increase in the share of firms employing G4 solutions, from 2% to 3%. More noticeable changes appeared regarding client relations: the share of firms using G1 and G2 solutions fell almost 22%, and those employing G3 and G4 solutions increased eight percentage points. In production management, only 10% of firms employed G3 and/or G4 solutions in 2017, while three years later, the proportion became one in every three. Therefore, firms-oriented digitalization more to enhance production management and be closer to clients and less so in the relations with suppliers. Optimizing production leads to greater efficiency while being closer to clients ensures that firms adopting more advanced digital technologies keep or even expand market shares in a demand contracting environment.

4.2 The adoption of different generations of digital solutions

The analysis by digital generations brings the results for the three business functions and the 299 firms, which means 897 observations for each possible movement (by firm and function). Rows in Table 2 inform the current adopted generation in 2017 and columns in 2019/20. The diagonal cells represent a digital standstill position in the two periods: cells above the diagonal report firms advancing from lower to higher digital generations. Conversely, cells below the diagonal indicate setbacks from higher to lower digital generations, in time.

Table 2 shows that for 35.6% of all business functions digital solutions remained unchanged (representing the proportion of the

TABLE 2
Changes in adoption by digital generation, 2017 vs 2019/20 (in %)

		Current adoption in 2019/20				Total
		G1	G2	G3	G4	
Current adoption in 2017	G1	21.0	12.4	11.5	0.7	45.5
	G2	14.5	8.4	10.1	1.1	34.1
	G3	7.1	5.2	6.2	0.7	19.3
	G4	0.6	0.2	0.3	0.0	1.1
	Total	43.1	26.2	28.2	2.5	100.0

Source: Own elaboration based on data from the I-2027 and I-2030 surveys.

diagonal values to total cells), that is, the digital solutions employed in 2019/20 belongs to the same generation of that employed in 2017. Alternatively, 36.5% of business functions present digital progress (values above the diagonal) while in 28% moved backwards (values below the diagonal). In 2017, G1 solutions were present in 45.5% of business functions and decreased to 43.3% in 2019/20. The share of business functions employing G2 solutions also fell, from 34.1% in 2017 to 26.2% in 2019/20. Conversely, an evolution towards G3 and G4 was from 19.3% to 28.2% and from 1.1% to 2.5%, respectively.

About 80% of all possible movements, either progress, standstill, or regression, are concentrated in G1 and G2. In 2017, 21.1% of total cases were adopting G1 solutions and remained there in 2019/20; 12.4% moved forward to G2; and 11.5% advanced to G3. However, 14.5% of cases using G2 solutions in 2017 returned to G1 later; 8.4% remained at G2; and 10.1% advanced to G3. Movements backwards prevail in firms adopting G3 and G4 in at least one business function. In 2017, 19.3% and 1.1% of all observations used G3 and G4 solutions, respectively; around 12,3% of the business function positioned in G3 in 2012 returned to G1 and G2, 6.2 stand in G3 and only 0,7% advanced to G4. In 2019/20, 0.3% of the observed business functions at G4 moved backward and none remained.

Firms moving forward or at least not changing the levels of digital adoption in time would be expected results, even in the context of a short time span between the two surveys. However, what calls the attention is the fact that, out of 897 observed possible changes in business functions, in 250 cases the digital solution is going to an older generation in 2019/20 compared to the 2017 generation. Three reasons can explain why firms would abandon investments made in favor of old assets. First, if clients or suppliers are not on pair with the newer technologies, firms bring older generation from stock, turn them on, and keep the new ones for future use temporarily in face of demand or supply conditions. A conservative reaction to a hostile and even uncertain framework conditions can be the second one. Anecdotal evidence in both directions was found during the interview phase of the second survey. Finally, for some firms, the perception of firms' representatives could have changed, as the person responding the two questionnaires[2].

