TOWARDS A FIRM-LEVEL TECHNOLOGICAL CAPABILITY FRAMEWORK TO ENDORSE AND REALIZE THE FOURTH INDUSTRIAL REVOLUTION IN DEVELOPING COUNTRIES
Towards a firm-level technological capability framework to endorse and realize the Fourth Industrial Revolution in developing countries

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Abstract

One essential precondition for developing countries to engage in the Fourth Industrial Revolution (4IR) is to accelerate the creation and accumulation of firm-level technological capabilities necessary for digital transformation. This study conceptualizes the firm-level technological capabilities against the new realities of the 4IR. Building on a systematic review of 4IR literature, we firstly define 4IR firm-level technological capabilities. Secondly, based on an analysis of secondary data collected from the systematic literature review, we present an updated framework of firm-level technological capabilities that accounts for the advanced digitalization requirements of the 4IR. The framework consists of a refined set of human and organizational activities, skills, experiences, knowledge and resources required by firms for the uptake of increasingly complex 4IR technologies and processes along their digital transformation journey. These are classified in the framework within four levels of increasingly complex technological capabilities and across six clusters of technological and organizational functions. The framework represents an initial basis for examining the micro-level capabilities required by firms to launch, endorse and realize the 4IR. This has implications for academic, policy and management practices.

JEL codes: O31, O32

Keywords: Capability-building, technological capabilities, fourth industrial revolution, developing countries, firm-level, manufacturing.
1 Introduction

The world has entered the Fourth Industrial Revolution (4IR) and is witnessing an acceleration in the development of heterogeneous digital technologies with the potential of inducing radical transformations in various areas of social, ecological and economic activity. These technologies commonly consist of cloud computing, Internet of Things, big data and data analytics, with applications for biotechnology, nanotechnology, photonics, new materials and renewable energies, among others. Several of these applications, such as artificial intelligence (AI), robotics or automation, are already well-established but their development is accompanied by renewed impetus, convergence and co-evolution with other technologies (UNCTAD, 2018; OECD, 2017). The convergence of these technologies promises to boost economic growth and development through the modernization of productive structures, especially for developing countries, and improve the quantity and quality of existing linkages and interdependencies across economic activities.

In this paper, we argue that firms\(^1\) need to identify, document and systematically devise strategies to build and accumulate the industrial technological capabilities essential for the adoption of increasingly complex technologies and processes along the 4IR readiness to maturity spectrum if they are to effectively address some of the opportunities and challenges the 4IR brings. Existing frameworks broadly categorize and describe levels of 4IR technological capabilities, depicting how to initiate and achieve digital transformation. By contrast, there are no frameworks that present a refined set of the human and organizational activities, skills, experiences, knowledge and resources that constitute these 4IR firm-level industrial technological capabilities, nor the systemic foundations necessary to build and accumulate them.

There is a need to establish suitable frameworks and tools to inform managerial practices and policy decision making, to develop robust diagnostics for determining the progress of the 4IR at both the country- and industry levels, and to carry out consistent assessments of the micro-level technological capabilities firms need to build and accumulate to endorse and realize the 4IR. In fact, emerging research highlights the need to better understand and refine such 4IR technological capabilities, including those that have so far focused on the degree of penetration of production machinery and robotization, and their implications for management systems, the development of platform economies, changes in standards and standardization systems, and skills requirements at the firm level, among others (Liao et al., 2017; Kenney and Zysman, 2016).

\(^1\) We specifically refer to manufacturing firms since we are dealing with the notions of industrial revolution and industrial technological capabilities.
This study presents a refined framework that identifies and classifies those micro 4IR firm-level industrial technological capabilities. The framework serves as a foundation for measuring firms’ progress along the digital transformation process—or 4IR readiness to maturity spectrum—and for guiding their technological capability-building and accumulation efforts. The focus on firms, as discussed further in the following sections of this paper, is justified by the fact that technological capabilities are created and accumulated by firms, and then reflected in their respective sectors and countries.

We acknowledge that firms in both developed and in developing countries face similar challenges in their digital transformation process; however, we focus on developing country firms, because they face additional exacerbated systemic conditions and challenges that often cumulate, making it difficult for them to fully endorse the 4IR (UNIDO, 2019). This line of argument is further developed in Sections 2 and 3 of the paper.

The contributions of this paper to academic, policy and management practices are as follows: first, from an academic perspective, our study updates the firm-level technological capability framework pioneered during the Third Industrial Revolution (3IR) by Jorge Katz and others in Latin America, by Sanjaya Lall in India and across other developing countries, and by Martin Bell, Keith Pavitt and others (Katz, 1987, Lall 1987, 1992; Bell et al. 1982; Bell and Pavitt, 1995). Technological capabilities as conceptualized by scholars in the field must be aligned with the new realities being ushered in by the 4IR.

Based on our findings, we conceptualize and define firm-level technological capabilities under the 4IR as the collection of human and organizational activities, skills, experiences, knowledge and resources that firms need to generate and manage digitalization through the adoption of more complex 4IR technologies and processes, as well as using these to generate new technologies and develop new products and processes. As firms upgrade their technological capabilities along the readiness to maturity spectrum, they improve their ability to solve more complex intra- and inter-firm issues related to digital transformation. Indeed, Butt (2020) highlights that the digital transformation process is underpinned by frequently changing, still emerging digital technologies, and we assert that such unpredictability can be effectively tackled once firms have accumulated a strong base of 4IR technological capabilities.

Secondly, from a policy perspective, the opportunities and challenges firms in developing countries face with reference to advanced technological and industrial foundations are of particular interest, particularly if they intend to avoid or overcome the middle-income country trap (Lee et al., 2019; Liu et al., 2017; Santiago, 2020). This reaffirms the pertinent confluence of
innovation policy and industrial policy as drivers of development (Santiago, 2020; Domínguez Lacasa et al., 2019), and the need to articulate 4IR-specific strategies with broader national development strategies² (UNIDO, 2019; Santiago, 2018). Our 4IR technological capability framework is a useful foundation for appraising ongoing trends commonly associated with the 4IR, and to inform corresponding policy interventions.

Third, from a managerial perspective, the diffusion of 4IR technologies and their effective use largely depends on firms’ ability to readily acquire and deploy new sets of technological capabilities suitable for underpinning their entry into increasingly sophisticated global value chains or segments, and to diversify and upgrade towards higher value-added activities and better quality jobs (UNIDO, 2019). In practice, significant efforts are underway in several quarters to develop diagnostics, toolkits and tailor-made blueprints to assess 4IR readiness, and to produce industry and/or country profiles showcasing the potential benefits of 4IR technologies, with emphasis on SME participation (Santiago, 2018; Deloitte, 2016; PwC, 2016; MITI, 2018).

In parallel, conceptual and empirical studies have also developed various 4IR maturity models. Schumacher et al. (2016), for example, explain that 4IR maturity models are commonly used as an instrument to conceptualize and measure a firm’s maturity or a process to achieve a specific target. They assert that 4IR readiness to maturity models capture the “starting-point and allows for initializing the 4IR development process” to the maturity level and process within the revolution (Schumacher et al., 2016:162). We expand on this line of work by introducing the notion of capabilities as latent dimensions which sustain the progression of firms within the readiness to maturity process.

Fourth, our study informs the efforts of international organizations (UNIDO, 2019) mandated to promote the technological capabilities required by developing country firms to endorse the 4IR and concretize its potential.

In summary, our framework firstly highlights in detail the firm-level technological capabilities required to move from 4IR readiness to the maturity level. Secondly, as we will discuss in the following section of the paper, it highlights the fact that the uptake and improvement of 4IR technologies by firms; demand efforts to better understand the economic benefits of digitalization; to overcome low scientific capacities and competencies in automation and digitalization; and to

² One precondition for operating advanced manufacturing plants is that countries must possess appropriate digital and other basic infrastructure, such as affordable and reliable access to electricity, connectivity and so on, to enable firms to endorse the 4IR. The scale of these infrastructural assets implies that unless they are already in place and provided by other important domestic and foreign systemic actors, investments by individual firms in 4IR technologies are rendered too risky and uneconomical.
upgrade human and financial resources and infrastructure (Raj et al., 2020; Calza and Fokeer, 2019), not only at the firm-level, but also among all systemic actors—governments, universities and research organizations, well-functioning domestic institutions, international organizations, domestic and foreign firms, e.g. suppliers/buyers—that firms interact with. Research should inform ways to support firms’ efforts towards upgrading, and to make the best possible use of 4IR technologies and processes (Raj et al., 2020), including through novel approaches to capacity-building, which is also in line with this study’s third contribution.

The paper proceeds as follows. In Section 2, we discuss the challenges and opportunities of developing country firms in terms of technological capability-building to endorse the 4IR. In Section 3, we elaborate the study’s conceptual framework by building on the literature developed by scholars during the 3IR, and highlight the relevance of an updated technological capability framework to address 4IR realities. In Section 4, we present the methodology of our study based on a systematic literature review and a qualitative analysis for developing an updated technological capability framework. In Section 5, we present the framework, four levels of 4IR technological capabilities and their refined human and organizational activities, skills, experiences, knowledge and resources. In Section 6, we discuss the implications of the study and conclude.

