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

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Abstract

This article proposes a framework for the assessment of the adoption of digital technologies by industrial firms. It is a contribution to research aimed at evaluating the extent to which digital technologies open (or not) venues for the strengthening of industrial development of nations, particularly developing countries. The increasing economic importance of digital technologies demand proper methods of assessment but this is a quite a challenge given their pervasiveness, intangibility, and fast rate of progress.

Such framework is inspired by the literature on the economics of innovation and by digital assessment experiences proposed by academics, consulting organisations, policy related institutions and statistical agencies. It is designed to enable three tasks: (i) the registering of information about current and prospective adoption of digital

[1] This article is a by-product of investigations conducted since 2017 by researchers from the Instituto de Economia, Universidade Federal do rRio de Janeiro, UFRJ, Instituto de Economia, Universidade estadual de Campinas, UNICAMP, and Faculdade de Economia, Universidade Federal Fluminense, UFF. Without the contributions from this group, this article would not exist. Special thanks go to Carolina Dias for her thorough text revision. Nevertheless, I am the sole responsible for the contents of the article. Along the years the Brazilian Industrial Board, CNI, UNIDO, and INTAL/IADB provided support for this research programme.

[2] I dedicate this paper to David Kupfer, my long-standing research partner, colleague, and friend

technologies by industrial firms, (ii) the development of indicators to capture the dynamics of digital adoption and, (iii) the association between these indicators and related determinants, requirements, and outcomes of digital progress of industrial firms. But be aware! This is an exercise of approximation towards references that just may not be there.

Keywords: Technical Progress, Digital technologies, Industry, Survey, Analytical framework,

JEL: D22, D83, L23, O32, O33

Introduction

This paper has two main goals: propose a method for assessing, through direct surveys, the adoption of digital technologies by industrial firms and, suggest how to develop from survey data, meaningful indicators and frames of reference for analytical and policy purposes. 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 (OECD/EUROSTAT, 2018). Thus, digitalisation does not only refer to the adoption of information and communication technologies (ICT). It also relates to a process in which integrated, interconnected and increasingly intelligent devices become an inherent and inseparable part of a business activity, transforming organisational processes, business models, inducing new sources of competitive advantages and potentially transforming market structures.

Amidst a fast pace of technological change, assessing digitalisation at the firm level is of paramount importance due to the increasing economic significance of such technologies. However, as Zolas et al. (2020, p. 3) noted, the "measurement of technology use at the firm-level has lagged considerably."

At least five inherent features of digital technologies make measuring digitalisation a conceptual and methodological challenge:

- Digitalisation results from the convergence and blending of different technologies.
- Digital technologies are incorporated into tangible and intangible assets such as software and databases.
- it is pervasive, applicable to most business functions performed in any economic activity.
- Progress is fast and firms may employ devices of different digital generations simultaneously, with positive economic returns.
- Determinants, requirements, and consequences of digital adoption are vast and difficult to accurately be assessed.

Conducting surveys about digital adoption requires capturing such elusive but pervasive phenomena through questions that must be understandable and answerable questions to representatives of firms, who must have sufficient knowledge about which and where digital technologies are being applied in their business. Answers are then translated into variables and variables into meaningful indicators for economic analysis. For that, solid concepts and a robust analytical framework are required.

Accounting systems of business and statistical offices face huge challenges to soundly introduce standardised measurement procedures. Nevertheless, significant efforts towards assessing digitalisation have been made and promising results are emerging. Still, such a phenomenon is yet to be systematically apprehended. As the next pages will demonstrate, assessing digital adoption is, presently, an approximation exercise because frames of reference are still at a developing stage. 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, with an applied perspective, and assessment exercises derived from different institutions involved in carrying out direct surveys to firms, to propose an experimental method for estimating the adoption of digital technologies by industrial firms and for the analysis of the related determinants, requirements and outcomes. A literature review of key concepts for understanding digitalisation from an applied economic perspective is combined with an account of recent assessment proposals, including the design of surveys. The theoretical references will be drawn chiefly from the Schumpeterian literature. The empirical applications will be derived from four different sources: academia, consulting companies, policy-related organisations, and statistics bureaus. The proposal in this paper also draws from recent investigations carried out in Brazil and other developing countries (IEL/NC et al., 2018, FERRAZ et al., 2019, ALBRIEU et al., 2019; KUPFER et al., 2019; UNIDO, 2020).