4.3 The firms' profile

Table 3 brings detailed comparative results distinguishing firms that advanced, remained standstill, or receded between 2017 and 2019/20 according to the nature of firms (size, sector of origin, the share of STEM qualified employees, engagement in R&D, training, and exports) and the type of movement (advance, standstill, regression). As to firms' profile, the adoption of digital technologies in small and small-medium size firms remained standstill for 37.7% of the observed business functions, whereas their larger counterparts show more business functions moving forward (39.3%). Almost all firms engaged in R&D, training, and exports in the period showed signs of progress in the digitalization of their business functions. In contrast, more than 70%

[2] Assertive conclusions about these possibilities would require supplementing a first round of direct survey with another set of systematic questions to examine the reasons for or the sources of progress, standstill, and backward movements. Another way of going about would be to undertake case studies or focal groups to gather sufficient observations that allow some level of assertiveness concerning the reasons for a certain direction of digital evolution. The on-going research program is planning to move in the latter direction.

TABLE 3
Changes in the adoption of digital technologies according to the profile of firms, 2017 vs 2019/20 (in %)

		% By the nature of firms					% By the type of movement		
		Moving forward	**Standing still**	**Moving backwards**	**Total**		**Moving forward**	**Standing still**	**Moving backwards**
Size	Small-medium & small	33.8	**37.7**	28.6	100		47.7	**54.5**	**52.6**
	Medium-large & large	**39.3**	33.3	27.4	100		**52.3**	45.5	47.4
						Total	100	100	100
R&D	Engaged in	**50.8**	29.1	20.1	100		**81.0**	47.6	41.8
	Not engaged in	16.5	**44.5**	38.9	100		19.0	**52.4**	**58.2**
						Total	100	100	100
Share of STEM qualified employees	Low	**41.2**	33.3	25.5	100		**32.1**	26.6	25.9
	Medium-low	28.7	35.1	**36.3**	100		15.0	18.8	24.7
	Medium-high	**41.0**	34.2	24.8	100		29.4	25.1	23.1
	High	29.4	**40.7**	29.9	100		15.9	22.6	21.1
	N/A	41.7	36.7	21.7	100		7.6	6.9	5.2
						Total	100	100	100
Training	Engaged in	**50.5**	29.7	19.8	100		**84.4**	**50.8**	43.0
	Not engaged in	14.5	**44.7**	40.7	100		15.6	49.2	**57.0**
						Total	100	100	100
Export	Engaged in	**48.3**	31.8	19.9	100		**56.3**	37.9	30.3
	Not engaged in	27.7	**38.4**	33.9	100		43.7	**62.1**	**69.7**
						Total	100	100	100
Sectoral digital intensiveness	Low	32.1	**37.1**	30.8	100		15.6	18.5	19.5
	Medium-low	**38.3**	34.2	27.5	100		**42.2**	**38.6**	**39.4**
	Medium-high	33.3	**37.3**	29.4	100		**30.9**	**35.4**	**35.5**
	High	**49.3**	32.0	18.7	100		11.3	7.5	5.6
						Total	100	100	100

Source: Own elaboration from I-2020 and I-2030 surveys; RAIS (BRASIL, 2021).
N/A: not available.

of the observed business functions of firms that do not perform R&D, training, and exports showed no progress at all, remaining standstill or receding in digital adoption. Concerning the share of STEM qualified employees over total employees, firms operating in low and medium-high sectors improved in more business functions than their peers. The propensities to advance, remain standstill, or recede are quite evenly distributed for firms operating in low or medium-high digital intensive sectors, although progress in digital adoption is slightly more pronounced in medium-low sectors (38.3%). However, almost a half of the business functions of firms operating in high digital-intensive industries move forward in digitalization.

As to the type of movement, the relative distribution of firms gives the relative importance of each variable (advance, remain standstill, or regression). Considering firm size, progress in digital adoption is higher among medium-large and large firms (52.3%). In contrast, smaller-size firms tend to remain standstill or recede in digital adoption (54.5% and 52.6%, respectively). Concerning the sector of origin, medium-low and medium-high digital intensity sectors are responsible for a very large proportion of all movements in digital adoption: 73.1% of cases of progress are in these two sectors, 74% of cases of standing still, and 74.9% of cases of recession towards a lower digital generation. Few are the cases of progress, standing still, or moving backwards in low or high digital intensity sectors.

Firms engaging in R&D and training tend to progress more (81% and 84.4%, respectively), whereas firms not undertaking these activities tend to recede in digital adoption (58.2% and 57%, respectively). Advancing in digital adoption is also a feature of export-oriented firms (56.3%), while inertia and receding are widely a feature of non-exporters (62.1% and 69.7%, respectively). Qualification in STEM competences does not offer a clear pattern. Advances are noted in firms with relative low qualification (32.1%), but also among firms with medium-high qualification.