2 Endorsing the 4IR puts a premium on accumulated technological capabilities

Terms such as the 4IR, Industry 4.0\(^3\) or advanced manufacturing have only recently, yet rapidly, permeated policy, academic and business environments. While these terms are not readily interchangeable (López-Gómez et al., 2017), it is generally agreed that they identify ongoing transformations in different dimensions of relationships between human beings, between human beings and machines, and between machines themselves. As surmised by scholars and policymakers, major changes will occur in global manufacturing and in the orientation of science, technology and innovation agendas. Rising demands for new, often difficult to determine sets of technological capabilities will be required by increasingly interconnected societies (MEXT, 2016; Schwab, 2016).

This section of the paper presents the backdrop of economic and industrial development that motivates this study – the fact that the adoption of 4IR technologies requires costly, time-consuming and purposeful efforts not only at the firm-level, but also by other systemic actors that firms engage with as part of their capability-building activities. Thus, to implement such a

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\(^3\) The term Industry 4.0 is an increasingly popular interpretation of the 4IR, with the “Smart Factory” or “Digital Factory” at the core of the future of manufacturing.
complex process at the national level, there is a simultaneous need to understand the capability requirements at the micro-level.

From a catching-up perspective, Andreoni and Anzolin (2019) assert that the diffusion of digital production technologies is a distinct and lengthy process in which different generations of technologies will co-exist for a long time, as social and economic agents slowly engage in learning and the deployment of earlier technological generations. This is consistent with Perez's (2001) finding that digital technologies tend to develop within interconnected systems, allowing for the coexistence of different generations of technologies and their convergence and coevolution with other technologies, organizational practices and institutional arrangements. Moreover, UNIDO (2019) argues that a necessary pre-condition for developing countries to endorse the 4IR is to accelerate the accumulation of technological capabilities that underpin industrialization.

The digital transformation process is challenging for firms in developing countries, as it implies technological upgrading in contexts in which firms primarily use, often ineffectively, technologies that are characteristic of the 3IR—basic automation and information and communication technologies (ICTs)—or are stuck in a trap using technologies and production processes characteristic of earlier revolutions. These challenges often cumulate, making it difficult for developing country firms to fully endorse the 4IR (UNIDO, 2019).

Furthermore, based on a meta-analysis of data from innovation surveys and the World Bank Enterprise Surveys for a number of developing countries, Bogliacino and Codagnone (2019) conclude that investing in human capital is paramount. The importance of investments in research and development (R&D) and innovation is contingent on contextual factors and the introduction of supplementary incentives to acquire advanced technologies and process innovations.

The diffusion of the 4IR imposes a twin challenge on developing country firms (Andreoni and Anzolin, 2019). First, firms may pursue a follower strategy, whereby their technological capability-building efforts enable them to weather the initial 4IR-related shocks, to adapt, to transition and to eventually thrive in the new technological, organizational and regulatory conditions prevailing in the market. Alternatively, firms may opt to adopt the more ambitious leadership strategy, whereby they aim to become the leading entity in specific markets. These firms will enter new markets as producers of 4IR-related technologies, or as providers of advanced products or services associated with it, first and foremost by expanding and enhancing their technological capabilities. These two scenarios lend support to Steinmueller's (2001) envisioned distinct specializations that countries can pursue, either in the use or in the production of novel
technologies, since it implies different stages of, and efforts towards, technological capability-building and accumulation.

Steinmueller (2001) also asserts that while catching-up in production and in the use of ICTs and related technologies is possible, it remains a relatively complex and uncertain process. Hence why the scope for developing countries to leapfrog tends to be greater in the use, rather than in the production of the new technologies, few countries possess the foundations of accumulated technological, including manufacturing and investment, capabilities that are required to lead the 4IR (Santiago and Horst, 2018).

From the above, it can be inferred that firms need to build and accumulate a set of technological capabilities to endorse and realize the 4IR. This process, however, is not automatic, passive or costless. It is firstly supported by purposive firm-level investments in technology absorption capabilities, the achievement of a minimum capability threshold or the development of basic production capabilities to foster upgrading and access to the enabling infrastructural capabilities necessary for deployment of newer and more advanced technologies.

Secondly, endorsing the 4IR entails the fostering of production system ‘retrofitting and integration’, which implies that firms’ capabilities need to either be transformed or created to retrofit and integrate manufacturing firms’ existing production technologies. Thus, the setting up of brand new plants, as frequently heralded by 4IR advocates, is rare, as this requires substantial long-term investments and promising market prospects. In parallel, risk avoidance by shareholders or firm owners intensifies given the path-dependent nature of investments and the high level of uncertainty that such emerging and rapidly evolving technologies entail (Steinmueller, 2001; Lee, 2019).

Thirdly, endorsing the 4IR necessitates the improvement of inter-firm interactions for technology access and affordability and for closing capability gaps. Advanced 4IR technologies are complex and frequently controlled by a limited number of leading firms from advanced countries (Daiko et al., 2017; UNIDO, 2019). Developing country firms’ strategic responses should include targeting the inter-firm establishment of different types of linkages. These include backward and forward linkages through, for example, supply chains, or with firms that are already meaningfully engaged in 4IR-technologies, or with other systemic actors such as research and other private or public organizations that may enable access to those technologies. Both Bogliacino and Codagnone (2019) and Andreoni and Anzolin (2019) concur on the need to strengthen firms’ cooperation capabilities with other actors in the innovation system. In particular, Andreoni and Anzolin (2019) suggest targeting existing ‘4IR islands’, i.e. firms in domestic markets with
advanced 4IR technologies and practices that may help shorten learning curves. This strategy—
aside from being reminiscent of the notion depicted in the development economics literature that
advanced (often foreign) firms in developing countries tend to operate within “enclaves” (Caves,
2007:186)—is risky, since common protocols and software platforms for the deployment of
advanced technologies and processes are missing due to the island or enclave effect.

The relationship with 4IR islands may be problematic for firms operating with earlier generation
technologies, which are often unable to meet the standards of the island firms, thus exacerbating
digital capability gaps between those island firms and potential suppliers/customers. Moreover,
and as previously highlighted in terms of the purposive efforts and investments required by firms,
many of the coveted 4IR technologies, such as all those from previous generations or revolutions,
are not simply “plug and play”. The acquisition of hardware, for example, is tightly linked to
expensive technology services and royalties for the use of the related software (Andreoni and
Anzolin, 2019) and the ability to deploy the appropriate learning mechanisms to acquire the
required tacit knowledge for the optimal implementation and use of hardware and software.
Hence, the latent risk of furthering verticalization and the concentration of power within these
island firms is very tangible.

Following the above discussion on the challenges the 4IR poses for developing country firms, we
present the conceptual framework of the study in the next section, which elaborates crucial
components for technological capability-building, and departs from well-known frameworks in
the field, with special emphasis on that of Bell and Pavitt (1995).

3 Towards a 4IR technological capability framework

This study aims to realign the conceptualization of firm-level technological capabilities developed
by scholars in the field on the 3IR to the new realities of the 4IR. It also aims to update the
technological capability framework, which serves to measure and evaluate firms’ progress along
the 4IR readiness to maturity spectrum.

In pursuing these aims, our guiding research question is: What is the spectrum of refined
technological capabilities that firms need to build and accumulate to fully endorse and realize
the 4IR?

To meet the study’s objectives and answer the research question, we conducted a systematic
literature review on the 4IR, which allows us to (i) define 4IR technological capabilities; (ii)
identify a refined set of the human and organizational activities, skills, experiences, knowledge
and resources that illustrate firms’ 4IR micro-level capabilities; and (iii) classify these into four
broad and increasingly complex levels of technological capabilities which characterize, guide and assess the progression of firms undergoing a digital transformation from 4IR readiness to maturity. An overview of our study’s conceptual framework is presented in Figure 1.

We present an overview of the 3IR technological capability framework which we depart from to develop our updated framework. This sets the premise for describing and justifying the study’s research methodology which we present in Section 4 of this paper.

3.1 Revisiting the 3IR technological capability framework

To design a technological capability framework for the 4IR, we revisit the foundational studies and relevant frameworks.

Under the 3IR, technological capabilities are defined as the stock of skills, knowledge, experience and resources that enable firms to carry out production/operational activities and differing degrees of innovative activities across the firm (Bell and Pavitt, 1995). Technological capabilities are often mistakenly and exclusively equated to physical systems and hardware. In fact, they involve both human capital (e.g. specialist professionals, knowledge bases and skills that are formally and informally allocated within specific firms, organizational units, projects and teams), and organizational aspects (firms’ internal and external organizational arrangements, such as their routines and procedures and managerial systems) (e.g. Dosi et al. 2000; Dutrénit, 2000; Kim, 1998; Bell and Pavitt, 1993).