The paper starts by discussing the nature of digital technologies and their properties, to raise the essential and necessary concepts for the design of surveys. Then it delivers an extensive but not exhaustive review of assessment practices. The following section

proposes a frame of reference for surveys and, from there, how draw out analytical indicators and analytical frameworks. The last section concludes.

1 Conceptual references

The increasing economic importance of digitalisation makes it relevant subject matter for research, from different angles. Sound evidence and analysis contributes to the advancement of knowledge, support the design of corporate strategies, and foster public policies while, at the same time, providing insights about the challenges associated with the catching up of firms and countries in a development context (LEE 2019). For that, the adequate construction of frames of reference is a pre-requisite and, in this realm, the essential conceptual features of digitalisation must be identified. This is the subject matter of this section.

1.1 The nature of digital technologies

Digital technologies can be considered as a generic technical base supporting every contemporary economic activity: these are pervasive or general-purpose technologies that can be applied, be useful and impact any economic activity (ROSENBERG, 1963; GAMBARDELLA; TORRISI, 1998; CANTNER; VANNUCCINI, 2012).

With semiconductors as its core device, digital technologies constitute a microtechnological paradigm (DOSI; NELSON, 2010), in contrast with the macro techno-economic paradigm proposed by Freeman and Perez (1988). Digital technologies are a "procedure-centred representation of technology" (DOSI; NELSON, 2010, p. 62). Along an evolutionary trajectory, they entail a specific pattern of problem-solving heuristics: the manipulation and the processing of increasing amounts of information, as required by contemporary societies (DOSI, 1982; NELSON; WINTER, 1982).

Digitalisation results from the convergence and blending of soft and hardware devices and components, with microelectronics as the primary input. They can be embedded into

tangible and intangible assets, such as computers and software, facilitating diffusion processes (OECD/EUROSTAT, 2018). Technical advance has significantly evolved over the years. More recently, with the emergence of the internet and systems and devices capable of capturing, processing, storing and communicating vast amounts of data progress has been even more pronounced. For instance, rapid prototyping through advanced 3D printers may contribute to the reduction of efficient minimum scales of production (KAGERMANN; WAHLSTER; HELBIG, 2013). Moreover, advanced digital solutions are scalable and increasingly embed intelligence in the sense of being capable of discerning, deciding, and initiating actions, preventively, operationally and/or correctively (IEL/NC et al., 2018).

Digital technologies can integrate business functions through communication networks and represent the real environment as a virtual one. By combining "soft" (big data) and "hard" technologies (sensors, robots, high-performance computers) through communication networks, they allow information to be made available in real time along a firm's value chain. The fast rate of cost reduction (per unit of output), the elasticity of demand and the potential increase in supply, and the wide extension of possible applications define the transformational potential of digital technologies. Adopting digital technologies can change the way firms produce and market their products, optimise workflows, link up suppliers and customers along their value chains. Therefore, adopting digital solutions extensively and intensively may induce transformations in business and organisational models, enhance firm competitiveness and even change market structures (IEL/NC et al., 2018; PORTER; HEPPELMANN 2014).

Digital technologies have been around for more than half a century. In this sense, an enterprise may be faced with the decision to put aside or to continue using previously acquired devices while incorporating new and more advanced ones, all under proper feasibility considerations. In practical terms, it is very likely that within any firm, and among firms, devices from different technological generations coexist. Digital solutions of earlier generations do not necessarily become obsolete (from either an economic or a technical perspective) and abandoned when newer generations come about. There are countless CAD and computer devices of different generations available in the market and still in use. The concept of digital generation is not stationary and atemporal but somewhat

contingent upon the moment of analysis. Moreover, the potential of technologies and the required capabilities to effectively use them do not evolve linearly from generation to generation[3].

In this sense, a digital technology generation can be understood as the dominant design of a single digital device or a set of combined digital devices prevailing during a period. The concept of dominant design is relevant because it is meant to represent a set of technical features of product and processes that emerge, find usefulness and achieve acceptance among user firms (ABERNATHY and UTTERBACK 1978, SUÁREZ and UTTERBACK 1995, SO, 2016). Docampo Rama, Ridder and Bouma (2001) even estimate that a dominant technology can "survive" for a period ranging from 15 to 30 years.