Tables 4A, 4B, and 4C provide detailed results considering the different digital generations and firm profiles according to the

TABLE 4A
Percentage distribution of moving forward cases, from 2017, in all business functions according to the profile of firms (%)

Moving forward	Generation*	Size		Digital Intensity				R&D		Training		Export	
		S-MS	ML-L	L	M-L	M-H	H	Yes	No	Yes	No	Yes	No
327 cases or 36.3% of total cases	G1	**37.0**	**30.0**	9.0	**29.0**	**22.0**	7.0	**52.9**	14.4	**56.0**	11.3	**36.7**	**30.6**
	G2	11.0	20.0	7.0	13.0	7.0	4.0	26.6	4.3	26.9	4.0	18.0	12.8
	G3	0.0	2.0	0.0	0.0	1.0	0.0	1.5	0.3	1.5	0.3	1.5	0.3
	ST	47.7	52.3	15.6	42.2	30.9	11.3	81.0	19.0	84.4	15.6	56.3	43.7

*Firms can move forward from G1 to G2 to G3 only. (ST) subtotals; (S-MS) Small-Medium/Small; (ML-L) Medium-Large/Large; (H) High; (M-H) Medium-High; (M-L) Medium-Low; (L) Low.
Source: Own elaboration based on data from the I-2027 and I-2030 surveys.

TABLE 4B
Percentage distribution of standing still cases (2017 vs 2019/20), in all business functions according to the profile of firms (%)

Standing still	Generation*	Size		Digital Intensity				R&D		Training		Export	
		S-MS	ML-L	L	M-L	M-H	H	Yes	No	Yes	No	Yes	No
319 cases or 35.6% of total	G1	**38.0**	**21.0**	13.0	**22.0**	**22.0**	3.0	14.7	**44.2**	16.9	**42.0**	14.4	**44.5**
	G2	11.0	12.0	3.0	10.0	10.0	1.0	16.6	6.9	16.9	6.6	10.7	12.9
	G3	4.0	**13.0**	3.0	7.0	3.0	4.0	**16.3**	1.3	**16.9**	0.6	12.9	**24.0**
	G4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ST	54.0	45.5	18.5	38.6	35.4	7.5	47.6	52.4	50.8	49.2	37.9	62.1

*Firms can stand still in all digital generations. (ST) subtotals; (S-MS) Small-Medium/Small; (ML-L) Medium-Large/Large; (H) High; (M-H) Medium-High; (M-L) Medium-Low; (L) Low.
Source: Own elaboration based on data from the I-2027 and I-2030 surveys.

TABLE 4C
Percentage distribution of moving backward cases, in 2019/20, in all business functions according to the profile of firms (%)

Moving backwards	Generation*	Size		Digital Intensity				R&D		Training		Export	
		S-MS	ML-L	L	M-L	M-H	H	Yes	No	Yes	No	Yes	No
251 cases or 28.0%	G2	**28.0**	**24.0**	12.0	**18.0**	**19.0**	3.0	17.5	**34.3**	16.7	**35.1**	14.3	**37.5**
	G3	**24.0**	19.0	7.0	**18.0**	**16.0**	3.0	22.7	21.5	**24.3**	19.9	14.7	**29.5**
	G4	1.0	3.0	0.0	**4.0**	0.0	0.0	1.6	2.4	2.0	2.0	1.2	2.8
	ST	52.6	47.4	19.5	39.4	35.5	5.6	41.8	58.2	43.0	57.0	30.3	69.7

*Firms can move backward from G4 to G3 to G2 only. (ST) subtotals; (S-MS) Small-Medium/Small; (ML-L) Medium-Large/Large; (H) High; (M-H) Medium-High; (M-L) Medium-Low; (L) Low.
Source: Own elaboration based on data from the I-2027 and I-2030 surveys.

adoption pattern observed in all business functions: moving forward, standing still, or moving backwards, respectively. The forward-movement of firms (Table 4A) is observed mostly in business functions of small and medium-sized companies departing from G1 in 2017 and medium large and large companies starting at G2. Sector-wise, firms operating in medium-low and medium-high digital intensity industries showed propensity to move away from G1. More than half of the observed cases of firms advancing from G1 and almost a quarter of those moving forward from G2 carried out R&D and training activities. The propensity to move forward from any initial generation adopted in 2017 is always higher among export-oriented firms.

