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ARTICLE
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Chasing the rainbow: towards an experimental methodological framework for the assessment of digitalisation at the firm level

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ABSTRACT

This paper proposes a methodological framework for assessing the adoption of digital technologies by industrial firms. Given the increasing economic importance of digital technologies, proper assessment methods are required. However, evaluating digital adoption can be quite challenging due to the pervasiveness, intangibility, and fast progress rate of such technologies. The proposed framework is designed to enable three tasks: (i) registering information about current and prospective adoption of digital technologies by industrial firms, (ii) developing indicators to capture the dynamics of digital adoption in time; and (iii) analysing digitalisation determinants, requirements, and outcomes. This paper contributes to building a reference framework to evaluating how digital technologies can strengthen the industrial development of nations, particularly developing countries.

KEYWORDS | Technical progress; Digitalisation; Industry; Survey; Analytical framework

1. Introduction

The objective of this article is to propose an experimental methodological framework for the assessment, through direct surveys, of the adoption of digital technologies by industrial firms, the related requirements, determinants and outcomes. Guiding the construction of such a framework are the following research questions: in any given economic environment, what is the current and expected levels of adoption of digital technologies? What are the main features of more and less digitally advanced firms? Do all firms move congruently, or do firms differ from one another in the pace of adoption of digital technologies? What are the potential competitive and policy implications of digital adoption[1]?

In line with the Oslo Manual, digitalisation is defined as the application and use of digital technologies by firms to run and improve business functions (ORGANISATION FOR THE ECONOMIC COOPERATION AND DEVELOPMENT, 2018). Digitalisation does not refer only to the adoption of information and communication technologies (ICT); it relates to a process in which integrated, interconnected, and increasingly intelligent devices potentially changes organisational models, competitive advantages of firms, and even market structures.

Assessing digitalisation at the firm level is of paramount importance for its increasing economic significance. However, given its fast pace of technological change, as Zolas et al. (2020, p. 3) noted, the "measurement of technology use at the firm-level has lagged considerably." At least three features of digital technologies impose conceptual and methodological challenges to intended assessments:

- Digitalisation results from the convergence and blending of various tangible and intangible technologies.

[1] The framework to be proposed is designed to be applied to any firm, belonging to any manufacturing sector, in any national context. For that it has to have an evolutionary character and be sufficiently flexible to capture different nuances and possibilities of digital adoption by firms. It is the analysis of the evidence to be collected from a survey that will reveal the stage of development and the related differences among firms, sectors and countries.

- Digital solutions are applicable to all business functions of firms, from any economic activity.
- Firms may employ, simultaneously, devices of different digital generations, with positive economic returns.

Conducting surveys requires capturing such an elusive phenomenon through questions that must be understandable and answerable by representatives of firms. Answers are represented as variables and variables translated into meaningful indicators for economic analysis. For that, a robust analytical framework is required.

Accounting systems of business and statistical offices have made significant efforts towards assessing digitalisation, and promising results are emerging. Still, such a phenomenon is yet to be systematically apprehended. As methods and procedures are still at a developing stage, this paper argues that, presently, assessing digital adoption is an approximation exercise towards elusive and moving targets. Hopefully, the accumulation of experiences will eventually form the bases upon which reliable, standardised measurement, and assessment procedures will emerge.

With these words of caution, this paper convenes theoretical contributions, from an applied economic perspective, and the experience of different institutions engaged in developing assessment frameworks or carrying out direct surveys to firms. These provide inspirations for the proposal of an experimental method for estimating the adoption of digital technologies by industrial firms and for the analysis of determinants, requirements, and outcomes of digitalisation. The ideas put forward are derived from investigations carried out in Brazil and other developing countries (INSTITUTO EUVALDO LODI, 2018; FERRAZ et al., 2020; ALBRIEU et al., 2019; KUPFER; FERRAZ; TORRACCA, 2019; UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION, 2020).

The key concepts for the design of surveys are discussed in the next section. Then a review of assessment practices is carried out. The survey framework, the derivation of indicators, and the suggestions for an analytical framework come next. Final considerations close the paper.

2. Conceptual references

The objective here is to discuss and bring to fore key conceptual issues that must be considered in the design of an experimental framework for the analysis of digitalisation processes at the level of industrial firms. Four topics are discussed to provide a leading thread for the latter sections: the essential nature of digital technologies; how wide the digital adoption within and among firms can be; the capability-related requirements for an effective adoption and, in the face of the rapidly changing nature of digital technical change, the importance of perceptions and expectations in business decision making processes.

2.1 The nature of digital technologies

Digital technologies are pervasive or general-purpose technologies that can be considered as a generic technical base supporting every economic activity (ROSENBERG, 1982; GAMBARDELLA; TORRISI, 1998; CANTNER; VANNUCCINI, 2017). Along an evolutionary trajectory, they entail a specific pattern of problem-solving heuristics: the manipulation and processing of increasing amounts of information (DOSI, 1982; NELSON; WINTER, 1982).

Digitalisation results from the convergence and blending of soft and hardware devices (SILVA NETO; BONACELLI; PACHECO, 2020; ORGANISATION FOR THE ECONOMIC COOPERATION AND DEVELOPMENT, 2018). The rate of technical progress has been even more pronounced with the emergence of the internet and integrated systems capable of capturing, processing, storing, and communicating vast amounts of data. As advanced digital solutions increasingly embed intelligence to discern, decide, and initiate actions, either preventively, operationally, and/or correctively the transformational potential of digitalisation increases (INSTITUTO EUVALDO LODI, 2018). The fast rate of cost reduction (per unit of output of digital devices), the high elasticity of demand and the significant increase in supply of digital

products and services, the very wide extension of possible applications and the potential scalability of digital devices open possibilities for a vast diffusion process in an economic system and define a very significant impact these technologies can bring about.

2.2 Digital technologies inside the firm

Identical twin firms do not exist; diversity or heterogeneity prevails (NELSON, 1991). Diversity is revealed by differences in strategic orientation, internal structure, organisational routines, style of relations with clients and suppliers, not to mention structural features such as size, ownership, and location. Thus, differences in capabilities and performance, within or among firms, even those operating in the same sector, are key features behind the dynamics of market competition. As Dosi and Nelson (2010, p. 100) argue,

> [...] straightforward candidates for the explanation of the differences in corporate performances are in fact (i) differences in the ability to innovate and/or adopt innovation […], (ii) different production efficiencies, (iii) different organisational arrangements, and (iv) different propensities to invest and grow.

The concepts of diversity or heterogeneity can also be applied to the adoption of digital technologies. Every firm will adopt technology devices in areas or business functions considered relevant by decision-makers.