1.2 Digital technologies within the enterprise

Identical twin firms do not exist; diversity or heterogeneity prevails (NELSON 1991). Diversity is revealed through a firm´s specific strategic orientation, internal structure, organisational routines, style of relations with clients and supplier revealed by a firms performance and 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 argue (2010, p. 100), "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. Just as the innovation capabilities of firms differ,

[3] Even taking into account Moore´s law that the number of transistors doubles about every two years,

digital capabilities and corresponding results also do. In time, if the adoption of digital devices is more effective to certain firms, their capacity to grow and prosper will increase compared to those lagging behind, and the distance between the two groups will become more pronounced. Among developing countries, if the change goes in this direction, depending on the rate of diffusion in a given population, digitalisation may reinforce the prevailing structural heterogeneity, as argued by Coutinho (2021).

Firms can employ digital solutions to perform any business function, including those that beyond the firm's borders, such as relations with clients, suppliers, and stakeholders. Moreover, digital solutions have an extensive and integrative dimension: devices can be applied to one specific operation, or they can reach all operational areas. Thus, if effectively used, the wider the adoption, the higher the digitalisation level, the more integrated the different areas are, the more probable the benefits may be accrued (IEL/NC et al., 2018).

Further, in one specific function, firms can adopt digital technologies with varying intensiveness. That is, a given task, function or area of a company may be covered in different proportions by digital solutions (FERRAZ; RUSH; MILES, 1992). 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. Thus, the capacity of a firm to enjoy the benefits of digitalisation would be, correspondingly, higher or lower. In short, the economic relevance of the adoption of digital technologies is defined by "how much" coverage such devices provide to a firm.

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 (FERRAZ, RUSH, MILES, 1992). 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). Digitalisation thus contributes to business diversification and can boost value creation, leading to superior market performance over standing business practices while changing the determinants for competitiveness (PORTER; HEPPELMANN, 2014; IEL/NC et al., 2018).

Effective digital adoption does not come naturally or immediately when technology is introduced and put into use. Adopting digital technologies involves strategic decisions and investments. It includes mobilising resources and taking actions to fully use the selected solutions and build the projected future (ANDREWS et al., 2018). Adopting digital solutions of a certain sophistication level requires mobilising equivalent sophisticated digital capabilities embedded in labour force skills, organisational routines, stocks of information. Thus, evolving from an older digital generation to an advanced one when performing similar tasks - for example, product design - is a non-linear process. That is, such an evolution is not a matter of adding up "units" of existing assets, but it may entail the introduction of entirely new capabilities.

In summary, in the presence of appropriate capabilities, digitalisation may lead to highly integrated, interconnected, and intelligent organisations (IEL/NC et al 2018). Such a generic model does not preclude the fact that, when taken up, digital solutions are implemented in specific forms by companies, depending on their sectors, value chains and markets attended.

1.3 Key features of digitalisation for a firm-level assessment framework

The core of the proposed framework for assessing digitalisation at the firm level is composed by four topics.

Firstly, digitalisation comes about by combining software and hardware devices of different technological generations (more or less updated), to perform and improve business functions, by supporting and undertaking data gathering, transmission, exchange, processing, interpretation and process execution. In the face of that, assessing

digitalisation at the firm level should focus on which digital solutions are used to perform specific business functions, instead of focusing only on the registering of which particular devices a firm operates.

Secondly, as firms can simultaneously use digital technologies of different generations, to perform a particular business function, the technical specification of all available digital generations becomes necessary, having the foreseeable (in the time span of the survey), commercially available, most advanced solution as the ultimate reference. Nevertheless, the nonlinearity of technology generations and corresponding capabilities must be considered.

Thirdly, firms differ on what digital solution is adopted, how intense is the usage and which technology generations are prevalent in different business functions. Nevertheless, comparability is essential for any assessment exercise. Therefore, in empirical-oriented assessments must be designed to reveal differences, while at the same time, expressing digital solutions, devices or technology generations in generic modes as to be applicable to any firm, regardless its structural feature such as size or sector of origin. Such approach is necessary if similarities and differences in digital adoption patterns across firms are considered to be a relevant research issue.