Table 4B provides information about firms not changing digital generations between 2017 and 2019/20. Remaining at G1 is a characteristic of small and small-medium size firms; little difference is found among those firms departing from G2, whereas the evolution from G3 to G4 is more pronounced among the largest group. The propensity to remain at G1 or G2 is distributed in the same order of importance among medium low and medium high digital intensity industries (22.0% and 10.0% each, respectively). Main differences are observed among firms that do and do not engage in R&D, training, and exports: in the standstill group approximately half comes from firms not performing these activities.

Finally, Table 4C brings information about firms' digital backward movement. Setbacks are concentrated in the G2 and G3 generations with a relatively even distribution in the business functions of firms of all sizes, although more prominently the medium-low ones (52.3%). The backward movement also cuts across sectors, regardless of their digital intensity, with a relatively higher weight for medium-low digital intensity. About one third of the firms that move backward are not engaged in R&D and training activities. Regarding performance, about 70% of receding companies are not exporters and most of them regraded from G2.

5. Factors affecting the adoption path of digital technologies

5.1 The hypothesis and the model

The empirical equation that tests the proposed hypotheses departs from the specification of the usual β-convergence models, where the growth rate of a variable (Δy) depends on its value at an initial moment (y_0) and the growth of other associated variables (DE LA FUENTE, 2002). When β_0, the parameter associated with y_0, takes a negative value, the convergence hypothesis is confirmed. That is, economic agents at a delayed stage of development are more likely to have more ground for growth compared to those at more advanced stages. In terms of digital adoption, the dependent variable (Δy) represents the rate of change in the adoption of digital technologies between 2017 and 2019/20. To test the proposed hypotheses, equations included three sets of variables: (T) for technological variables; (O) for organizational variables; and (E) for environmental or market related variables, as follows:

$$\Delta y = \alpha + \beta_0 y_0 + \beta_1 T + \beta_2 O + \beta_3 E + \in \quad (1)$$

As the expected outcomes and the independent variables are categorical, the usual OLS model cannot be applied. Therefore, the empirical estimation follows an ordered logistic regression (WILLIAMS, 2016). The logistic regression is a consensually accepted as a methodological strategy for survey-based data and categorical variables. The ordered version of logistic regressions is applicable when a relative ordering of known response values is available, but the exact distance between them is unknown. By using a logistic function, this method estimates the probability of an outcome variable being associated with independent variables (either categorical or continuous). Thus, the logistic function estimates the likelihood of occurring a specific event associated with the categorical response variable (LONG; FREESE, 2006, 2014).

The ordered logistic regression (proportional odds model) is a special case of general ordered logistic models (partial proportional model). Considering an outcome with $j = M$ categories, where i means each independent variable and α_j represents the intercept correspondent for each category, the basic proportional odds model is specified as follows (AGRESTI, 2002):

$$P(Y_i > j) = \frac{exp(\alpha_j + X_i\beta_j)}{1 + [exp(\alpha_j + X_i\beta_j)]}, j = 1, 2, \ldots, M - 1 \quad (2)$$

Where $(M - 1)$ equations are simultaneously simulated with $(M - 1)$ coefficients. For the specific case of ordered logistic (proportional odds), the betas are the same for each j.

From a path-perspective, the model aims to estimate the probability of digital adoption advancing under the influence of the considered technological, organizational, and environmental variables. Equations 3 and 4 were derived from Equation 2 to test all propositions:

$$P(\Delta G_0 > 0) = f(G_{0-17}, s, l, i) \quad (3)$$

$$P(\Delta G_0 > 0) = f(G_{0-17}, r, t, x) \quad (4)$$

The specification of the empirical Equations 3 and 4 corresponds to the best adjustment of the model considering that some of the variables could be correlated (the lowest AIC i Akaike Information Criterion) and the best-fitted model. A deviance test was used to select them all. The estimated coefficients display the expected change in log odds in response to a unit increase in each independent variable (LONG; FREESE, 2014). When the odd ratio is higher than one, the exposure of a specific independent variable is associated with higher odds of outcome, and the opposite is verified.