According to Bell and Figueiredo (2012), these capabilities were drawn from a wave of in-depth firm-level qualitative studies under the 3IR led by renowned scholars in the field (Katz, 1987; Lall, 1987, 1992; Bell et al. 1982; Bell and Pavitt, 1995). These studies generated a comprehensive approach for operationalizing technological capability levels based on revealed capability, rather than specifically identifying them in terms of concrete quantities and qualities of human resources, skills, knowledge bases, etc. (Bell and Figueiredo, 2012). They therefore identified levels of increasing novelty and the significance of innovative activity, which inferred that different capability levels underlie different degrees and types of innovative activities (Bell and Figueiredo, 2012). These empirical efforts led to the creation of a refined typology of 3IR technological capabilities.
Figure 1 Conceptual framework of the study

Aims of the study:
1. Update the technological capability framework from the 3IR to the 4IR
2. Create a framework for assessing 4IR industrial technological capabilities

Methodology:
Systematic literature review on the 4IR

We define 4IR technological capabilities

From the systematic literature review, we identify a refined set of 4IR human and organizational activities, skills, knowledge, experiences and resources that illustrate the firm’s 4IR micro-level technological capabilities

We organize them into clusters of technological/organizational functions of the firm

We classify these illustrative capabilities from each cluster along four levels of increasingly complex technological capabilities on the 4IR readiness to maturity spectrum of digital transformation

We thematically created these four levels of technological capabilities

The outcome is an assessment framework for future empirical studies.
Our conceptual framework and methodology builds on a typology with four levels of technological capabilities as developed by Lall (1992) and Bell and Pavitt (1995), and shown in Appendix 1. Their typology is one of the most concise approaches and is therefore well-suited to explain our conceptual framework.4

The typology classifies technological capabilities across different technological and/or organizational functions of the firm on a scale of increasingly complex degrees of novelty and technological activities. This classification typically involves sequences that start with the production capability level and ultimately leading to innovative capability levels.

The framework that we apply as a baseline in our study starts at the lowest level of technological complexity, which is the operational/production capability level. At this level, firms have the capability to produce goods at given levels of efficiency and input requirements. The firms’ capability is mainly concentrated in technology-using skills and in simple organization arrangements for routine production. Production/operation capabilities, therefore, do not entail any form of innovative capabilities.

The ensuing three levels are basic, intermediate and advanced innovative capability levels. Their full descriptions can be found in Appendix 1. They entail the capability to create, change or improve products, processes and production organization or equipment. They are described as change-generating capabilities, consisting of technology-changing skills, knowledge, experiences and organizational arrangements. At the basic innovative capability level, firms have the ability to make incremental adaptations and improvements to process, products and equipment. At the intermediate innovative capability level, the firm has full production skills, process innovation and product design capability, and can engage in innovative reverse engineering and implement major organizational changes. Finally, at the advanced level, the firm has full R&D capabilities across the various functions of the firm and engages in radical innovations. Thus, the production and innovative capabilities taken together constitute what the development and innovation studies literature commonly terms as the technological capabilities of the firm. The distinction between these two types of capabilities may be blurred in practice, and production/operational capabilities often overlap with—and may even contribute to—the accumulation of innovative capabilities (Bell and Figueiredo, 2012; Peerally et al., 2019; Peerally and Cantwell, 2012).

4 Other studies have also distinguished four levels of technological capabilities (e.g. Hobday et al., 2004; Tsekouras, 2006; Peerally et al., 2019; Peerally and Cantwell, 2012), while some have developed more detailed schema consisting of six or seven levels (Figueiredo 2003, Ariffin and Figueiredo 2004, Ariffin 2010).
This typology has been extensively and successfully used in studies with different degrees of technological capability level disaggregation, ranging from longitudinal, historical and qualitative case-based studies (e.g. Dantas and Bell, 2011; Figueiredo, 2002; Dutrénit, 2000; Peerally et al., 2019) to quantitative, large sample, survey-based studies (e.g. Peerally and Cantwell, 2012; Yoruk, 2011; Ariffin, 2010).

In terms of hardware and software, recent frameworks (Peerally et al., 2019; Peerally and Cantwell, 2012) illustrate that firm-level technological capabilities involve integrating automatic/semi-automatic processes, implementing full-scale automation with computer aided/controlled systems and developing full-scale new production processes and standards with some degrees of digitalization (computer-aided design/manufacturing systems) and basic components of cyber physical systems such as the use of sensors on the production floor. Other recent works (Figueiredo and Cohen, 2019; Figueiredo et al., 2020) also include a fifth level in the typology, namely world-leading technological capabilities. These refer to the capability to create new technologies and implementing cutting-edge innovations based on world-class R&D (for applied and basic research) and engineering, either intra-firm and standalone or inter-firm through collaborations with other actors in the firm’s innovation system. Thus, the technological capability framework and its individual levels of technological capabilities ranging from basic to advanced to world-leading has always been consistent with the different editions of the Oslo Manual for measuring innovation (OECD, 2018). Markedly, these recent works highlight the uptake of more advanced 3IR practices, technologies and processes by firms and thus bringing the latter closer to the 4IR frontier – a frontier that is blurred in terms of technologies.

We conclude this section of the paper with three noteworthy aspects about the technological capability literature and framework. First, technological capability-building is supported by firms that deliberately engage in intra-firm and inter-firm technological learning (Bell and Figueiredo, 2012; Figueiredo, 2001). Learning is defined as the various costly and deliberate processes by which additional technical skills and knowledge are acquired by individuals and firms (Bell, 1984) through intra and inter-firm linkages with other economic and non-economic agents. Bell and Figueiredo’s (2012) work comprehensively covers the inter- and intra-firm learning mechanisms employed by firms to build-up their technological capabilities.

Second, a major attribute of the 3IR technological capability framework is that it captures the process of technological transformation within a wide spectrum of technological and organizational functions in the firms, especially those that precede R&D capabilities and are crucial to the initial growth of developing country firms. Thus, the conceptual language used within the 3IR technological capability literature is quite precise so as to closely convey the
upgrading of firms’ technological capabilities. The conceptual language includes words such as ‘implementing, integrating and using’ which refer to the firm acquiring off-the-shelf technologies and processes, and therefore reflect lower levels of innovative capabilities. The words ‘developing and designing’ refer to a firm’s ability to create the required technologies and processes in-house and it is therefore designated as having higher levels of innovative capabilities.

Third, the technological capability framework developed by Bell and Pavitt (1995) was less about the producers of capital goods or original equipment manufacturers (OEMs) and more about the users of capital goods. The former, according to Bell and Pavitt (1995), is mostly associated with the diffusion of technology from developed to developing countries, while the latter is associated with the process of innovation through the accumulation of firm-level technological capabilities. While technological development and change is brought about by both capital goods suppliers and users, their framework focuses on the processes that recipient firms in developing countries engage in to build their own capabilities to become and stay internationally competitive. As the literature evolved and as firms in developing countries accumulated more advanced technological capabilities, some firms emerged as important OEMs or suppliers of capital goods to other developing country firms. Initially, the Republic of Korea and the Republic of China (Taiwan), and later China, are such examples. Hence, according to Bell and Pavitt (1995), suppliers of capital goods and OEMs are not the sole creators and sources of innovations. Users of capital inputs and original equipment often play active and creative roles in innovating and upgrading the technology and equipment sourced from others. This dynamic, we surmise, will continue to prevail under the 4IR as well.

4 Methodology

Our research methodology and strategy are driven by our main research question which is: What is the spectrum of technological capabilities that firms need to build and accumulate to fully endorse and realize the 4IR?

Our study is based on a qualitative research approach involving a systematic literature review. As mentioned in the previous section, 3IR technological capabilities were initially derived from a wave of in-depth firm-level qualitative case studies. Since the 4IR literature is rather dense and extensive, it represents a rich, fertile ground of existing—yet discombobulating—secondary qualitative data on the human and organizational activities, skills, experiences, knowledge and resources that constitute the 4IR technological capabilities. Thus, a systematic literature review provides the valuable data needed to achieve the aims of our study.
Our research methodology involved collecting, analysing and classifying the data, i.e. human and organizational activities, skills, experiences, knowledge and resources—referred to as illustrative capabilities from hereon—into (i) specific clusters of technological and organizational functions and ultimately (iii) into four increasingly complex 4IR levels of technological capabilities. We used the insights gained from the 4IR systematic literature review and theoretical underpinnings of the technological capability literature to guide this process. This is further explained in the next subsection.

### 4.1 Data collection through a systematic literature review

We conducted a systematic review periodically over a period of three years (2018–2020). It was completed with the last round of the literature review in August 2020.