Finally, given the fast rate of change of digital technologies, taking an evolutionary approach with a current and prospective time reference could capture interesting nuances of technology adoption by firms. If the assessment exercise takes a direct approach to firms, respondents should be enquired about their perceptions concerning the firms' current situation and expectations for the future. Perceptions and expectations of qualified representatives for firms concerning their current and prospective use of digital technologies would then constitute the empirical base for such an assessment exercise.

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 technology adoption decisions are made. It tries to capture how firms' perceptions of usefulness of a given technology are formed

and affected and then translated into intentions, decision-making, and resource allocation, ending up in the actual adoption of new devices (CHIAN, 2010; KOUL; EYDGAHI, 2017). Assessing digitalisation involves examining individuals' awareness and discernment about the current and future adoption of digital technologies in their work environment.

Expectations are a strong belief that something will happen or be the case in the future. According to Rosenberg (1982, p. 105), business owners' expectations and behaviour towards the technological future usually differ due to uncertainty and risk aversion. However, in his view, the economic literature has not given sufficient attention to the study of expectations in technology diffusion processes, calling 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 environment. Thus, the "grounding" of firms' prospective views becomes necessary when assessing digital adoption. With that purpose, researchers must 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.

2 Assessment experiments

Assessment exercises about the adoption of digital devices by industrial firms have been carried out by different types of institutions, with a variety of purposes, approaches, and results. This section reviews contributions 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. This non-exhaustive literature review aims to provide archetypical qualitative evidence on how assessments practices targeting digitalisation at the firm level have been carried out by these different parties, in search of lessons to be drawn up.

2.1 Academics

Nylén and Holmstrom (2015) provide a methodological framework for assessing the adoption of digital technologies. As shown in Table 1, the authors define three dimensions to be evaluated: product, environment, and organisation. In each dimension, the following elements are observed: user experience and value proposition, for products; monitoring clients, for the environment; skills and improvisation, for the organisation. The purpose is to guide the building-up of strategic actions by firms to introduce, deploy, and use digital products and services. The authors pay special attention to the role digitalisation in monitoring the firm's internal and external environments, to verify the status of operations and the performance of employees, suppliers, and clients. They are also concerned with how firms mobilise the necessary skills and capabilities to use digital innovations effectively, including continuous learning processes.

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).

Such a framework is operationalised in the form of questions posed to qualified business representatives. For example, to define the organisational/skill readiness towards digitalisation, representatives are asked whether they agree, partially agreed, or do not agree at all that continuous learning about the unique properties of digital technologies is 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 could be extracted and put forward.

Based on an extensive literature review, Schumacher and Sihn (2020) propose 143 key-performance indicators (KPI) in nine 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 (2019) propose three stages of digitalisation, each with related organisational and strategic implications. The stages are (i) spot digitalisation or automating specific routines and tasks; (ii) integrated digitalisation or incorporating

digitalisation into processes and products or services; and (iii) digital transformation, or implementing new business models, due to the pervasive and intensive adoption of digital solutions in all aspects of the organisation (Table 2).

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 (2019, p. 892).

All these academic scholars propose 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 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, the focus here is centred on organisational learning and the business transformation by digital devices; their frames of reference are intended to provide inputs for further empirical analysis and guide strategic decision-making.

2.2 Consulting organisations

Consulting firms are mainly concerned with providing tools to firms interested in adopting digital technologies. Two broad research approaches can be identified: 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, 2019).

McKinsey 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 (MCKINSEY, 2019). It attributes values to each practice and compares the results obtained by any given firm to international best practices, thus allowing decision-makers to learn the relative position of their firms and draw conclusions on how to move forward.

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 is also engaged in providing 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 (from being a novice to a digital champion), according to four stages of digital evolution, in six different business functions and/or activities, as shown in Table 4 (PWC, 2021).

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 firms' capacity to perceive where they stand at and indicating paths for their further development. By doing so these organisations intend to technically qualify themselves to better meet the needs of their potential clients while differentiating themselves from competitors.