Firms can employ digital solutions to perform any business function, including those beyond the firm's borders, such as relations with clients, suppliers, and stakeholders. Digital solutions provide operational flexibilities to firms, making changing technical and operational parameters fast. They can ease, even partially, process rigidities, from research to design, production, and delivery activities, and also increase and diversify a firm's capacity to meet changing demands of suppliers and customers (INSTITUTO EUVALDO LODI, 2018). In addition, digital solutions, such as artificial intelligence and

augmented reality, allows virtual simulations of product, production, and market environments, expanding the potential efficiency of research, development, testing, and marketing. By increasing the digital component of products, firms can move away from being mere product and device providers to become providers of "solutions" adjusted to clients' needs. This phenomenon is called servitisation or servicification (BAINES et al., 2017).

However, as digital technologies have been around for more than half a century, in practice, it is very likely that devices from different technological generations, such as CAD and computers, coexist in each firm. Docampo Rama, Ridder and Bouma (2001) even estimate that a dominant technology can "survive" for a period ranging from 15 to 30 years.

Thus, just as innovation capabilities of firms differ, digital capabilities and corresponding results also do so. In time, if the adoption of digital devices is more effective to certain firms, their capacity to grow and prosper will increase relatively to those lagging behind, and the distance between the two groups will become more pronounced. At country level, especially developing nations, one could argue along similar lines: a differentiated rate of diffusion within a given digital user population, may reinforce prevailing structural heterogeneity, as argued by Coutinho (2023).

2.3 The adoption process and the related digital capabilities

Digital technologies have an extensive and an integrative dimension: devices can be applied in one specific operation, or they can reach all operational areas with different intensities. For example, the percentage of operations monitored by sensors can be high or low or, in the case of external relations, many or a few suppliers can be linked up in real time with a firm. In other words, a given administrative, or production task, function or area of a company may be covered in different proportions by digital solutions (FERRAZ; RUSH; MILES, 1992). The "intensity" of digitalisation, thus, varies within a firm and among firms.

The more extensive and intensive the adoption of digital devices is, the more likely they may induce transformations in business and organisational models, enhance firm competitiveness and even change market structures. That is an overarching and effective process of digitalisation can boost value creation, leading to superior market performance while, at the same time changing the determinants for competitiveness (PORTER; HEPPELMANN, 2014). In short, the economic relevance of the adoption of digital technologies is defined by "how much" coverage such devices provide to a firm: the higher the intensiveness and the more integrated the different areas are, the more benefits are likely to be accrued (INSTITUTO EUVALDO LODI, 2018).

Effective digital adoption does not come naturally or immediately when technology is introduced and put into use. Just as any other process of technology adoption, effectiveness involves strategic decisions and investments and depends on the ability of a firm in mobilising capabilities to respond to changes and maintain or create competitive advantages (NELSON; WINTER, 1982). Adopting digital solutions of a certain sophistication level requires mobilising equivalent sophisticated capabilities embedded in labour force skills, organisational routines, stocks of information, to fully use the selected solutions and build a projected future (ANDREWS; NICOLETTI; TIMILIOTIS, 2018).

Moreover, the potential of technologies and the required capabilities to effectively use them do not evolve linearly from one digital generation to another. Evolving from an older digital generation to an advanced one for the performance of similar tasks - for example, product design - is a non-linear process. Evolution is not a matter of adding up 'units' of assets; technologies may have superior levels of sophistication over existing generations which will require entirely new capabilities for their proper usage.

2.4 Perceptions and expectations in a context of rapid technical change

Digital adoption in the face of rapidly changing technologies impose challenges for firms When to adopt which digital generation?

What are the capabilities implications? What advantages may be accrued: When to invest in which digital solution? At the level of firms, as digital technologies are constantly and dynamically changing, it is very unlikely that decision making processes are solely constructed based on trustworthy and permanently valid information base. Accumulated tacit knowledge and experience, perceptions of which are the possible requirements and benefits and expectations about future prospects also contribute to the decision processes of firms.

For questions posed by analysts (how to capture evidence and make analytical sense of moving targets?), as the next section will further demonstrate, standardised and objective indicators of processes of adoption of digital technologies do not exist in current accounting systems, administrative registries and survey practices by statistical offices of nations. Thus, to a great extent, academic scholars, consulting organisations, policy-related institutions and statistical offices rely on information (perceptions and expectations), about business digitalisation practices, provided by qualified representatives of firms, as it will be seen in the next section.

Perception is the ability to be aware of something and the way of regarding and understanding things. It depends on how individuals register and interpret things, apprehend, and represent information, and is shaped by their memory and learning abilities (SCHACTER, 2011; GREGORY, 1997). Research on technology diffusion often uses the concept of perception to examine how much usefulness a given technology may have in the eyes of decision-makers and then translated into intentions, investment decisions, resource allocation, ending up in the actual adoption of new devices (CHIAN, 2010; KOUL; EYDGAHI, 2017).

The changing nature of digitalisation also asks for an evolutionary approach to be built in assessment exercises. For that, a dynamic time reference could capture interesting nuances of the process of technology adoption by firms. That is, survey-oriented exercises should try to pose questions not only about the current digital adoption practices by firms, but also about the perspectives for the future. This means that the empirical base for digital assessment exercises should be constituted

by the perceptions about current usage and the future expectations of digital adoption by qualified representatives of firms.

Expectations are beliefs that something will happen or be the case in the future. According to Rosenberg (1982), expectations and behaviour of business leaders towards the technological future usually differ among firms due to uncertainty and risk aversion. However, as the economic literature has not given sufficient attention to the study of expectations in technology diffusion processes, he calls for studies to highlight entrepreneurs' expectations towards adopting fast or slow-changing technologies. Drawing from history, he argues that business owners may withdraw from adopting rapid-changing technology based on a perception that future improvements are likely to continue 'by extrapolation' of the recent past (being the opposite also true). As technological changes slow down and stabilise in time, confidence in the future builds, leading to the adoption of current technology generations. Balcer and Lippman (1984) attained a similar understanding through a modelling approach.

As inputs to building business strategies and capabilities, expectations are largely influenced by how decision-makers 'read' their technological, competitive, market, and political environments. Thus, the 'grounding' of firms' prospective views becomes necessary when assessing digital adoption. With that purpose, a survey exercise should examine how firms are preparing for the future regarding plans and actions in motion in the present. Firms' current stage of preparation or readiness provides credibility to their expectations involving future digital adoption. The higher the firm expects to forge ahead, transitioning from a less to a more advanced technology stage, the more important current preparedness for such a future is.