In both equations, the endogenous variable is the variation of current digital adoption between 2017 and 2019/20 (ΔG_0). Since the model is categorical, this variable will take values [1,2,3] when a firm recedes in digital adoption, remains in the same digital generation, or moves forward, respectively[3]. However, to simplify, ΔG_0 was transformed into a dichotomic variable, assuming a value [1] if the firm remains standstill or recedes; or [2] if the firm advances for another digital generation in the second survey compared to the first one. Moreover, in both equations, the generation adopted in 2017 (G_{0-17}) corresponding to the initial digital generation adopted to perform each business function, takes the values [1,2] when the firm reports being in generation 1 or 2 and in generation 3 or 4, respectively. The exogenous variables reported in the 2019/2020 survey are the following:

In Equation 3: firm size (s), STEM qualification of employees (l), and sectoral digital intensiveness (i). Size is a dummy variable divided in two ranges: small and medium-small firms (code 0) and medium-large and large firms (code 1). The variable for qualification of the labor force (l) takes the values [1,2,3,4] depending on the proportion of STEM educated employees to total labor force firm: low, medium-low, medium-high, and high levels, respectively. The sector digital intensiveness is divided into four categories: (1) low, (2) medium-low, (3) medium-high, and (4) high.

- In Equation 4: if a firm engages in R&D or not (r), values are [1,0], respectively; if it promotes training programs or not (t), values are [1,0], respectively; and if it exports or not (x), values are [1,0], respectively.

5.2 Results

The results concerning the odds ratio (significant at 1% level) indicate that, for firms that already employed solutions of more advanced digital generations to perform any of the business functions, the odds of advancing to a higher digital generation decrease almost 50% from 2017 to 2019-20, everything else held constant (Table 5). Such a result confirms proposition 1: firms that adopt more advanced

3 Equations were run with 897 observations, representing the adoption of digital technologies in three business functions by 299 industrial firms.

TABLE 5
Ordered logistic regression results: Equation 3

Variables	Odds Ratio	Std. Err.	z	P>z	[95% Conf. Interval]	
Current_ Adoption_2017	0,496648	0,0839501	-4,14	0.000***	.3565884	.6917198
Size	1,33808	0,2027869	1,92	0.055*	.9942185	1,800869
Digital Intensity: contrasting with low digital intensity						
Medium-Low	1,174069	0,2480338	0,76	0.447	.7760122	1,776308
Medium-High	0,940225	0,2082944	-0,28	0.781	.609059	1,1451457
High	2,171465	0,6559755	2,57	0.010***	1,201197	3,925467
Skill level: contrasting with low skill						
Medium-Low	0,5626376	0,1217864	-2,66	0.008***	.3681128	.8599566
Medium-High	0,9720233	0,1824165	-0,15	0.880	.672875	1,404168
High	0,630548	0,1350863	-2,15	0.031**	.4143429	.9595695
Intercept	0,0162819	0,3711691			-.7111962	.7437601

Notes: (*) significant at a 10% level; (**) significant at a 5% level; (***) significant at a 1% level. The overall p-value of the model was 0.0000.
Source: Own elaboration based on data from I-2027 and I-2030 surveys.

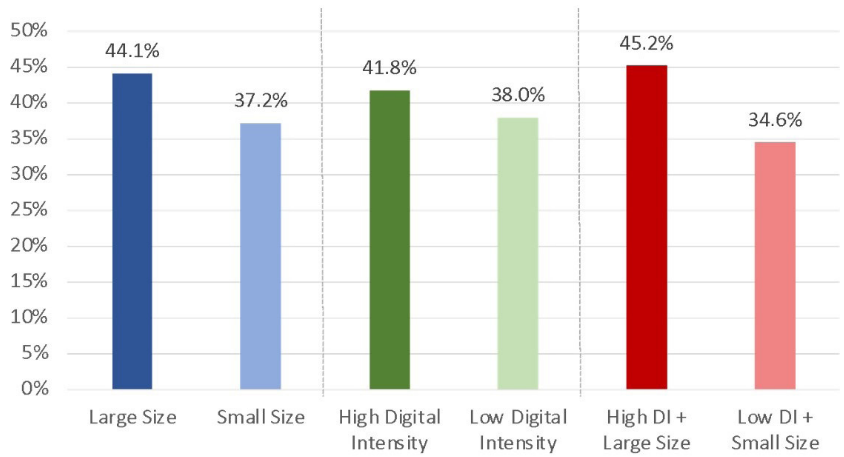
digital generations in 2017 are less likely to move forward, because they are already closer to the digital technological frontier. Results for firm size and sector of origin were also significant: being a large firm increases in 33.8% the odds of moving forward in digital adoption from one period to the other, all else constant. Operating in a digital-intensive sector increases by 117.1% the likelihood of adopting more advanced digital technologies to perform any business functions. These results confirm propositions 2 (size matters) and 4 (sector of origin and engagement in exports matter).