2.3 Policy-related institutions

The German Industrie 4.0 initiative is a digitalisation-oriented policy landmark. It was launched in 2011 to modernise the country's industry, with a focus on small and medium size firms (PFEIFFER, 2017). Such initiative proposed and made available resources,

consultancy and technical services to firms, with the support of an assessment tool – "Toolbox Industrie 4.0"-, to provide firms with an instrument to identify where they stand and how to move forward (VDMA n.d.). The assessment tool, proposed by the German Engineering Federation, VDMA, encompasses two dimensions: products and production processes. For each, it discerns different business activities, or functions, and specifies different technological and sequential development stages. The guide is not a ready-made solution. Rather, it provides information about possible procedures for decision-making. Table 5 illustrates the functions and the stages of digital development for the production dimension.

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 (n.d., p. 9).

The Korea Institute for Industrial Economics and Trade also proposes an instrumental tool to support the Korea Smart Factory Initiative. Such an initiative aimed at disseminated 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. The Korean model specified four development stages in the management of manufacturing activities (generically defined) with an indication of their correlation with the German model. Table 6 summarises the Korean-German based model.

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).

In 2017, the Singapore Economic Development Board (SEDB) launched the Smart Industry Readiness Index (SEDB, 2017). The index comprises three dimensions: technology, process, and organisation, and eight corresponding 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 (SEDB, 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, their tools specify stages of digital development. Thus, these are instrumental tools with two purposes: to enable firms to perceive where they stand at in relation to best practices, to support digitalisation strategies, plans and actions and to provide background information for the design of policies and programmes

2.4 Statistics related organisations

The statistical office of the European Union (Eurostat) has the longest standing and comprehensive initiative on how countries should conduct surveys about the adoption of information and communications technologies (ICT) by enterprises. Their main concern is with capturing where firms stand at in relation to the stage of progress of these technologies in a given moment of time. Naturally, along the years, questions change reflecting improvements in an existing technology or the introduction of new ones. 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 similar and different questions extracted from the first (2002) and the latest (2021) questionnaires. In 2002, a special focus was placed on e-commerce - purchases and sales via the internet and barriers on e-commerce - and questions 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, bringing in questions about three emerging digital technologies: cloud computing services, Internet of Things and Artificial Intelligence. Such an approach allows for the appreciation of how firms evolve along the years in few "permanent" issues while constantly updating the questioning to firms whether they are engaging in new technologies.

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
	% Employees using a portable device provided by the enterprise
Does your enterprise use or plan to use Internet?	
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?	**During 2020, did your enterprise have EDI-type sales of goods or services?**
What percentage of the total sales (in monetary terms) did the sales via EDI or networks other than Internet represent in 2001?	**What percentage of total turnover was generated by EDI-type sales of goods or services, in 2020?**
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	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. 2002 version can be accessed at https://businessdocbox.com/Marketing/126358173-Community-survey-on-ict-usage-e-commerce-of-enterprises-2002.html. The 2021 version at https://circabc.europa.eu/sd/a/f9dc8b66-a429-49e2-ae01-f7424ec389f0/MQ_2021_ICT_ENT.pdf

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 progress in a similar function (interconnection,

for example) exerted by digital devices. The literature would designate this as "incremental technical change". However, the case of digital technologies is quite different, given the exponential progress embedded into devices that exert the same function. The case of the speed of transmission of information is exemplary: for internet connection, a similar question asked 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 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. The surveys EUROSTAT proposes then seems to be intentionally designed to provide such type of externalities, to be captured in assessment exercises based on the analysis of available data.

As a member of the Partnership on Measuring ICT for Development (ITU-D, 2021), UNCTAD 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 (UNCTAD, 2021). The manual includes guidance for conducting surveys, processing data, and disseminating results, and provides working tools for organisations from developing countries, such as statistical offices, with limited budget assigned to economic and social surveys. For that, UNCTAD proposes surveys based on simple and objective questions concerning: (i) the existence or not of a relatively number of digital devices (the use of computers, the existence of internet and intranet, the type of internet connection and whether an enterprise places and receives business orders), 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 been conducting surveys on ICT usage at the firm level since 2005. Carried out by its Regional Center for Studies for the Development of the Information Society (CETIC.BR, the Portuguese acronym), the CGI surveys follow UNCTAD and Eurostat methodological standards to allow for international comparability. 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. Table 8 provides more details on the CGI survey questions related to big data use (CETIC.BR, 2020).