3. Digital adoption assessment experiments

This section reviews assessment exercises about the adoption of digital devices by industrial firms from academic scholars, consulting organisations, policy-related institutions, and statistics agencies to identify

the outstanding features of each group's approach to digitalisation, as well as commonalities and differences among them. Each of these quarters has (or at least try to have) a unique approach to the way they conduct their digital adoption assessment. The available and published literature is vast; a systematic review is, therefore, much beyond the scope of this article. Nevertheless, in search of lessons to be drawn up, a selective literature review for each of the above-mentioned groups suffices as the objective is to provide archetypical qualitative evidence on how digital assessments exercises have been carried out.

3.1 Academics

Nylén and Holmstrom (2015) propose a framework for assessing the adoption of digital technologies based on three dimensions: product, environment, and organisation (Table 1). For each dimension, the following elements are observed: user experience and value proposition of products; monitoring the clients' environment and, the organisation skills. The purpose is to support strategic actions of firms to introduce, deploy, and use digital products and services. Special attention is given to how digital devices can support the monitoring of the firm's internal and external environments, the status of operations and the performance of employees, suppliers, and clients. They are also concerned with how firms mobilise the necessary capabilities to use digital innovations effectively.

Such a framework is operationalised in the form of questions posed to qualified business representatives. For example, to define the organisational/skill readiness, representatives are asked whether they agree, partially agreed, or do not agree that continuous learning about the unique properties of digital technologies is actually promoted by the firm. Depending on the score attained, together with other issues (for instance, roles and teams, see Table 1) a set of recommendations are possible to be made.

Based on an extensive literature review, Schumacher and Sihn (2020) put forward 143 key-performance indicators (KPI) in nine

TABLE 1
Nylén and Holmstrom dimensions and topics for assessing digitalisation

Dimension	Topics	Scope	Element
Product	User experience	Digital products and services must offer usability and aesthetic properties designed to evoke user engagement	Usability
			Aesthetic
			Engagement
	Value proposition	Digitalisation implies a value proposition articulated with customer segmentation, including pricing, product portfolio positioning, articulation with sales channels.	Targeting
			Bundling
			Commissions
Environment	Monitoring digital evolution	Digital solutions must enable firms to monitor their environment, by collecting data about marketing channel performance and user behaviour.	Devices
			Channels
			Behaviour
Organisation	Skills	Internal and external skills appropriate to the firm for the intended digital functions, promoting continuous learning on the properties of digital technologies.	Learning
			Roles
			Teams
	Improvising	The flexibility and low cost of digital technologies can provide improvisational experiences.	Space
			Time
			Coordination

Source: Based on Nylén and Holmstrom (2015, p. 61).

dimensions: strategy and leadership; products and customer contact; value creation by employees; employee management; production planning and control; production processes shop floor; logistic processes shop floor; procurement and supplier contact; and cyber security. After experimenting with such a framework on a few cases, the authors argue that their methodology may contribute to increasing management control over digitalisation.

Verhoef et al. (2021) propose three stages of digitalisation, each with related organisational and strategic implications. The stages are (i) spot digitalisation; (ii) integrated digitalisation, and (iii) digital transformation (Table 2).

These academic scholars suggest frameworks for analysing digital adoption by firms, with a focus on the capability requirements to deal with new technologies. They undertake a literature review to extract

TABLE 2
Verhoef *et al.* digitalisation stages model

Type	Examples	Digital Resources	Organisational structure	Digital growth strategies	Metrics	Objectives
Spot Digitalisation	Automated routines and tasks	Digital assets	Standard top-down hierarchy	Market penetration	Traditional Critical Performance Indicators (KPIs)	Efficient deployment of resources to existing activities
Integrated Digitalisation	Addition of digital components to the product or service.	Digital assets + digital agility	Agile and separate units	Market penetration + Platform-based market actions	Traditional and digital KPIs: user experiences	Revenue increase, enhanced customer experience
Digital transformation	Introduction of new business models	Digital assets + digital agility + Big Data Analytics	Separate units with flexible organizational forms	Market penetration + Platform-based market actions + Platform diversification	Digital KPIs: digital participation	New cost-revenue model

Source: Based on Verhoef et al. (2021, p. 892).

and adapt analytical concepts to the context of business endeavours. Their contribution is expressed through classification tables defining, in one axis, capability requirements and, in the other, either stages of development or business areas where these capabilities are relevant. In short, scholars provide inputs for further empirical analysis and guide strategic decision-making. Their common focus of attention is on organisational learning necessary for the business transformation induced by digital devices.

3.2 Consulting organisations

Consulting firms are concerned with providing two types of tools to enhance the capacity of firms adopting digital technologies: stock-taking experiments and business support tools.

IDG conducts worldwide stock-taking surveys to verify whether and how firms use specific advanced technologies (5G, artificial intelligence, internet of things, and others) and the expected outcomes: meeting customer expectations; promoting employees' efficiency; enhancing

performance-based management; generating new revenue sources, etc. Having best practices as generic references, these surveys can reveal possible pathways for firms interested in engaging in digital-related investments (IDG COMMUNICATIONS, INC., 2019).

McKinsey (2019) developed a decision-making support tool, the *Analytics and Digital Quotient*, to evaluate business practices for the effective and value-creating adoption of digital technologies. It encompasses four dimensions (strategy, capabilities, organization, and culture) and 22 practices, shown in Table 3. It attributes values to each practice and compares the results obtained by any given firm to international best practices. Thus, business leaders will know their relative position and draw conclusions on how to move forward. Such framework was used to evaluate 124 Brazilian firms of different sectors. The evidence shows that Brazilian digital leaders follow international best practices and have a better financial performance relatively to their less advanced peers.

TABLE 3
McKinsey's Analytics and Digital Quotient

Strategy	Capabilities	Organisation	Culture
Awareness of change	Digital marketing and sales	Structure	Agility
Long-term ambitions and aspirations	Customer journeys	Collaboration between business practices and technology	Testing and learning
Business and digital strategy	Data and *analytics*	Talents	Experimentation
Customer centrality	Technology platform	Proficiency in analytics and digital	Internal collaboration
Growth opportunities	Focus on value creation	Governance and metrics	External orientation
Firm-specific roadmap			Data-driven mindset

Source: Based McKinsey (2019, p. 5).

PWC (2021) also provides support tools to assess digitalisation. *The Industry 4.0 / Digital Operations Self-Assessment Tool* is an online

platform where a firm can determine its current digitalisation level, according to four stages of digital evolution, in six different business functions and/or activities (Table 4).