At the beginning of the systematic literature review, we focused mainly on searching for the terms “Industry 4.0”, “Fourth Industrial Revolution” and “4IR” in the databases. Since these terms encompass a plethora of modern and advanced technologies across multiple disciplines and applications, our searches generated thousands of publications. We narrowed down our search by inserting relevant terms such as “digitalization and manufacturing”, “Internet of Things”, “cloud computing”, “cyber physical systems”, “smart factories”, “smart products”, “cloud system”, “enterprise resource planning”, “virtual manufacturing”, “artificial intelligence” and “intelligent robotics”. The documents we retrieved from our search are peer-reviewed research articles, book chapters, reports from international organizations, working papers, white papers and government reports. Supplemental details related to the systematic literature review are provided in Appendix 2. Additionally, following Oztemel and Gursequ (2018), we reduced the scope of academic publications to those in engineering, manufacturing and management, while those published by international organizations and governments mostly focus on policies and diagnostic tools and processes. We identified 640 documents in total, and their content was skimmed to determine whether, in accordance with our theoretical lens, they cover 4IR technological capability levels and the human and organizational activities, skills, experiences, knowledge and resources that constitute technological capabilities. We identified three documents that broadly categorize and describe 4IR capability levels\(^5\) and 115 documents on illustrative capabilities for in-depth scrutiny in the ATLAS.ti software.

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\(^5\) The first is the Singapore Economic Development Board’s (EDB) framework with 6 levels of 4IR capabilities. It is based on the Reference Architecture Model Industrie 4.0 (RAMI 4.0) developed by the German Electrical and Electronic Manufacturers’ Association (ZVEI) to support Industry 4.0 initiatives. Both approaches have gained broad acceptance worldwide. The two other frameworks were developed by Albrieu et al. (2019) and Gökalp et al. (2017), who identify 4 levels and 5 levels of 4IR capabilities, respectively. However, these frameworks do not provide the refined activities, skills, knowledge, experiences and resources established within these broad levels of capabilities.
Based on abductive reasoning, we used open coding to identify the illustrative capabilities in the 115 documents. Abductive reasoning was necessary since some studies clearly state 4IR illustrative capabilities and others only imply them.

We achieved saturation early in the data collection process, but nevertheless, for research rigour and consistency, we coded all 115 documents. Once all of the illustrative capabilities from these documents were coded, our data collection process was completed.

4.2 Data analysis

First, we reviewed the collected illustrative capabilities and removed all duplications. In the end, we obtained a total of 155 illustrative capabilities. Second, in this and the subsequent steps of our data analysis, we built matrix data displays. For the first matrix we used deductive logic to group the 155 illustrative capabilities into six clusters of identified 4IR technological or organizational functions across the manufacturing firm, as shown in Figure 2. These clusters were derived from the systematic literature review.

These six clusters on technological or organizational functions are: (1) data integration, management and protection; (2) project management; (3) predictive and smart maintenance; (4) product development; (5) manufacturing processes and organization; and (6) supply chain management.

From the six clusters, two based on their breadth of activities and categorization in the existing 4IR literature, were further subdivided into sub-clusters. Firstly, the cluster on data integration, management and protection was subdivided into: (A) techniques and tools, (B) acquisition of skills and resources, and (C) threats and security. Secondly, the manufacturing processes and organization cluster was subdivided into: (A) cloud manufacturing, (B) collaborative manufacturing, (C) self-optimizing and knowledgeable manufacturing systems, (D) additive manufacturing, and (E) context-aware manufacturing information.

Following our conceptualized definition of 4IR technological capabilities, we subsequently built matrix data displays for each cluster and subcluster, whereby the illustrative capabilities were analysed using deductive reasoning, and classified in order of increasing complexity along the spectrum of the starting point that launches the 4IR development process to the 4IR maturity state.

The final analytical step involved generating our four increasingly complex levels of 4IR technological capabilities. Through an iterative process of cycling back and forth between the

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6 It must be noted that we tried to classify the 155 illustrative capabilities for each cluster in the 4IR capability levels from Albrieu et al. (2019), Gökalp et al. (2017), and the Singapore Economic Development Board (EDB, 2017). This
matrix data displays of the illustrative capabilities across the six clusters, our knowledge of the
technological capability literature, and the conceptual and empirical insights gained during our
systematic review of the 4IR literature, we engaged in a deductive process of thematic analysis to
create and label four levels of increasingly complex technological capabilities. The illustrative
capabilities that were already classified in order of increasing complexity in the previous step,
were then regrouped into these four thematic 4IR-labelled levels of technological capabilities.

These four levels are therefore grounded in and emerged from our secondary data analysis, which
is based on our systematic 4IR literature review of empirical and conceptual research in the field.
Theorizing was therefore part of this process as well, since Levels 2 to 4 of any 4IR capability
framework have yet to be fully realized in practice. In fact, one of the latest publications
(Niemeyera et al., 2020) on Germany, where the 4IR concept was incepted, shows that current
learning by SMEs with the support of the government accelerator Digital Capability Center, is
based on the retrofitting of existing machinery and equipment to help SMEs launch their digital
transformation process.

The four levels of 4IR technological capabilities, as seen in Figure 2, is one of the conceptual
contributions of this study. It starts at the lowest level of 4IR technological complexity (Level 1),
which is the retrofitting and readiness capability stage and ends at the highest level of 4IR
technological complexity (Level 4), which is the smart – intelligent – capability stage, whereby
the firm achieves, or is close to achieving, the smart factory or digital factory status. These are
discussed further in the next section of the paper.

5 Findings

In this section, we present our framework which identifies four levels of 4IR technological
capabilities and numerous illustrative capabilities for each level. This framework contributes to
the identification of technological capabilities required for firms to endorse and realize the 4IR.
For practical purposes, the 4IR technological capability framework is extended over several
figures (see Figures 3 – 13).

While we undertook all the necessary steps to ensure that our research was designed in a structured
and rigorous manner, the extent of illustrative capabilities presented in our framework is not
exhaustive for the ever-evolving 4IR domain. However, our research approach ensures that the

was unproductive, as with further analysis we found that the illustrative capabilities we collected from the systematic
literature review determined the nature and description of the 4IR technological capability levels, and not these three-
existing works. Thus, our four levels of 4IR technological capabilities are grounded in the secondary data we collected.
Nevertheless, the capability levels from these three works inspired our own description and categorization of 4IR
technological capability levels.
Figure 2: The clusters and subclusters of 4IR-related functions and the four levels of 4IR technological capabilities

Clusters and subclusters of identified technological and organizational functions across the manufacturing firm

- **Cluster 1: Data integration, management and protection**
  - Subclusters:
    - A. Techniques and tools
    - B. Acquisition of skills and resources
    - C. Threats and security

- **Cluster 2: Project management**

- **Cluster 3: Predictive and smart maintenance**

- **Cluster 4: Product development**

- **Cluster 5: Manufacturing processes and organization subclusters**
  - A. Cloud manufacturing
  - B. Collaborative manufacturing
  - C. Self-optimizing and knowledgeable manufacturing systems
  - D. Additive manufacturing
  - E. Context-aware manufacturing information systems

- **Cluster 6: Supply chain management**

These clusters and subclusters are further disaggregated into refined sets of the 4IR human and organizational activities, skills, experiences, knowledge and resources and categorized in an order of increasing complexity in accordance with the four levels of technological capabilities.

**Level 1:**

- **Retrofitting and readiness capability**

  The firm has the capability to integrate the legacy operations, technologies and production systems from the 3IR with retrofit kits and to develop the pre-required skills, knowledge and resources to launch digital transformation. The implementation of new industrial ‘Industry 4.0 ready’ equipment.

**Level 2:**

- **System integration capability**

  The firm has the capability to implement 4IR technologies for integrating systems within the firm. There is physical-digital technology integration and intra- and inter-firm data integration networks. It develops 4IR-specific accreditations and quality standards. It integrates more advanced 4IR technologies and systems in production. It can embed products with algorithms and software and engage in early smart product evaluation and prototyping. It uses event-based and data-driven information systems. There is optimization of supply chain management and performance.

**Level 3:**

- **Enhanced horizontal and vertical digitalization capability**

  The firm has the capability to identify its critical digitalization needs and implement them horizontally and vertically across the firm. It can develop digital technologies to gain benefits from data. There is advanced use of simulation and visualization technologies across the firm. It manufactures the first smart and 4IR product prototypes. There is enhanced horizontal and vertical digitalization of lifecycle management of products and processes. It initiates the integration of advanced 4IR technologies across the entire supply chain, i.e. across firms. It uses advanced robotics and automation solutions.

**Level 4:**

- **Smart – intelligent – capability**

  The firm has the capability to be self-optimized and autonomized. Its 4IR operations, technologies and production systems are fully integrated end-to-end, i.e. across the firm and the supply chain. There is end-to-end digitally integrated engineering and end-to-end virtual supply chain visualization. Systems are in place for scaling data management, for mass-customization of products and for smart product and life cycle management.
framework can be updated periodically with forthcoming studies that identify additional firm-level 4IR technological capabilities.