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 CETIC.BR (2019)

In the US, the US Census Bureau introduced questions about the adoption of digital technologies in its 2018 Annual Business Survey. The objective was to gather information about the adoption of specific advanced digital technologies and profile more and less technologically 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.

Besides questions on expenditures in cloud computing services and the use of specific advanced technologies, the US Census took a new approach by questioning the perception of representatives of firms about the intensity of the adoption of digital solutions to perform certain tasks or business functions (Table 9) and the intensity of adoption, if any, 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 US 2021 Annual Business Survey plans to apply a similar technology module. Also, attempts will 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 undertaken by statistics related institutions place emphasis on the adoption of ICT and pose simple questions to be answered by any firm. With

complementary approaches, they offer indisputable contributions on how to conduct exploratory assessments about how firms use digital technologies.

2.5 Summarising assessment experiences

In this section, a non-exhaustive review of concepts and survey tools used by different types of institutions was carried out. It was found 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 the primary information provider and quite often questions rely on respondents' perception about the adoption of advanced digital solutions in specific business functions.

From the nature of questions posed by institutions that have carried out surveys recurrently it is possible to derive an underlying understanding that the adoption of digital technologies is a long, complex process that starts with simple devices introduced in specific business locations and evolves towards the digital transformation of the whole firm. The different approaches are also based on the same 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.

3 Chasing the rainbow: towards an experimental assessment framework

3.1 The assessment approach: digital generations and business functions

Digitalisation is associated with the collection, processing, and transmitting of vast amounts of information through devices increasingly embedded with learning capacity. For that, the concurrent use of tangible and intangible assets of different technological generations is required. Digital technologies are pervasive and, ultimately, these technologies may lead to more integrated, interconnected, and intelligent business/organisational models. The adoption of digital technologies is a dynamic but non-linear process as, within firms, older digital generations remain functional and effective even when newer ones are introduced. So different generations of digital technologies may be employed simultaneously with positive outcomes. Also, digital solutions are unique to firms, value chains, locations, and markets. As a result, digitalisation may allow firms to strengthen its sources of competitive advantages and enhance value creation.

Given the above, the methodological approach for assessing the adoption of digital devices by firms must presuppose that diversity and/or heterogeneity among and within firms are prevailing features to be found in direct surveys. These assumptions are particularly relevant when assessing digitalisation in developing countries, where differences in capabilities and performance among economic agents are outstanding structural features.

An experimental framework for assessing and analysing digitalisation of industrial firms is proposed in this section along three stages involving: (i) the specification of digital technology generations in relation to business functions; (ii) the development of indicators concerning dynamic digitalisation positioning; and (iii) the setting of analytical guidelines for associating indicators of digital adoption to possible determinants, requirements, 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 level 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?

This proposal is derived from the framework 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 (IEL/CNI et al., 2018). The I-2027 framework discerned four stylised[4] generations of digital technologies employed by industrial firms to perform several business functions, in two separate moments of time (present and future), together with the efforts firms were undertaking to prepare for the projected future. 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).

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: (*) G4 is defined by the best foreseeable technologies.

Source: Based on IEL/NC et al (2018).

[4] Engineers, tech experts, and international surveys supported the development of this stylization in the I-2027 initiative, as well as experiences of similar surveys.

Three conceptual issues must be cleared. 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, this mode of assessment assumes that digital technologies offer sets of solutions to support the undertaking of discernible business functions. In such a framework, a digital generation relates to a specific set of solutions which demands specific capabilities to use these technologies effectively. The digital solution approach is preferable over the pre-definition of specific digital devices to avoid the likely limitations of asking firms what device, A or B, is employed to perform what type of business function. The solution-oriented approach also allows for determining the intensity of digital usage as firms are asked about which digital generation is employed to perform most activities related to a given business function.