TABLE 4
PWC Industry 4.0 Assessment

Function/Stage	Digital Novice	Vertical Integrator	Horizontal Collaborator	Digital Champion
Business models, products & service portfolio	First digital solutions and isolated applications	Digital product and service portfolio with software, network (m2M) and data as key differentiator	Integrated customer solutions across supply chains boundaries; collaboration with external partners	Development of new disruptive business models with innovative product and service portfolio
Market access & customer	Online presence is separated from offline channels; focus on products instead of customers	Multichannel distribution with integrated use of online and offline channels; data analytics deployed	Individualized customer approach and interaction with value chain partners	Integrated customer journey management across all digital marketing and sales channels with customer empathy and CRM
Value Chain & Processes	Digitised and automated subprocesses	Vertical digitization and integration of process and data flows within the company	Horizontal integration of processes and data flows with customers and external partners; intensive data use	Fully integrated partner ecosystem with self-optimised, virtualized processes; decentralized autonomy
IT Architecture	Fragmented IT architecture in house	Homogenous IT architecture inhouse	Common IT architectures in partner network	Partner service bus; secure data exchange
Compliance, Legal, Risk, Security & Tax	Traditional structure, digitisation not in focus	Digital challenges recognized but not comprehensively addressed	Legal risk consistently addressed with collaboration partners	Optimizing the value chain network
Organization & Culture	Functional focus in silos	Cross functional collaboration but not structured and consistently performed	Collaboration across company boundaries, culture, and encouragement of sharing	Collaboration as a key value driver

Source: Based on PwC (2021).

In summary, the primary focus of attention of consulting organisations is to develop tools for strengthening the capacity of decision-makers to perceive where they stand at and paths for their further development. By doing so these organisations intend to meet the needs of their potential clients while expecting to provide better tools than their competitors.

3.3 Policy-related institutions

The German Industrie 4.0 initiative is a policy landmark. It was launched in 2011 to modernise the country's industry, with a focus on the digitalisation of small and medium size firms (PFEIFFER, 2017). Industrie 4.0 proposes and made available resources, consultancy, and technical services to firms, with the support of an assessment tool – *Toolbox Industrie 4.0* –, to identify where they stand and how to move forward (VDMA, 2016). Proposed by the German Engineering Federation (VDMA), this tool covers products and production processes. For each, business functions are associated with solutions technologies can provide, along a sequential development stage. The guide is not a ready-made solution but an information source for decision-making. Table 5 illustrates the functions and the stages of digital development for the production dimension.

The Korea Institute for Industrial Economics and Trade also proposes an instrumental tool for the so-called *Korea Smart Factory Initiative*. Such an initiative aimed at disseminating digital practices to up to 60% of a pool of 67 thousand small and medium size firms until 2025, with the support of government and large corporations. Drawing from the German experience, the Korean model specified four development stages in the management of manufacturing activities (generically defined). Table 6 summarises the Korean German based model.

In 2017, the Singapore Economic Development Board (SEDB) launched the *Smart Industry Readiness Index* as a technical assistance initiative in the support of the country's manufacturing industry,

TABLE 5
VDMA Production Toolbox Industrie 4.0

Function/Stage	I	II	III	IV	V
Data processing in the production	No processing of data	Storage of data for documentation	Analysing data for process monitoring	Evaluation for process planning / control	Automatic process planning / control
Machine-to-machine communication (M2M)	No communication	Field bus interfaces	Industrial ethernet interfaces	Machines have access to internet	Web services (M2M software)
Companywide networking with the production	No networking of production with other business units	Information exchange via mail / telecommunication	Uniform data formats and rules for data exchange	Uniform Data formats and inter-divisionally linked data servers	Inter-divisional, fully networked IT solutions
ICT infrastructure in production	Information exchange via mail telecommunication	Central data servers in production	Internet-based portals with data sharing	Automated information exchange (e.g. order tracking)	Suppliers / customers are fully integrated into the process design
Man-machine interfaces	No information exchange between user and machine	Use of local user interfaces	Centralized / decentralized production monitoring / control	Use of mobile user interfaces	Augmented and assisted reality
Efficiency with small batches	Rigid production systems and a small proportion of identical parts	Use of flexible production systems and identical parts	Flexible production, systems and, modular designs for the products	Component-driven, flexible production of modular products within the company	Component-driven, modular production in value-adding networks

Source: Based on VDMA (2016, p. 9).

TABLE 6
Korea and Germany equivalence of digitalisation levels

Korean Stage	German Level	Implementation
Basic	Lv.1~Lv.2	Basic logistics information collection level using barcode and RFID. Quality history management through lot-tracking. Partial process automation.
Intermediate 1	Lv.2~Lv.3	Real-time data collection from the facility and monitoring. Real-time information exchange based on information management and factory operation.
Intermediate 2	Lv.4~Lv.5	Automation of facility control. Real-time decision making and direct facility control.
Advanced	Lv. 5	Intelligent production with self-diagnostics and control using CPs, IoT, and big data. Real-time customised service through value chain.

Source: Yu (2018).

responsible for about 20% of its GDP (SINGAPORE ECONOMIC DEVELOPMENT BOARD, 2017). The index comprises three dimensions: technology, process, and organisation, and eight pillars,

such as operations, supply chain, connectivity, and talent readiness. These eight pillars represent 16 critical aspects or competencies, such as workforce learning, leadership, and collaboration. In 2019, SEDB launched a self-assessment tool to help firms to define where they stand in relation to world best practices. Assessment scores are meant to support firm-level digitalisation strategies based on cost and revenue considerations and key performance indicators (SINGAPORE ECONOMIC DEVELOPMENT BOARD, 2019).

In summary, the primary concern of policy related institutions is to propose practical tools to identify the stage of digital development of firms, especially those of smaller size. Having best practices as references, these tools specify stages of digital development with two purposes: to enable firms to perceive where they stand at in relation to best practices, to support digitalisation strategies of firms and to provide background information for the design of policies and programmes.

3.4 Statistics related organisations

The statistical office of the European Union (Eurostat) has the longest standing experience in the support of how countries should conduct surveys about the adoption of information and communications technologies (ICT) by enterprises. Their main concern is capturing where a firm stands at in relation to the stage of progress of these technologies. Along the years, reflecting improvements or the introduction of new technologies, questions change. As national surveys have a wide coverage, questions are designed to be answerable by any firm. For that, Eurostat proposes thematic and interconnected modules of questions of two types: (i) Yes/No questions, based on the perception/knowledge of respondents about digital usage; (ii) objective quantitative information such as the percentage of employees using digital devices, speed of internet connection, sales, or procurement over the internet.

Table 7 highlights some of the similar and different questions extracted from the first (2002) and the latest (2021) questionnaires.