Table 5 shows that a high share of STEM-educated employees decreases the odds of a firm moving forward between 2017 and 2019/2020 by 37%. Such a result challenges part of our third proposition. Even though having highly qualified employees are undoubtedly a strategic asset, formal education does not ensure the effectiveness of operational skills in the use of digital technologies. In this sense, and as the data shows, even firms with a lower share of STEM-related educated workforce could move forward in digital adoption if employees are provided with appropriate operational training.

Figure 2 provides evidence confirming the likelihood of 2017 G1 or G2 users moving towards G3 and G4 in 2020. It also combines such evolution with size and sector of origin of firms. Larger firms have a 44.1% probability of performing business functions with digital G3 and G4 solutions by 2020, in contrast to a 37.2% probability for smaller-size firms. Sector-related differences are not as significant: a 41.8% probability for high digitally intensive activities compared to a 38% probability for low digitally intensive sectors. These determinants of digitalization become even more pronounced when firm size and sector of origin are jointly considered. Figure 3 shows that firms of larger size and belonging to high digitally intensive sectors are more likely to move from G1 and G2 in 2017 to G3 and G4 in 2019/2020 than their smaller size, low-digitally-intensive-sector peers (45.2% versus 34.6%).

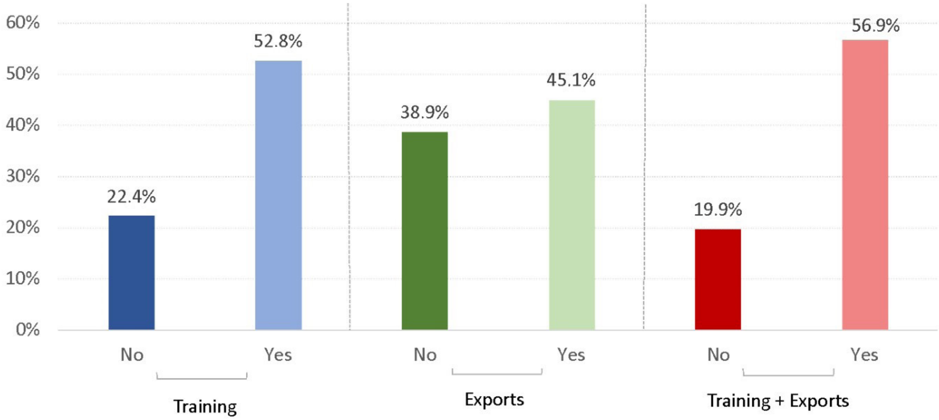
Equation 4 includes variables related to R&D activities, workforce training, and exports. The current digital generation adopted in 2017 has the same effect that in Equation 3, confirming proposition

FIGURE 2
Probability of 2017 G1 and G2 users advancing in 2019/20 according to the profile of firms: Equation 3



Source: Own elaboration based on data from I-2027 and I-2030 surveys.

FIGURE 3
Probability of G1 and G2 users (engaged in training and exports, or not) advancing to G3 and G4: Equation 4



Source: Own elaboration based on data from I-2027 and I-2030 surveys.

1 once more. The positive effects of engaging in R&D on moving forward (a 58.9% increase in the odds) were not statistically significant. This result partially rejects proposition 3, which could mean that R&D is not as relevant as intuitively expected for advancing in digital adoption (Table 6). However, it could only be a consequence of the best adjustment to the model. Providing training is statistically significant and exerts a strong positive effect (around a 300% increase) on the odds of firms moving from lower to higher digital generations in the 2017-2019/20 period. This result confirms proposition 3. Finally, being an exporter influences positively and significantly digital adoption, confirming proposition 4. Among export-oriented firms, the odds ratio of moving forward to more advanced digital generations increases by 34%, everything else held constant.