5.1 The four levels of 4IR technological capabilities

In line with previous studies (e.g. Bell and Figueiredo, 2012; Bell and Pavitt, 1995; Peerally et al., 2019; Peerally and Cantwell, 2012), these four levels of technological capabilities (see Figure 2) distinguish between increasingly complex levels of capabilities needed by firms to endorse the 4IR, from launching the 4IR development process to reaching the 4IR maturity state.

The retrofitting and readiness capabilities entail integrating the legacy operations, technologies and production systems of the 3IR with retrofit kits and to develop the pre-required skills, knowledge, experience and resources to launch the digital transformation. This level also involves the acquisition and implementation of 4IR ready new industrial equipment.

The system integration capabilities involve the implementation of 4IR technologies to integrate systems within the firm. At this level, physical-digital technology integration occurs and the firm establishes intra- and inter-firm data integration networks. It develops 4IR-specific accreditations and quality standards, and integrates more advanced 4IR technologies and systems in production. The firm can embed products with algorithms and software, and engage in early smart product evaluation and prototyping. It uses event-based and data-driven information systems. Moreover, supply chain management and performance are optimized.

The enhanced horizontal and vertical digitalization capabilities entail the firm’s ability to identify critical digitalization needs and to implement them horizontally and vertically across the firm. At this level, the firm can implement digital technologies to gain benefits from data. There is advanced use of simulation and visualization technologies across the firm. It manufactures the first smart and 4IR product prototypes. There is enhanced horizontal and vertical digitalization of life cycle management of products and processes. It initiates the integration of advanced 4IR technologies across the entire supply chain, i.e. across firms. It uses advanced robotics and automation solutions.

The smart-intelligent-capabilities involves self-optimization and autonomization. At this level, the firm’s 4IR operations, technologies and production systems are fully integrated end-to-end, i.e. across the firm and supply chain. There is end-to-end digitally integrated engineering and end-to-end virtual supply chain visualization. Systems are in place for scaling data management, for the mass-customization of products and for smart product and life cycle management. Thus, at this level, the manufacturing firm is or closely resembles the smart factory or digital factory.
The distinction between these four capabilities levels is blurred in practice, since the digital transformation process is not linear. This blurriness represented a concrete challenge during our data analysis phase. The data emphasized the fact that the digital transformation process is extremely iterative in nature, and that during this process, firms tend to recursively implement and build on different 4IR technologies and systems. This is further complicated by the fact that this recursive digital transformation process also occurs at the vertical and horizontal levels within the firm, and then across the supply chain with other firms.

The issue of blurriness also arises with regard to the types of technologies that are at the core of the 4IR. While it has been established that nine technologies lie at the core of the 4IR, namely robotics, big data, augmented (virtual) reality, additive manufacturing, cloud computing, cybersecurity, Internet of Things, systems integration and simulation (Santiago, 2018), their related capabilities cannot be neatly organized into self-contained boxes within the context of the manufacturing firm, since these often overlap and the lines between them are blurred. Moreover, these nine technologies have relevant applications across several technological or organizational functions of the firm, and this aptly applies, for example, to the case of systems integration and simulation. Even though Level 2 of our framework is titled system integration capability, we acknowledge that system integration is both a capability and a technology, and follow an iterative development pathway along the digital evolution of the firm, with development starting at this capability level.

The building and accumulation of technological capabilities is not a passive or cost-free process under the 4IR. As in the case of the 3IR, it requires purposive and sustained investment and learning by firms. The nature of firm learning has transcended these two revolutions. It encompasses all the ways in which firms acquire the knowledge, skills and other cognitive resources needed to adopt more complex 4IR technologies and processes. These include inter-firm knowledge sourcing through interactions and collaborations with other systemic actors within the 4IR innovation system, and intra-firm knowledge creation through the many learning mechanisms that have been extensively documented by Bell and Figueiredo (2012).

As discussed in Subsection 3.1, technological change under the 3IR was associated with 'implementing, integrating and using' off-the-shelf technologies from capital good suppliers; the use of learning mechanisms allowed firms to upgrade these off-the-shelf technologies and eventually 'develop and design' their own technologies in-house. Thus, the accumulation of technological capabilities through learning mechanisms allowed firms to increasingly amass higher levels of innovative capabilities. Within the context of the 4IR, we postulate that those firms that have embarked on the digital transformation journey, have already amassed advanced
and world leading innovative capabilities. Their objective is less about amassing capabilities for the creation of new 4IR original equipment, as the complex task of configuring legacy equipment for the new industrial ecosystem is hampered by investment risk and lack of technical expertise (Zambetti et al., 2020). Thus, our 4IR technological capability framework is designed for 4IR capital goods users, i.e. manufacturing firms, rather than for 4IR OEMs. The former, as posited earlier, are engaged in building and accumulating technological capabilities to adopt more complex 4IR technologies and processes to implement and manage digitalization transformation. This does not, however, preclude them from developing new technologies, products and processes in-house, if and when needed. We present our framework in the next subsection.

5.2 A refined firm-level 4IR technological capability framework

Our refined framework maps six clusters on technological or organizational functions against four levels of 4IR technological capabilities (see Figures 3 – 13).

It must be noted that some of the classified 155 illustrative capabilities in the framework are sometimes duplicated across technological or organizational functions, which in particular applies to the manufacturing processes and organization cluster and the subclusters of capabilities. Alternative clusters can be derived depending on the theoretical premises applied by researchers; interesting areas include those related to the circular economy, sustainability and the consumer stage of product life cycles. However, deriving more clusters would imply re-stating the capabilities we present in our framework, but in different combinations of technological or organizational functions.

The findings for Cluster 1 on data integration, management and protection are presented in Figures 3 and 4, and include the subclusters of techniques and tools, the acquisition of skills and resources, and threats and security. The illustrative capabilities classified are considered prerequisite capabilities of 4IR readiness, since this revolution is information-intensive and big data-driven. To achieve readiness, firms must first integrate existing data with additional data sources derived from the implementation of new digital technologies across the firm. In a first step, the purpose of this integration is to, firstly, achieve a communication-based working environment between all of the firm’s horizontal and vertical activities and the product’s entire life cycle, which is secure and safe from external threats, such as hacking. Secondly, this integration is ultimately aimed at gaining efficiencies on multiple levels, to create end-to-end data and information streams across the value and supply chains. To achieve 4IR readiness and later 4IR maturity, one of the initial key steps for firms is to acquire and develop the resources needed to integrate, manage and protect these large amounts of data.
<table>
<thead>
<tr>
<th>Levels of 4IR technological capabilities</th>
<th>Subcluster A. Techniques and tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrofitting and readiness capability</td>
<td>Storing and exchanging data in the form of proprietary applications and using heterogeneous database solutions between various departments or production halls.</td>
</tr>
<tr>
<td>System integration capability</td>
<td>Implementing cloud computing and service platforms for data collection and analytics. Implementing semantic interoperability by applying the protocols for executing efficient and effective communication and transaction of data between different devices/machines. Implementing quality of service, which involves managing network resources by setting priorities for different data types and providing better service over a congested network (e.g. bandwidth delay).</td>
</tr>
<tr>
<td>Enhanced horizontal and vertical digitalization capability</td>
<td>Developing new algorithms and new models to use and gain actual benefits from the data. Developing new tools and platforms to integrate data at the production and firm-level. Developing new algorithms and visualization techniques to use and gain actual benefits from the data. Implementing visual computing to acquire, analyse and synthesize visual data by means of computers that provide automation and flexibility to the production process. Integrating self-organizing and adapting features to enable the system to retrieve data from heterogeneous devices in the required format and to monitor the system’s functioning.</td>
</tr>
<tr>
<td>Uptake along the 4IR readiness to 4IR maturity spectrum</td>
<td>Developing new products to use and gain actual benefits from the data. Developing new tools and platforms to integrate data across the supply chain and inter-firm.</td>
</tr>
</tbody>
</table>

Source: Based on authors’ own research and elaboration derived from the systematic literature review.
Figure 4  Illustrative capabilities of Subcluster B on acquisition of skills and resources and Subcluster C on threats and security under Cluster 1 on data integration, management and protection function