TABLE 7
Eurostat community survey on ICT usage and e-commerce in enterprises (*)

2002 Version	2021 Version
% Employees using computers in their normal work routine (at least once a week):	% Employees with access to internet for business purposes
Does your enterprise use or plan to use Internet?	% Employees using a portable device provided by the enterprise
Type of external connection to the Internet in 2001? (Mobile phone, modem, ISDN, xDSL, Other fixed connection) Question range: less than 2 Mbps to at least 2 Mbps.	**Does your enterprise use any type of fixed line connection to the internet? (ADSL, SDSL, VDSL, fiber optics technology, cable technology, etc.)? What is the maximum contracted download speed of the fastest fixed line internet connection? (Question range: Less than 30 Mbps to at least 1Gbps)**
Does the enterprise have a Web site or homepage?	**Does your enterprise have a website?**
	Does your enterprise use social media?
What percentage of the total turnover did Internet sales represent in 2001?	**% Turnover generated by web sales of goods or services, in 2020.**
Breakdown of Internet sales in 2001 by destination (own country, EU, World)	**Web sales to customers located in (own country, EU, World)**
Did the enterprise use EDI or networks other than Internet?	
What percentage of the total sales (in monetary terms) did the sales via EDI or networks other than Internet represent in 2001?	**During 2020, did your enterprise have EDI-type sales of goods or services?**
Problems and barriers related to on-line sales (Much important, some importance, not important, don´t know): Products, customers not ready, security over payments, legal uncertainty, logistics	**What percentage of total turnover was generated by EDI-type sales of goods or services, in 2020?**
	Does your enterprise use ERP software?
	Does your enterprise buy any cloud computing services used over the internet? (Email, office software, finance, database, computing power, etc
	Does your enterprise use interconnected devices or systems that can be remotely controlled via the internet (Internet of Things)? (Energy, security, logistics, maintenance)
	Does your enterprise use any of the following Artificial Intelligence technologies? (Text mining, language Generation, deep learning, robotics, sales)
	Does your enterprise use Artificial Intelligence software or systems for any of the following purposes? (Marketing or sales, production processes, organisation of business administration processes, management of enterprises, logistics, ICT security, human resources management or recruiting)

Note: (*) In bold relatively comparable questions.
Source: Based on 2002 and 2021 Eurostat ICT usage in enterprises questionnaires (STATISTICAL OFFICE OF THE EUROPEAN COMMUNITIES, 2002, 2021).

In 2002, a special focus was placed on e-commerce -purchases and sales via the internet and barriers on e-commerce – and on the use of internet, including the type and speed of connection. Some of these issues remain in 2021, such as the usage of internet and e-commerce, while, at the same time, introducing new questions about three emerging digital technologies: cloud computing services, internet of things, and artificial intelligence. Eurostat approach, then, allows for the appreciation of how firms evolve along the years in few "permanent" issues while constantly updating the questioning to firms about their engagement with new technologies.

Such twenty-year long experience in designing and implementing digitalisation surveys provide an interesting angle to observe the evolution of technical progress, from two perspectives. In one, questions illuminate the progress digital devices allow in a similar function (speed of interconnection, for example). The literature would designate this as "incremental technical change". However, given the exponential progress incorporated in new devices to realise the same function, it is open to questioning whether such classification stands. The case of the speed of transmission of information is exemplary: for internet connection, a similar question was posed along the years: the potential top nominal speed of connection. The reference in questionnaires though increased from 2 Mbps in 2002 to 1 Gbps in 2021. Such an increase leads not only to gains in efficiency; it opens venues for new applications within a similar function. From a second perspective, the surveys bring in emerging digital technologies which can be used to generate new products, services, and processes such as the use of Internet of Things, to open new markets, for example, or the use of sensors to offer clients new shopping experiences. Eurostat surveys, thus, provides valuable insights to be captured in assessment exercises based on the analysis of available data.

United Nations Conference on Trade and Development (2021), member of the Partnership on Measuring ICT for Development (TELECOMMUNICATION DEVELOPMENT SECTOR, 2021), has produced a statistics manual on how to measure and assess different

aspects of the digital economy, such as the production and trade of ICT goods and services, and the usage of ICT in households and businesses. The manual guides the undertaking of surveys, processing data, and disseminating results. It is designed as a working tool for organisations from developing countries, such as statistical offices, with limited budget assigned to economic and social surveys. For that, the proposed survey is based on simple and objective questions concerning: (i) the existence or not of a specific number of digital devices (the use of computers, the type of internet connection and whether an enterprise places and receives business orders through such mean), and (ii) the associated proportion of employees or business transactions involved.

In Brazil, the Internet Steering Committee (CGI.br, the Portuguese acronym), the organisation managing the country's Internet, has conducted surveys on ICT usage by enterprises since 2005, following international standards. Table 8 provides an example about how the CGI survey poses questions. The latest survey was carried out in 2019 and addressed ICT usage in seven dimensions: ICT systems, internet connections, interactions with government agencies, e-commerce, skills, software, security, and new technologies. The survey inquired about the nature of the software applications firms used, whether proprietary or not, and the efforts to customise them according to their needs and circumstances. It addressed ICT-related risk assessment and management, whether firms employ cloud computing, big data, service robots, and 3D printing in different business functions (CENTRO REGIONAL DE ESTUDOS PARA O DESENVOLVIMENTO DA SOCIEDADE DA INFORMAÇÃO, 2020).

In the US, the Census Bureau introduced questions about digital technologies in its 2018 Annual Business Survey. The objective was to gather information about the adoption of specific digital technologies and to profile more and less advanced firms as the "scarcity of firm-level data has been cited as a central bottleneck in developing a better understanding of these technologies' impacts on workers, firms, and market dynamics" (ZOLAS et al., 2020, p. 3). The survey aimed at 850,000 US firms; above 500,000 questionnaires were returned.

TABLE 8
Brazilian ICT enterprise survey: question for companies making use of big data

In the last 12 months, were Big Data analytics undertaken from the following sources of data?	YES	NO
Company data from intelligent devices or sensors, such as data exchanges between machines, digital sensors, radio frequency identification labels, etc.		
Geolocation data from the use of portable devices such as mobile phone, wireless connection, or GPS		
Data generated from social media such as social networks, blogs, or multimedia content sharing sites		
Other Sources of Big Data		

Source: Based on Centro Regional de Estudos para o Desenvolvimento da Sociedade da Informação (2020).

Besides questions on expenditures and the use of specific advanced technologies, a new approach by the US Census through questioning firms about the intensity of the adoption of digital solutions to perform certain tasks or business functions (Table 9) and the intensity of adoption of specific advanced technologies (Table 10).

TABLE 9
An US experiment: intensiveness of adoption of digital solutions in business functions

In 2017, how much of each type of information was kept in digital format at this business? (Select one for each row)						
Business functions/ Intensity	**None**	**Up to 50%**	**More than 50%**	**All**	**Don´t know**	**This type of information not collected by this business**
Personnel						
Financial						
Customer feedback						
Marketing						
Supply chain						
Production						
Other						

Source: Based on Zolas et al. (2020, p. 46).