Additional exercises were carried out to examine more thoroughly whether combining the two most outstanding variables (engagement in exports and training) positively affect firms' digitalization drive. Figure 3 shows that being an exporter and providing training increases firms' probability of moving forward from G1 or G2 to G3 or G4 by just about 57%.

TABLE 6
Ordered logistic regression results: Equation 4

Variables	Odds Ratio	Std. Err.	z	P>z	[95% Conf. Interval]	
Current Adoption_2017	0.3821444	0.0683334	-5.38	0.000***	0.2691655	0.5425448
R&D	1.588728	0.5205435	1.41	0.158	0.8359016	3.019563
Training	4.001667	1.35538	4.09	0.000***	2.060325	7.77224
Exports	1.350784	0.2389716	1.70	0.089*	0.9549864	1.910622
Intercept	0.7149326	.2601902			0.2049691	1.224896

Notes: (*) significant at a 10% level; (***) significant at a 1% level.
Source: Own elaboration based on data from I-2027 and I-2030 surveys.

6. Concluding remarks

The objectives of this paper were twofold: examine the digital adoption path for a panel of Brazilian manufacturing companies between 2017 and 2019/20 and determine the influence of technological, organizational, and environmental/market-related features of firms on the perceived evolution. This type of exercise is scarce in the literature, which makes this experiment a novelty with some words of caution: the 299 firms interviewed in both periods do not represent, statistically, the Brazilian manufacturing industry. Nevertheless, the variety of firm profiles in this panel does find some resonance on the standing diversity of this industry. Results cannot be extrapolated but can certainly suggest different realities exist, so academic, businesses and public policy discussions about such an economically relevant phenomenon must not take it for granted. Variety prevails and only through analyzing variety can the required substantial knowledge for the debate be generated.

The 299 Brazilian manufacturing firms informed that 35.6% of all surveyed business functions remained in the same digital technology generation; 36.5% moved to more advanced solutions; and 28% receded to less-developed digital generations. This evidence reveals that technical progress within firms is not unidirectional. Factors related to an unfavorable economic environment, the hurdles involved in the adoption of new technologies, and even the respondents' perception may compel corporate decision-makers to move forward, stay put, or even abandon certain technical solutions to perform a given business function. More research is certainly needed on this subject.

By 2017, firms performed around 20% of all business functions with the support of G3 and/or G4 digital technologies. Three years later, that share increased ten percentage points. This is a significant progress. However, this panel of firms still has a long road towards digital progress: two-thirds of all surveyed business functions were still performed using localized or partially integrated digital solutions (G1 or G2). Moreover, considering each business function separately, advances in digital adoption were more pronounced in production management. Client relations are in the same path. This evidence suggests that the adverse economic environment and the fast rate of technological change have led Brazilian manufacturing firms to prioritize internal housekeeping and strengthen forward-oriented relations with clients, along their value chain. The perception that firms could extract more value from adopting more advanced digital solutions to perform such business functions might be the main reason behind such strategic orientation.

The econometric results confirm most propositions put forward about the technological, organizational, and environmental determinants of digital adoption. A more lagged initial adoption (G1 and G2) determines a higher probability of moving forward, while staying put or backtracking were more frequent for those in advanced positions (G3 and G4). Concerning organizational determinants, the larger the firm size, the higher the probability of adopting more advanced digital generations, regardless of the business function performed. Results related to STEM-related qualification of the labor force were not significant, suggesting that formal education *per se* is not sufficient to push firms forward in digital adoption. Conversely, providing training is a quintessential requirement for firms willing to seize opportunities derived from digital technologies. At least for the sake of digital adoption, labor training is more important than promoting R&D, although the latter also has a positive but less significant effect. This result is expected given that digitalization is a matter of using technological innovations and not producing them. As users, firms must learn by training, rather than by searching for new ways of doing things through formal research. Finally, concerning market or environmental conditions, the more digital intensive the sector is and the more engaged in exports the firm is, the higher the probability of digital progress, because it subjects firms to higher competitive pressure and allows them to observe the digitalization strategies of their rivals. Market conditions stimulate the contagion effects and increases the probability of firms moving forward in digital adoption.