<table>
<thead>
<tr>
<th>Levels of 4IR technological capabilities</th>
<th>B. Acquisition of skills and resources</th>
<th>C. Threats and security</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrofitting and readiness capability</td>
<td>Hiring and retaining qualified technicians, engineers, and managers. Developing digital skills required for strategic planning, market research, business analysis, and improving general firm performance. Developing soft skills necessary to ensure collaborative work among professionals. Developing basic digital skills, related to the effective use of technology, including web research, online communications, etc. Developing advanced digital skills related to technology development such as coding, software and app development, etc.</td>
<td>Ensuring protection of information related to financial activities and human resources. Protecting data across the value chain. Protecting the firm from malfunctioning devices. Ensuring that manufactured electronic products do not contain viruses from production facility.</td>
</tr>
<tr>
<td>System integration capability</td>
<td>Developing expertise to transfer data into other systems, e.g. knowledge of system landscape transformation, and extract, transform and load methods. Developing/acquiring the skills and capacity to analyse large amounts of data collected across all functions of the firm, across the supply chain and across the entire lifecycle of a product.</td>
<td>Ensuring data privacy and protecting against intellectual property theft and counterfeit products. Protecting data sent via public networks from unauthorized viewing or manipulation through the use of inherent blockchain encryption. Using blockchain to control the usage of the digital property.</td>
</tr>
<tr>
<td>Enhanced horizontal and vertical digitalization capability</td>
<td>Developing software capabilities for shop-floor- and production-related applications and data-driven services. Acquiring software licenses. Continuous updating and upgrading of software and hardware in the production environment.</td>
<td>Protecting critical industrial systems and manufacturing lines from cybersecurity threats, e.g. hackers. Developing secure, reliable communications as well as sophisticated identity and access management of machines and users.</td>
</tr>
<tr>
<td>Smart – Intelligent – capability</td>
<td>Scaling the data management system where it can manage increased loads of large data and applications under extreme environments.</td>
<td>In-house design of systems for the protection of data. In-house design of redundant systems for the storage of data.</td>
</tr>
</tbody>
</table>

*Source:* Based on authors’ own research and elaboration derived from the systematic literature review.
The illustrative capabilities of Cluster 2 on project management are presented in Figure 5. The organizational function is contended by the United Kingdom’s Office for National Statistics to be the least at risk from automation (Dore, 2019). The capabilities we classify reveal the extent of the impact the new 4IR technologies and processes will have on firms as well as on the skills and role of project managers and officers in this process from interfacing and integrating the physical world with digital technologies to leading the development of 4IR conformity and accreditations and to innovating business models.

The illustrative capabilities of Cluster 3 on predictive and smart maintenance are presented in Figure 6. The maintenance function affects the performance of machinery and equipment and is therefore closely tied to the productivity of manufacturing processes, investment returns of capital invested and the firm’s final bottom line, namely profits. Thus, a smart factory requires predictive and smart maintenance management capabilities as these play a crucial role in securing productivity and profits. The 4IR changes the way traditional maintenance is conducted, and the integration of digital technologies and information that is generated by the interconnected devices and machines gives rise to predictive and smart maintenance. As illustrated in Figure 5, a gradual building and accumulation of predictive maintenance to smart maintenance management capabilities is needed as firms increasingly adopt more complex technologies to achieve a full integration of the industrial Internet of Things to enhance preventative and smart maintenance management.

The capabilities under Cluster 4 on product development are presented in Figure 7. As the figure illustrates, the capabilities are extensive and complex since the 4IR requires the integration of physical and digital technologies with the different phases of the product, i.e. from the development phase to the semi-finished and finished product, to the consumption, disposal and recycling phases. The integration between physical and digital technologies requires the accumulation of capabilities that enable the mass customization of products, the reduction of product development time, and the time required to market the finished product. The development of smart products, among other things, entails accumulating capabilities that will allow products to self-identify and provide information about their progress throughout their life cycle, while storing information about all of the process steps within the value chain, and providing information about further process steps regarding the products’ production, maintenance and consumption.
### Figure 5  Illustrative capabilities of Cluster 2 on the project management function

<table>
<thead>
<tr>
<th>Levels of 4IR technological capabilities</th>
<th>Cluster 2. Project management function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrofitting and readiness capability</td>
<td>Risk probability and impact assessment.</td>
</tr>
<tr>
<td></td>
<td>Running feasibility studies before choosing appropriate 4IR technologies.</td>
</tr>
<tr>
<td></td>
<td>Active monitoring and control of feasibility studies, 4IR technology search and sourcing and project scheduling.</td>
</tr>
<tr>
<td></td>
<td>Providing project management services intra-firm (to primary and support departments) and inter-firm (clients and other firms in the supply chain) for the uptake of 4IR technologies and processes.</td>
</tr>
<tr>
<td></td>
<td>Designing protocols required for executing efficient and effective communication and transaction of data between different devices/machines.</td>
</tr>
<tr>
<td></td>
<td>Engaging in multi-stakeholder collaborative efforts to develop global standards and protocols on data sharing.</td>
</tr>
<tr>
<td>System integration capability</td>
<td>Engaging in multi-stakeholder collaborative efforts and with conformity assessment bodies to develop 4IR-specific accreditations.</td>
</tr>
<tr>
<td></td>
<td>Development and implementation of a 4IR project risk management framework.</td>
</tr>
<tr>
<td></td>
<td>Implementing and integrating physical and digital technologies across the firm and its processes through interfacing networks.</td>
</tr>
<tr>
<td></td>
<td>Ensuring compatibility which keeps the firm’s system’s components working together in a functioning environment without implementing any changes to the system.</td>
</tr>
<tr>
<td></td>
<td>In-house development and implementation of Quality 4.0 standards.</td>
</tr>
<tr>
<td>Enhanced horizontal and vertical digitalization capability</td>
<td>Simulating a virtual environment for system analysis and optimization.</td>
</tr>
<tr>
<td></td>
<td>Using big data, modeling and simulation and 4IR system integration technologies before manufacturing the first smart and 4IR product prototypes.</td>
</tr>
<tr>
<td></td>
<td>Developing the communication and working environment between all horizontals and verticals of an organization for the entire lifecycle of a product.</td>
</tr>
<tr>
<td>Smart – intelligent – capability</td>
<td>Using big data and analytics to assess innovative business models.</td>
</tr>
<tr>
<td></td>
<td>Implementing innovative business models through integrative frameworks.</td>
</tr>
<tr>
<td></td>
<td>Augmented reality for monitoring the environmental, design, operational and technical risks of the project.</td>
</tr>
</tbody>
</table>

*Source:* Based on authors’ own research and elaboration derived from the systematic literature review.
Figure 6  Illustrative capabilities of Cluster 3 on the predictive and smart maintenance function

<table>
<thead>
<tr>
<th>Levels of 4IR technological capabilities</th>
<th>Cluster 3. Predictive and smart maintenance function</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Retrofitting and readiness capability</strong></td>
<td>Incrementally replacing real-time systems with more advanced complex adaptive systems and multi-processing, to predict the rejection of machined parts. Using models to predict which parts of machines are going to fail or become vulnerable in production.</td>
</tr>
<tr>
<td><strong>System integration capability</strong></td>
<td>Collecting and using data from machines to provide remote diagnostics and offer maintenance services from remote locations. Implementing machine-to-machine communication which supports the maintenance of machines. Using fog and cloud computing for the management of maintenance and preventative maintenance tasks.</td>
</tr>
<tr>
<td>Enhanced horizontal and vertical digitalization capability</td>
<td>Implementing early warning systems within processes to detect changes in the condition of the system, i.e. they address down time, service reliability, updating, error-detection and failures to carry out maintenance services. Mastering condition-based maintenance for predicting failure with real-time asset data as a step towards developing the foundations for advanced predictive maintenance. Implementing logistics assistance systems. Improving the availability of linear assets through the effective use of autonomous robots and data from different sources.</td>
</tr>
<tr>
<td><strong>Smart – intelligent – capability</strong></td>
<td>Implementing systems for remote setting of parameter or operating conditions. Implementing new software applications in wireless sensors and distributed peer-to-peer networks to enable communication within larger complex adaptive systems of the firm infrastructure. Using autonomous inspection and maintenance systems for linear assets to reduce maintenance costs, human involvement, etc. Full integration of industrial Internet of Things to enhance preventative and smart maintenance management.</td>
</tr>
</tbody>
</table>

*Source: Based on authors’ own research and elaboration derived from the systematic literature review.*
### Illustrative capabilities of Cluster 4 on the product development function

<table>
<thead>
<tr>
<th>Levels of 4IR technological capabilities</th>
<th>Uptake along the 4IR readiness to 4IR maturity spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrofitting and readiness capability</td>
<td>Leveraging existing product development capabilities from previous generations of technologies. Designing flexible products at an affordable cost.</td>
</tr>
<tr>
<td>System integration capability</td>
<td>Running simulations on product lifecycle management. Developing methods to identify customers’ requirements and the use of suitable product representations to support communication in early product evaluation and prior to prototyping. Creating products with algorithms and software embedded in them for the purpose of collecting data analytics. Creating products with algorithms and software embedded in them for the purpose of providing end-users with technical or after sales support. Achieving shorter product development times and an increased productivity.</td>
</tr>
<tr>
<td>Enhanced horizontal and vertical digitalization capability</td>
<td>Developing increasingly complex or smart products that integrate new materials, functionalities and production processes technologies. Using efficient digital product modelling and simulation tools during the development of complex or smart products to decrease product development time, optimize resource consumption and eliminate waste by the firm and consumers.</td>
</tr>
<tr>
<td>Smart – intelligent – capability</td>
<td>Using digital technologies to provide a full understanding of product features and benefits, facilitating the interactive exploration of the new product’s functionalities in the development phase between every stakeholder. Choosing and integrating the digital technologies that comprise advanced computing platforms, such as virtual reality, augmented reality or mixed reality for product development and prototyping. Integrating product customization by consumers into the entire manufacturing process. Developing smart products that are integrated in the entire manufacturing process and actively support the manufacturing process by controlling individual production stages autonomously. Developing smart products that are aware of the parameters within which they should be used, and provide information about their status during their whole lifecycle. Integrating cyber physical systems that enable better lifecycle management of products or the development of new services, especially for maintenance purposes at the consumer end.</td>
</tr>
</tbody>
</table>