TABLE 10
An US experiment: intensiveness of usage of specific digital technologies in production

In 2017, to what extent did this business use the following technologies in producing goods or services? (Select one for each row)						
Digital technology/ intensiveness	**No use**	**Testing, but not using in production or service**	**In use for less than 5% of production or service**	**In use between 5% - 25% of production or service**	**In use for more than 25% of production or service**	**Don´t know**
Augmented reality						
Automated guided vehicles						
Automated storage and retrieval systems						
Machine learning						
Natural language processing						
Radio-frequency identification inventory systems						
Robotics						
Touchscreen/ kiosks for customer interface						

Source: Based on Zolas et al. (2020, p. 14).

According to Zolas et al. (2020), results were so promising that the 2021 version of the *Annual Business Survey* was to include a similar technology module. Also, attempts are planned to be made to validate responses against different existing business-related surveys census data on technology usage and to link up the observed results with other sources of administrative data registries, such as patents.

In summary, most surveys from statistics-related institutions place emphasis on the adoption of ICT and pose questions capable to be answered by any firm. With similar approaches, they offer valuable contributions on how to conduct assessments about how firms use digital technologies.

3.5 Summarising assessment experiences

The non-exhaustive review of concepts and survey tools used by different types of institutions informs that scholars, consulting organisations, policy-related institutions, and statistical organisations have undertaken considerable efforts to specify questions to firms about how they adopt digital technologies. All approaches take the firm as a unit of information and quite often questions rely on respondents' perception about the adoption of digital solutions in specific business functions.

The common underlying understanding is that the adoption of digital technologies is a long, complex process that starts with simple devices, introduced in specific business areas, and evolves towards the digital transformation of the whole firm. The different approaches are also based on a similar assumption that digital technologies enhance business management, performance, and value creation. Finally, they all provide assessment tools aimed at supporting firms' plans and actions to move forward their digitalisation strategies, having best practices as references. As such, they offer indisputable contributions for initiatives aiming at conducting comprehensive assessments about how firms use digital technologies.

4. Chasing the rainbow: towards an experimental assesstment framework

An experimental framework for assessing and analysing the adoption of digital technologies by industrial firms is proposed in this

section. Such framework will be constructed along three stages, taking into consideration the conceptual issues raised in the first section: (i) the specification about how to capture the adoption of digital technologies, taking into consideration that different digital generations may exist in different business functions; (ii) the development of synthetic indicators to represent changes over time; and (iii) the design of analytical guidelines to associate indicators of digital adoption to possible determinants, requirements, and outcomes. As mentioned in the introductory section, it is expected that the proposed framework, if further properly applied in a field survey, could provide evidence about similarities and differences, among firms, of levels of adoption of digital technologies, the main features of more and less digitally advanced firms, the requirements and impediments of digital progress and the potential competitive and policy implications of digital adoption, among others.

4.1 The assessment approach: digital generations and business functions

This framework was initially developed for the 'I-2027' initiative - an investigation on the risks and opportunities of emerging technologies for the Brazilian industry, which included a survey about the adoption of digital devices by industrial firms (INSTITUTO EUVALDO LODI, 2018). This approach relies on three conceptual pillars drawn from the reviews of literature and assessment experiences: the specification of generations of digital technologies employed by industrial firms to perform different business functions, in two separate moments of time (present and future), together with the efforts firms were undertaking to prepare for the projected future.

Firstly, the concept of business function designates a set of activities or tasks performed with a broad common end, rather than a department or organisational unit. The three business functions considered – relations with suppliers, relations with clients, and production management – surely do not cover the whole set of

functions of an industrial organisation. Nonetheless, these functions are recognisable and undertaken by any and every industrial firm.

Secondly, it is assumed that digital technologies offer sets of solutions to support the undertaking of discernible business functions. In such a framework, a digital generation is a set of specific solutions, each demanding proper capabilities to its effective usage. The digital solution approach is preferable to avoid the likely limitations of asking firms what device, A or B, employed in a business function. This solution-oriented approach also allows the appreciation of the intensity of digital usage as firms are asked about which digital generation is employed to perform most activities in a business function.

Thirdly, the digital generation framework explicitly considers the dynamics of technical change in time and the possibility of different adoption patterns coexisting among firms. For that the experiment relies on perceptions and expectations of business representatives about current and future (5 to 10 years) adoption of digital solutions. To 'ground' expectations, the approach incorporates questions about the resources currently mobilised to achieve the expected future: doing nothing, starting studies on technologies, planning actions, or implementing digitalisation plans.

As shown in Table 11, each generation represents a stage of development of digital technologies. An evolutive approach from a less to a more advanced generation is taken, starting with an isolated, locally applied solution (generation 1) and ending with the most integrated, interconnected, and intelligent digital solution (generation 4).

4.2 From variables to indicators

Variables extracted from survey questions provide useful information for descriptive exercises. However, to bring economic meaning to the collected data, synthetic indicators must be derived with the support of conceptual propositions and empirical references.

Given the scope of questions proposed, indicators can be designed from four sets of variables: (i) four generations of digital devices (G1 to

TABLE 11
Digital generations in business functions (*)

Digital Generation/ Business Function	Relations with suppliers	Process management	Relations with clients
G1	Manual transmission of orders (e.g., fax)	Stand-alone automation	Spread sheet registry of contacts
G2	Electronic transmission of orders (e.g., email)	Partially or fully integrated CAD-CAM	Automated devices to support sales
G3	Digital system for processing orders, stocks & payments	Process execution automated system	Internet based support for sales & after services
G4	Real time web-based relation	Machine to Machine -M2M system	Client relationship based online monitoring product use

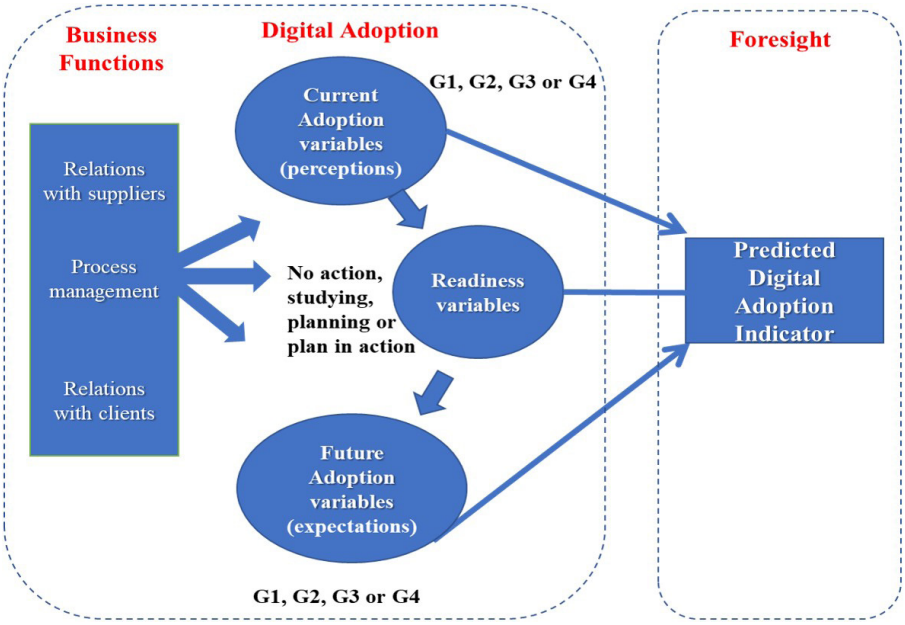
Note: (*) Engineers, tech experts, and international surveys supported the development of this stylization. G4 is defined by the best foreseeable technologies.
Source: Based on Instituto Euvaldo Lodi (2018).