Findings revealing changes in digital adoption and the relative importance of technological, organizational, and environmental determinants were quite robust. However, these results must be interpreted against the Brazilian economic conditions. Decisions involving investments in digital technologies are certainly affected by the economic context. When uncertainty is high, the expected *ex-ante* assumption is that investments in digital technologies would be at the minimum. Indeed, about a third of the panel declared no change in the adoption pattern, another third backtracked, and, surprisingly, the other third indicated positive progress in digital adoption. These results confirm that firms differ from one another, as proposed by the Schumpeterian literature and even more so amidst economic uncertainty: decision-makers do not act convergently, in unison. Even against all odds, some firms seize opportunities to increase their competitive advantages. Large firms from digital intensive sectors and especially those engaged in exports and labor training have been more "digitally progressive" compared to their peers.

The multidirectional variety of digital progress and the diversity of firm features found in this experimental longitudinal analysis opens an instigating research and policy agendas. Firstly, one needs more evidence to confirm and/or generalize which propositions will stand. Secondly, framework conditions must be systematically incorporated into further research; the role played by respondents' perceptions must also be assessed. Thirdly, the longitudinal approach can be improved by incorporating a foresight, future-oriented perspective. Fourthly, to ensure a better understanding of such complex phenomenon and contribute to the policy debate, future research must address the consequences of digital adoption variety and diversity of determinants defining whether firms progress, standstill, or backtrack. It is necessary to test whether windows of opportunities still exist for a wider diffusion of digital progress in the Brazilian industry.

As the most relevant driving forces behind digitalization lies within the realm of behavioral determinant factors, one possible scenario would be to let the digitalization process of Brazilian companies to its own fate, with the risk of unknown, but probably, sub-optimal outcomes. Alternatively, it is necessary to investigate, based on solid evidence, the extent to which challenge-oriented, concerted public and private actions towards digitalization can be designed to foster the productive development of the Brazilian manufacturing industry.

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APPENDIX 1
Description of the generations by firms' funcions

Relationship with Suppliers
G1 - Transmission of orders manually: use of telephone, fax or email and the like
G2 - Transmission of orders by electronic means: use of EDI (Electronic Data Interchange) and similar
G3 - Computerized support of purchasing, inventory, and payment processes: use of purchasing and relationship portals, electronic catalogues, ERP for the integration of supplier management and similar
G4 - Real-time monitoring of orders and supplier logistics: use of Web services, with support of Artificial Intelligence and use of Big Data Analytics Real-time monitoring of orders and supplier logistics: use of Web services, with support of Artificial Intelligence and use of Big Data Analytics
Production Management
G1 - Simple (rigid) automation with unconnected machines, i.e., using machines that operate in isolation, e.g., CNC (Computer Numerical Control) and similar machines.
G2 - Partially or fully automated process, that is, it uses PLC (Programmable Logic Controller), Robots and similar.
G3 - Integrated process execution systems, ie, it monitors the orders and activities performed together, as well as the flow of materials, exemplified using MES (Manufacturing Execution System); AGV (Automatic Guided Vehicles); Unit identification of products (RFID, QR Code etc.); Control of production in a fully electronic medium ("paperless"); mobile devices in production control and similar.
G4 - M2M Communication (Machine-Machine), that is, it makes dynamic management of the production system in real time with the possibility of exchanging information between machines and between machines and components, via, for example, the use of individual digital model of the products (digital twin) ; Sensors with real-time data collection and adjustments; M2M communication; Collaborative robots; indoor GPS; Augmented reality; Additive manufacturing for final components and the like with the support of Artificial Intelligence and use of Big Data Analytics.
Relationship with Customers
G1 - Execution of contacts and records manually: e.g., using telephone, fax, or email and the like.
G2 - Sales force automation using customer databases, i.e., contact and action record; support for sales processes), such as CRM (Customer Relationship Management) and similar.
G3 - Internet-based integration and support system, with integration of web channels; support for mobile sales force; integration with social networks; data analysis support), exemplified using integrated CRM for multiple channels; mobile devices; Data Analytics and similar,
G4 - Customer lifecycle monitoring and management through connected devices to collect and analyze product and service usage data, such as the use of Sensors to collect data on products/services; Internet-connected products/services; Analysis and offer of services with support of Artificial Intelligence and use of Big Data Analytics.