*Source*: Based on authors’ own research and elaboration derived from the systematic literature review.
The illustrative capabilities of Cluster 5 on manufacturing processes and the organization function includes five subclusters: (A) cloud manufacturing, (B) collaborative manufacturing, (C) self-optimizing and knowledgeable manufacturing systems, (D) additive manufacturing, and (E) context-aware manufacturing information. These, as illustrated in Figures 8 to 12, are also extensive and complex, with some key retrofitting and readiness capabilities duplicated across the five subclusters. This duplication reflects firms’ shift from using 3IR processes and technologies to implementing 4IR ones. This involves leveraging on existing manufacturing capabilities from the previous generation of technologies and incrementally adopting new processes and managerial strategies to support and launch the implementation of the 4IR’s manufacturing digitalization process and smart manufacturing practices. It also involves standardizing infrastructure to implement increasingly advanced technologies and processes across the manufacturing function. This is required for integrating heterogeneous devices/components in automation systems in subsequent stages, and developing smart devices and sensor technology. From the retrofitting and readiness capability level to the smart – intelligent – capability level, we can observe the accumulation of required capabilities across all nine technologies that lie at the core of the 4IR.

The illustrative capabilities of Cluster 6 on supply chain management—or the Supply Chain 4.0—are illustrated in Figure 13, and cover those ranging from assessing cost reduction strategies and challenges and opportunities in supply chain management practices to the most advanced one, namely the full digitalization of the supply chain within and across firms. The digitalization of supply chain activities is considered one of the most important characteristic features of the 4IR, and is said to enable all its other characterizing features (Pfohl et al., 2015). With the advent and implementation of smart logistics and the smart factory, and the full digitalization of the supply chain, the supply chain will be structurally and technologically transformed with enormous potential benefits for sustainability, among others. Nonetheless, some researchers (see e.g. Tjahjono et al., 2017) have argued that while theoretically, there are many 4IR impacts on supply chain management, there are only a few stipulated examples of its actual or realized impacts in practice. Indeed, Pfohl et al. (2015) found that out of 49 identified technologies and concepts within the 4IR supply chain realm, only 15 are of high practical significance. This represents one of the many challenges that comes with the 4IR.
Figure 8  
Illustrative capabilities of Subcluster A on cloud manufacturing from Cluster 5 on manufacturing processes and organization function

<table>
<thead>
<tr>
<th>Levels of 4IR technological capabilities</th>
<th>Subcluster A. Cloud manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrofitting and readiness capability</td>
<td>Leveraging on existing manufacturing capabilities from the previous generation of technologies and incrementally adopting new processes and managerial strategies to support and launch the implementation of the manufacturing digitalization process. Using cloud platform and services, which allow systems and partners to work from anywhere, communicate and collaborate in the real-time cloud environment. Integrating the heterogeneous devices/components in automation systems and developing smart devices and sensor technology.</td>
</tr>
<tr>
<td>System integration capability</td>
<td>Using cloud-based software and analytics applications for production-related undertakings. Increasing data sharing through cloud-based manufacturing across sites and company boundaries. Running simulations on cloud-based manufacturing.</td>
</tr>
<tr>
<td>Enhanced horizontal and vertical digitalization capability</td>
<td>Deploying machine data and functionality to enable more data-driven services for production systems. Implementing cloud-based systems that monitor and control processes. Using rapid manufacturing techniques and technologies. Implementing cloud-based manufacturing processes focused on recycled materials, exploitation of biomaterials or the reuse of products/materials.</td>
</tr>
<tr>
<td>Smart – intelligent – capability</td>
<td>Implementing individualized production which will allow for mass customization manufacturing. Adopting equipment and devices enriched with embedded computing capable of communicating and interacting both with one another and with more centralized controllers within the firm. Integrating autonomous robots manufacturing (i.e. using/developing algorithmic techniques that make it possible for computers and machines embodying computers to mimic human actions).</td>
</tr>
</tbody>
</table>

*Source: Based on authors’ own research and elaboration derived from the systematic literature review.*
Figure 9  Illustrative capabilities of Subcluster B on collaborative manufacturing from Cluster 5 on manufacturing processes and organization function

<table>
<thead>
<tr>
<th>Levels of d4R technological capabilities</th>
<th>Cluster 5. Manufacturing processes and organization function</th>
<th>Subcluster B. Collaborative manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrofittability and readiness capability</td>
<td>Leveraging on existing manufacturing capabilities from the previous generation of technologies and incrementally adopting new processes and managerial strategies to support and launch the implementation of the manufacturing digitalization process. Integrating heterogeneous devices/components in automation systems and developing smart devices and sensor technology. Developing intra- and inter-firm collaborative networks so risks can be shared and resources combined to expand the range of perceivable market opportunities.</td>
<td></td>
</tr>
<tr>
<td>System integration capability</td>
<td>Using integrated IT systems to create more cohesive intra- and inter-firm (including suppliers and customers) data-integration networks. Carrying out simulations and modelling the impact of process steps on products - across company borders – with collaborators.</td>
<td></td>
</tr>
<tr>
<td>Enhanced horizontal and vertical digitalization capability</td>
<td>Engaging in intra- and inter-firm collaborative training (e.g. training operators to interact with machines virtually. They also can change parameters and retrieve operational data and maintenance instructions). Using simple visualization techniques of context-sensitive data to illustrate information for effective collaboration. Implementing collaborative robotics to develop physical interaction between robots and humans in a collaborative workspace, which provides an added incentive to achieve quality production, accuracy and precision in the manufacturing process.</td>
<td></td>
</tr>
<tr>
<td>Smart – intelligent – capability</td>
<td>Using advanced visualization techniques of context-sensitive data (e.g. via virtual reality) to illustrate information for effective collaboration. Developing a virtual process chain that allows for end-to-end engineering and visualization of production networks intra- and inter-firm with collaborators. Implementing industrial system integration leading to more cohesive, inter-firm (including suppliers and customers) universal data-integration networks and which enable truly automated value chains, e.g. a collaboration platform between industries.</td>
<td></td>
</tr>
</tbody>
</table>

*Source:* Based on authors’ own research and elaboration derived from the systematic literature review.
### Illustrative capabilities of Subcluster C on self-optimizing and knowledgeable manufacturing systems from Cluster 5 on manufacturing processes and organization function

<table>
<thead>
<tr>
<th>Levels of 4IR technological capabilities</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrofitting and readiness capability</td>
<td>Leveraging on existing manufacturing capabilities from the previous generation of technologies and incrementally adopting new processes and managerial strategies to support and launch the implementation of the manufacturing digitalization process. Integrating the heterogeneous devices/components in automation systems and develop smart devices and sensor technology.</td>
</tr>
<tr>
<td>System integration capability</td>
<td>Integrating variability management mechanisms needed for flexibility at various levels of production. Using a decentralized system of digital ledger-keeping that is transparent and efficient based on blockchains internet-based peer-to-peer networks. Using distributed systems that can produce much smaller batch sizes. Bringing process standardization and synchronizations between various company departments to provide flexibility in an effective manner.</td>
</tr>
<tr>
<td>Enhanced horizontal and vertical digitalization capability</td>
<td>Adopting reverse logistics to ensure the execution of corrective actions on products. Adopting reverse logistics to ensure the execution of corrective actions on process development. Extracting large amounts of data for virtualization of the process- and supply-chain and used for end-to-end engineering. Using wireless sensor technology that offers real-time insights on how to boost productivity, optimize resource efficiency, reduce interruptions or minimize down time.</td>
</tr>
<tr>
<td>Smart – intelligent – capability</td>
<td>Allowing for individualized production, end-to-end engineering in a virtual process chain and production networks. Developing self-configurable and routable systems and self-optimizing technologies and processes. Using end-to-end digitally integrated engineering along the entire value chain using advanced methods of communication and virtualization for significant optimization. Implementing autonomous robots that perform work intelligently and accurately with high safety, versatility and flexibility for a given period.</td>
</tr>
</tbody>
</table>

*Source: Based on authors’ own research and elaboration derived from the systematic literature review.*
Figure 11   Illustrative capabilities of Subcluster D on additive manufacturing from Cluster 5 on manufacturing processes and organization function