G4); (ii) three business functions (relations with suppliers, production management, and relations with clients); (iii) two moments in time (present and 5 to 10-year future); and (iv) current level of preparedness for the future. Figure 1 illustrates the relations among these variables.

Potentially, the number of combinations of business functions, digital generations, moments of time, and actions to prepare for the future is exponential. A delimitation is necessary and made possible only if an analytical perspective is taken up. The significance of a synthetic indicator is revealed by its ability to represent essential aspects of a firm's adoption pattern in the most elucidative manner. Albrieu et al. (2019), Britto et al. (2023), and Torracca et al. (2023) propose a convergent approach by representing an indicator of predicted digital adoption by combining current and future digital adoption with readiness efforts.

Albrieu et al. (2019) classified firms into three groups (condors, alpinists, trekkers) based on two attributes: firm's current position in digital adoption and a certain degree of dynamism. It is based on the understanding that a company is dynamic not only because it expects to move forward in time, but also because it takes actions to do so.

FIGURE 1
Current and expected adoption of digital technologies by business function



Source: Author elaboration.[2]

Torracca et al. (2023) propose the Digital Adoption Ratio (DAR) and the Digitalisation Readiness Index (DRI). DAR estimates the share of firms adopting each digital generation (from G1 to G4) over the total number of firms. DRI is a synthetic indicator that also combines a firm's current and expected digital generation with what it is currently doing to prepare for the future.

Britto et al. (2023) developed the Current Adoption Index (CAI) and the Conditional Digitalisation Index (CDI). The authors estimated CAI for each business function by attributing different but progressive values to the various digital generations in a non-linear manner. Like the other indicators, CDI forecasts firms' future position in the adoption in digital technologies based on three factors: the digital generation currently adopted, the future digital generation, and the level of current preparedness to achieve their objectives.

[2] Jorge Britto, professor at the Fluminense Federal University (UFF), a long-standing research partner, is the person behind the initial idea of linking up relationships along these lines.

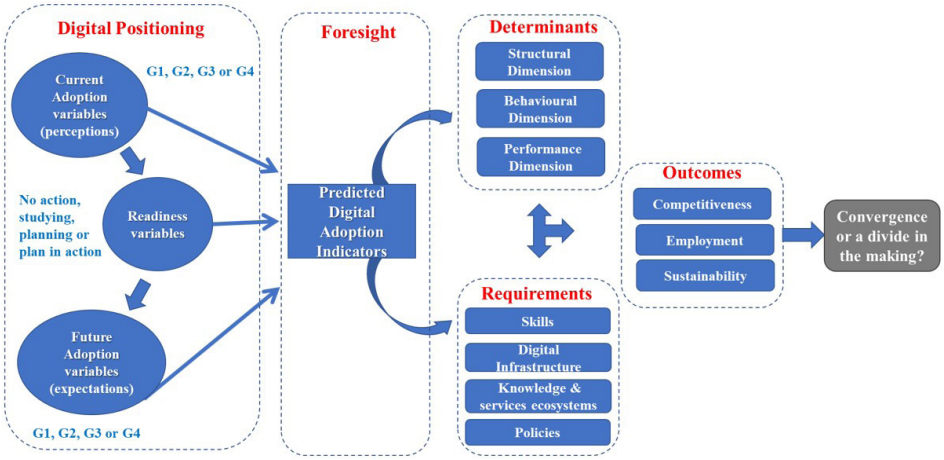
These exercises demonstrate the feasibility of coming to terms with variety expressed by possible combinations of variables. The proposed indicators were empirically tested, arriving at suggestive results. Initially indicators were used to stratify firms in stylised layers according to stages of digital development under the inspiration of the seminal work by Abramovitz (1986). Such an exercise provided a valuable appreciation about the proportional distribution of firms, in different countries, according to stages of digital development. These indicators were also used to determine the structural and behavioural profiles of more and less digitally advanced firms and to analyse how each group of firms performed in different issues such exports and or employment generation and labour skills.

4.3 Determinants, requirements, and outcomes of digitalisation

Analysing the adoption of digital technologies at the firm level should go beyond determining the firm's relative position. It is of academic, strategic and policy interests to investigate whether determinants and requirements of digital adoption are endogenous or exogenous to firms, as well as the potential outcomes of digital technologies. Such line of interest guides this paper's approach, shown in Figure 2.

It is quite challenging to propose only one model that associates the adoption of digital technologies with economic, financial, production, or competitive determinants and outcomes. In this context, establishing the existence or not of expected relations, such as the contribution of digital technologies to efficiency, should be avoided while determining the value of such contribution is necessary but still quite difficult to assess, given the development stage of knowledge about the phenomenon. To partially offset these shortcomings, one alternative is to inquire firms about their strategic formulations and how much advanced digital devices may affect certain strategic business attributes (competitiveness or sustainability, for instance). This type of information, combined with data on firms' relative market position or readiness level, may

FIGURE 2
A framework for the analysis of digitalisation processes, determinants, requirements, and outcomes



Source: Authors' elaboration.

reveal the potential contribution of digitalisation to business strategy, an information with interesting analytical significance.

As to requirements, especially those placed externally to firms, one way of estimating their effective contribution is by determining the degree of importance firms place on factors leading to, or impeding, the adoption of digital technologies. These may include the availability of ICT infrastructure, the skilled workforce supply, or the existence and nature of specific public policies. Answers to these issues would reveal the perception and even the understanding of business representatives about how external requirements affect the effective adoption of digital technologies.

Finally, concerning determinants, the more features a firm can be characterised by, the larger the possibilities for discerning which business profile is more likely to be more and/or less prone to digital investments and which factors may determine digital progress, stagnation, or regression in time. It thus opens the way for deriving lessons to be learned for different purposes such as business strategies and/or public policies.