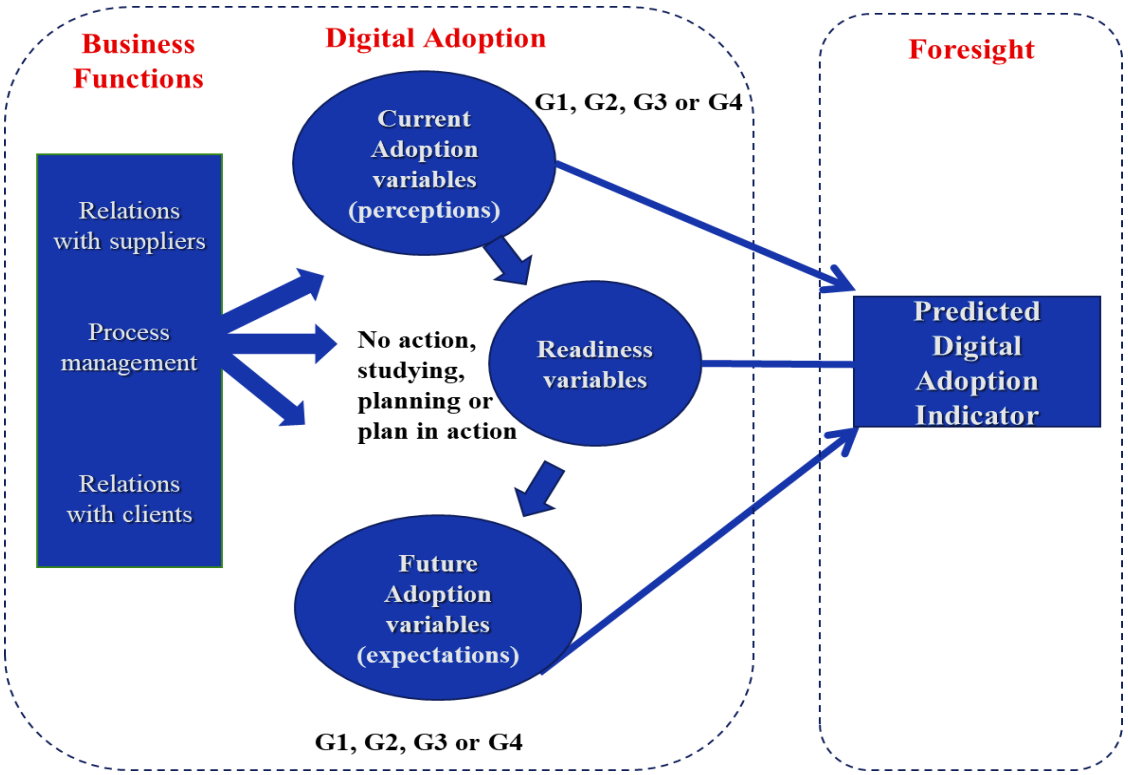
Thirdly, the digital generation framework explicitly considers the dynamics of technical change in time and the possibility of different adoption patterns coexisting among firms. For that the experiment relies on perceptions and expectations of the representatives for firms about current and future (5 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.

3.2 Deriving indicators from variables

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

The proposed way of going about to develop indicators is built on the following four variables: (i) four generations of digital devices (from G1 to G4); (ii) three business functions (relations with suppliers, production management, and relations with clients); (iii) two moments in time (present and 10-year future); and iv) the current level of preparedness for the future (actions currently undertaken to achieve the projected future). Figure 1 illustrates the relations among these variables.

Figure 1 – Current and expected adoption of digital technologies by business function



Source: Authors' own elaboration[5].

An exponential number of combinations is possible when considering business functions, different digital generations, varying moments of time and a possible number of actions to prepare for the future are considered. The delimitation of combinations is a necessity and becomes possible if and only if a synthetic perspective is taken up. Designing

[5] 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.

meaningful indicators is challenging in any research field. 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. The correlated works by Albrieu et al. (2022), Britto et al. (2022), and Torracca et al. (2022) manifested a convergent interest in designing indicators by representing a predicted digital adoption through the combination of current and future digital adoption with readiness efforts.

Albrieu et al. (2022) 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.

Torracca et al. (2022) 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. (2022) 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.