Once the relationships are established, researchers can explore these issues from different perspectives, using different typologies and econometric

techniques to build models explaining how digitalisation determinants, requirements, and outcomes relate to the dynamics of digital progress encapsulated in proper indicators. Appropriate quantitative tools thus can be mobilised. If surveys are based on categorical variables, among other techniques, ordered logistic methods are quite useful (AGRESTI, 1996, 2002). These models allow for the relative ordering of response values even if the exact distance between them is not. By means of a logistic function these models estimate probabilities that an outcome variable is associated to independent variables (also categorical): the regression produces the likelihood occurrence of a specific event from the logistic function to predict the corresponding target class of the categorical response variable (LONG; FREESE, 2006, 2014). Within such a framework, levels of digitalisation progress can be associated with variables representing different features of firms and/or requirements and/or outcomes.

5. Concluding remarks

5.1 Directions taken

Digital technologies are becoming economically relevant and gaining prominence in business strategies. Still, whether these technologies open windows of opportunities for the progress of firms and their value chains and the development of industries of nations, particularly developing countries are still open questions. These are much-debated issues and open areas for research, from theoretical, methodological, empirical and policy perspectives.

Assessing which digital solutions is adopted by industrial firms, in time, and the related requirements, determinants, and outcomes is an exercise of approximation. It is so because the subject and object of research - the adoption of digital devices by enterprises - is an elusive phenomenon that is yet to be accurately captured, given the state of advance of conceptual and empirical knowledge about these technologies. Nevertheless, experimental assessment exercises are much needed.

In this line, this paper proposes an experimental framework for the design and implementation of direct surveys about the adoption of digital solutions by industrial firms. The proposed framework is based on a conceptual and an empirical pillar. To define the essential and necessary elements for the design of surveys, the conceptual pillar largely relies on the Schumpeterian literature. To draw out lessons on how to design and to whom address questions, the empirical pillar was constructed from exercises proposed and implemented by academics, consulting organisations, policy-related institutions, and statistical agencies. These contributions led to the proposition that a valid approach is to rely on the perceptions and expectations of qualified business representatives as the basic source of information.

5.2 A synthesis of an experimental framework

This paper draws a three-stage framework for the assessment of digitalisation in industrial firms. The first stage is to collect data on the adoption of digital technologies; the second is to derive analytical indicators from questionnaire variables; the third stage is to relate indicators to factors affecting the adoption of digital technologies and possible outcomes.

The collection of data requires: (i) specifying business functions to situate and circumscribe the adoption of digital technologies to specific domains: relations with suppliers and customers and process management; (ii) taking a solution-oriented approach to digitalisation, distinguishing four technology generations in order to avoid the specification of device A or B, as they may not be applied to every industrial situation, and to take into account the coexistence of digital devices of different 'ages,' but still effective in supporting the execution of productive tasks; (iii) enquiring about current and future usage of digital solutions, given the fast rate of technical change, but with a best available technology in the prospective horizon; and (iv) questioning firms about the current actions (preparedness) towards the projected future to "anchor" expectations.

The second stage aims at reducing the exponential number of combinations of variables. This was achieved by synthetising variables in appropriate digital adoption indicators to represent essential aspects of a firm's adoption pattern in the most elucidative manner.

The third stage is analytically oriented. Its purpose is to search for and establish relational linkages between digitalisation and: (i) determinants of adoption, concerning the profile of firms in accordance with the well-established industrial organisation approach such as the structural, behavioural, and performance features of firms; (ii) requirements, concerning the factors that enable or impede the adoption of digital technologies, such as the skilled labour supply or the services provided by the knowledge ecosystems; and (iii) outcomes, relating to the potential contribution of advanced digital technologies to strengthening firms' competitiveness and environmental sustainability.

5.3 Lessons learned

This article proposes an experimental framework for the analysis of the process of adoption of digital technologies by industrial firms, the way of going about in developing analytical indicators and the related requirements, outcomes and determinants. Propositions made benefited from the theoretical contributions mainly from the shumpeterian school, from similar assessment exercises coming from different sources of knowledge and institutions and from an on-going research programme in Brazil and other developing countries. From such experience and background nine issues are drawn up, with the hope that these can be useful for similar works elsewhere.

- Firstly, assessment exercises should be guided by two principles: conciseness and simplicity in the way questions are posed.
- Secondly, questionnaires and questions must be designed to allow for comparability with exercises carried out elsewhere.
- Thirdly, assessing digitalisation should encompass the extent of usage of digital technologies in the various activities of companies, as well

as the identification of the intensity of usage in one or all business operations. The joint evaluation of these dimensions allows for an adequate view of the allocation of resources and efforts directed to digital technologies and on the strategic importance of these technologies for the performance and competitiveness of businesses.

- Fourthly, the dynamics of technical progress and the variety of available digital solutions must be accounted for by means of distinguishing different generations of solutions.
- In fifth place, the rapid rate of change strongly suggests the need for evaluations that consider past, current, and prospective adoption of digital solutions by firms.
- Sixth: given the stage of knowledge about processes of digitalisation, which is yet to be translated in objective indicators, assessments should rely on perceptions and expectations of qualified respondents. The identification and access to qualified representatives of firms is an essential element for a survey with quality.
- Seventh, to be meaningful, assessment exercises should allow for analytical connections of digital adoption to determinants, requirements, and outcomes.
- Eighth: a quantitative exercise should be accompanied by in-depth case studies of firms or groups of firms. Case studies can highlight dimensions of the adoption of digital technologies that a questionnaire-based survey simply cannot reach out.
- In nine place, and this is an issue to be further tested, the framework was designed to be applied to firms belonging to any manufacturing sector, considering that they can be in different stages of advance in terms of the digital solutions they are adopting (or expect to adopt in the future), in any national context. The capacity of a framework to capture different stages of progress matters! It is the analysis of the evidence to be collected from a survey that will reveal similarities and differences among firms and their constituting elements (sector, size, nationality, strategy, etc.).

This article ends with words of caution that, to some extent, reveal the challenges faced in the development of this proposed framework. The title of the article is purposeful. This is a proposal for an experimental methodological framework for the assessment of digitalisation at the firm level. As "experimental" it suggests that this is one of many possible approaches to the issue of digital adoption. The concept of "framework" also matters. This is not a finished product in search of opportunities for empirical application. It is just one modest contribution to increase the knowledge base on how to go about researching subjects where uncertainty prevails. The fast pace of technical change and the complexity of the process of investment decisions of firms define an open and long road ahead before a consolidated, normalised methodology comes about. In a nutshell, frameworks of the assessment of digital adoption by firms must be constantly revaluated and renewed.

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