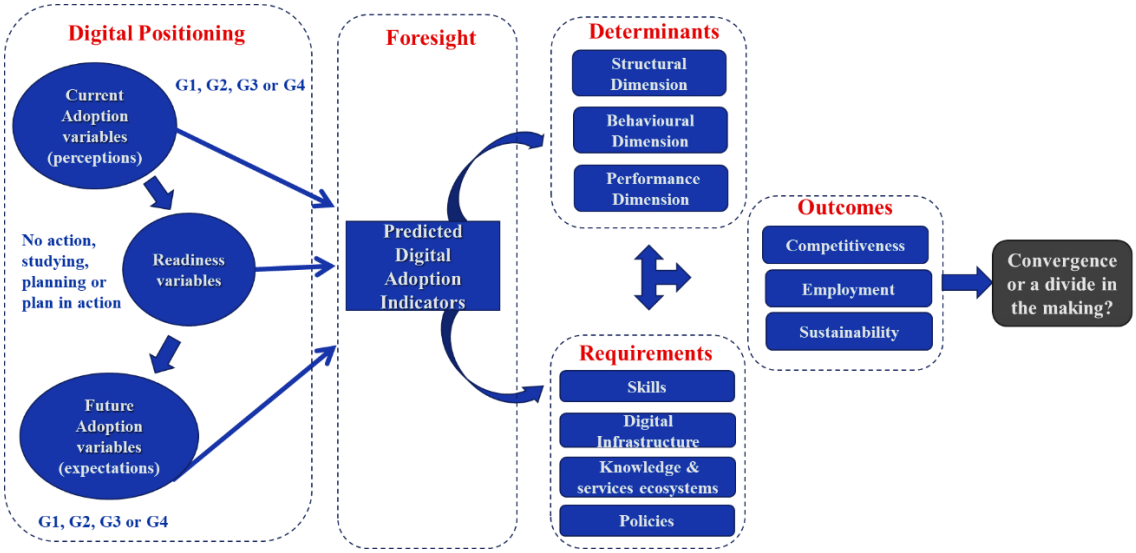
These three exercises demonstrate the feasibility of coming to terms with a complex set of questions. More importantly, indicators were empirically tested, arriving at suggestive results. Initially indicators were used to stratify firms in stylised layers according to stages of digital development. In this case, all classification exercises were inspired by the Abramovitz (1986) proposal of national development processes (forging ahead, catching up, and lagging behind). Such an exercise provided a valuable appreciation about the proportional distribution of firms, in different countries, according to stages of digital development. Secondly, these indicators were used to determine the structural and

behavioural profiles of more and less digitally advanced firms and analyse how each group of firms performed in different issues such exports and or employment generation and labour skills.

3.3 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.

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



Source: Authors' own elaboration.

It is quite challenging to propose a model associating the adoption of digital technologies with economic, financial, production, or competitive determinants and outcomes. Obvious, simple relations, such as the contribution of digital technologies to efficiency, must 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 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 will reveal the perception and even the understanding of representatives for firms 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

Concluding remarks

An account of intentions

Digital technologies are becoming economically important and gaining prominence in business strategies. Still, can 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? This is a much-debated issue and an open area 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 registered accurately, 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 reference framework for the design and implementation of direct surveys to industrial firms on the topic of digital adoption. The proposed frame of reference was built on a conceptual and an empirical pillar. The conceptual pillar largely relied on the Schumpeterian literature to raise the essential and necessary elements to the design of survey exercises. The empirical pillar was constructed from exercises proposed and implemented by academics, consulting organisations, policy-related institutions, and statistical agencies to draw out lessons on how to design and to whom address questions. These contributions suggest that a valid approach is to rely on perceptions and expectations of qualified representatives for firms as the source of information for the assessment experiment.

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 stage 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.

To collect data on digital adoption 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 specific 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 (business functions, digital generations, moments of time, and actions to prepare for the future) at an operational level. This was achieved by synthetising variables in appropriate digital adoption indicators.

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.

Lessons learned

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 a clearer view of the allocation of resources and efforts directed to digital technologies and on the strategic importance of digitalisation in performance and business competitiveness. 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. Six: given the stage of knowledge about processes of digitalisation, which is yet to be translated in objective indicators, assessments can rely on perceptions and expectations of qualified respondents. Seven, to be meaningful, assessment exercises should allow for analytical connections of digital adoption to determinants, requirements, and outcomes. Finally, as digital technologies and the adoption behaviour of firms are constantly changing, assessment frameworks are, in essence, exercises of approximation towards moving targets. They also must be constantly revaluated and renewed.

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