<table>
<thead>
<tr>
<th>Levels of 4IR technological capabilities</th>
<th>Retrofitting and readiness capability</th>
<th>System integration capability</th>
<th>Enhanced horizontal and vertical digitalization capability</th>
<th>Smart – intelligent – capability</th>
<th>Uptake along the 4IR readiness to 4IR maturity spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Leveraging on existing manufacturing capabilities from the previous generation of technologies and incrementally adopting new processes and managerial strategies to support and launch the implementation of the manufacturing digitalization process. Integrating heterogeneous devices/components in automation systems and developing smart devices and sensor technology. Adopting visualization tools in design processes.</td>
<td>Adopting technologies such as 3D printing, rapid prototyping, direct digital manufacturing, layered manufacturing and additive fabrication.</td>
<td>Configurating and implementing additive manufacturing technologies and processes to support the lifecycle management of products and processes. Implementing additive manufacturing technologies to upgrade current recycling processes within the firm. Implementing additive manufacturing technologies to support the remanufacturing of products or components.</td>
<td>Combining computer-aided design and manufacturing or any other 3D software that creates digital models, with 3D printers that build products by adding materials in layers for mass customization. Creating highly customized products. Engaging in small batch production. This involves producing under 500 units per style. Traditionally, 1,000 units is the industry standard for a minimum order quantity. Implementing augmented-reality-based systems which improves decision making and work procedures and support a variety of services (such as selecting parts in a warehouse and sending repair instructions over mobile devices). Customized manufacturing involving the production of a single device on-demand such that it fits within a desired form factor. This enables on-demand production of a single electronic device with fixed lead times and cost structure, significantly reducing the time to design and launch of a product on the market.</td>
<td></td>
</tr>
</tbody>
</table>

Source: Based on authors’ own research and elaboration derived from the systematic literature review.
Figure 12  Illustrative capabilities of Subcluster E on context-aware manufacturing information from Cluster 5 on manufacturing processes and organization

<table>
<thead>
<tr>
<th>Levels of 4IR technological capabilities</th>
<th>Subcluster E. Context-aware manufacturing information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrofitting and readiness capability</td>
<td>Leveraging on existing manufacturing capabilities from the previous generation of technologies and incrementally adopting new processes and managerial strategies to support and launch the implementation of manufacturing digitalization.</td>
</tr>
<tr>
<td></td>
<td>Integrating the heterogeneous devices/components in automation systems and developing smart devices and sensor technology.</td>
</tr>
<tr>
<td></td>
<td>Accessing real-time data in production related to machines operating in the factory.</td>
</tr>
<tr>
<td></td>
<td>Accessing real-time data in production related to processes.</td>
</tr>
<tr>
<td></td>
<td>Accessing real-time data in production related to products.</td>
</tr>
<tr>
<td>System integration capability</td>
<td>Using event-based and data-driven information systems, which helps create a holistic view of assets.</td>
</tr>
<tr>
<td></td>
<td>Using event-based and data-driven information systems, which helps create a holistic view of people and inventory.</td>
</tr>
<tr>
<td></td>
<td>Using event-based and data-driven information systems, which helps limit human errors by production line engineers and operators by reducing their cognitive load.</td>
</tr>
<tr>
<td>Enhanced horizontal and vertical digitalization capability</td>
<td>Using reconfigurable manufacturing systems.</td>
</tr>
<tr>
<td></td>
<td>Implementing self-configurable and routable systems that coordinate with other networked heterogeneous devices for information sharing between source and destination.</td>
</tr>
<tr>
<td></td>
<td>Implementing automation system virtualization, which maximizes real-time visibility of the operation processes to offer reliable and efficient solutions.</td>
</tr>
<tr>
<td>Smart – intelligent – capability</td>
<td>Implementing self-optimizing technologies and processes that acquire the current state of the system as well as of the system’s environment and adapt their behaviour accordingly.</td>
</tr>
</tbody>
</table>

*Source: Based on authors’ own research and elaboration derived from the systematic literature review.*
### Figure 13  
Illustrative capabilities of Cluster 6 on supply chain management function

<table>
<thead>
<tr>
<th>Levels of 4IR technological capabilities</th>
<th>Cluster 6. Supply chain management function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrofitting and readiness capability</td>
<td>Assessing cost reduction strategies and challenges and opportunities in supply chain management practices. Deploying a network of sensors that collect data and provide greater insights into the flow of materials, products and information. Promoting knowledge management in the supply chain to improve supply chain sustainability and logistics performance.</td>
</tr>
<tr>
<td>System integration capability</td>
<td>Enhancing transportation, warehousing, and storage processes and management systems to reduce costs within the supply chain and increase efficiency across the supply chain. Optimizing supply chain management and performance through, e.g. probabilistic neural networks or the modelling of material flows. Using blockchain technology for product portfolio and parts management and to track product deletion such as in inventory, waste and information management and regulating financial flow within the supply chain. Implementing machines and algorithms for real-time monitoring of existing stocks and in-process inventory to ensure uninterrupted functioning of the manufacturing process. Using blockchain technology for tagging products to enable after-use collection, sorting, waste management and repurposing.</td>
</tr>
<tr>
<td>Enhanced horizontal and vertical digitalization capability</td>
<td>Implementing automatic identification, data collection and radio frequency identification technologies, which help collect, manage and analyse data within transportation processes in the supply chain. Implementing machine-to-machine communication in the supply chain, which enables (i) the automated recording and communication of process information in the production facilities and in the distribution networks; (ii) new payment methods for the firm’s sales function, and (iii) new services such as fleet management or track and trace systems. Using blockchain applications, which is connected with radio frequency identification, Internet of Things and global position sensors, and can collect accurate data and address traceability issues across the entire supply chain. Developing inter-firm eco-efficient technological processes, which integrates sustainability in the process and increases the supply chain’s efficiency and effectiveness. Using advanced robotics and automation solutions to facilitate automatic sorting and the management of solid waste.</td>
</tr>
<tr>
<td>Uptake along the 4IR readiness to 4IR maturity spectrum</td>
<td>Developing autonomization in logistics whereby there is autonomous decision-making, controlling, planning and initiation of logistics activities. Developing transportation systems that perform autonomous decisions based on pre-implemented algorithms and the logistics processes that are already within the autonomization process. Developing/using engineered learning tools or perception-based modelling, as well as problem-driven solution-making systems that can be used to address specific problems within the supply chain (e.g. related to waste, pollution and other negative costs). Integrating artificial intelligence to automatically and remotely monitor efficiency across the manufacturing process and at the end of products’ lifecycle. Full digitalization and industrial inter-firm integration of the supply chain with the implementation of intra/inter-logistic processes that support manufacturing, systems with sophisticated applications, such as cyber-physical systems and driverless-transporting-systems, execution of intra-logistics processes within the manufacturing firm and across the supply chain to other firms.</td>
</tr>
</tbody>
</table>

**Source:** Based on authors’ own research and elaboration derived from the systematic literature review.
6 Discussion and conclusions

The aim of this study was to update the firm-level technological capability framework for the 4IR. Our framework elaborates the human and organizational activities, skills, experiences, knowledge and resources required by firms to endorse and realize the 4IR. It highlights that firms’ technological capabilities grow into more complex ones over time, thereby allowing firms to increasingly adopt more complex 4IR technologies and processes. The study also accounts for the new demands, challenges and requirements that must be addressed when embarking on the digital transformation journey.

Conceptually, we make an important contribution to the technological capability literature by departing from the frameworks conceived during the 3IR. We acknowledge that these technological capability frameworks will continue to inform industrial development for many years to come, since developing country firms often lack the capacities to engage in the knowledge and production activities required for the 4IR. However, they potentially stand to gradually become obsolete if they are unable to capture the transformations that occur inside firms and industries, partially as the result of accelerated developments of various advanced technologies and digitalization. Our updated framework pre-empts such obsolescence by presenting the initial building blocks for firm-level industrial technological capability-building and accumulation under the 4IR.

Our framework also adds the clarity that has been missing from the practical perspective of firms that are still grappling with the process of launching their digital transformation and the demands or constraints that greater digitalization will put on their resources, capabilities and competencies. One of our contributions is to emphasize that the process of 4IR technological capability-building requires the elaboration of strategies that engage firms and other systemic actors in an active process that first builds on retrofitting and readiness capabilities, and then moves up to system integration capabilities and enhanced digitalization capabilities, to ultimately build smart intelligent capabilities. This contribution is also relevant for policymakers. Since digital technologies are rapidly evolving, it is equally pressing for policymakers to devise and enact policies that facilitate the accumulation of technological capabilities at firm-level.

UNIDO (forthcoming) argues that despite the significant attention the 4IR has received as a potential game changer for the future of industrial development, the empirical evidence on the diffusion and uptake of 4IR technologies and practices remains scarce, mostly due to the lack of adequate and consistent firm-level data for analysis. The scarcity of data is particularly notorious in the case of developing and emerging economies. Thus, another contribution of our study is a
useful assessment framework for future empirical studies. As in the case of its predecessors, our framework provides the foundation to collect primary data and generate the empirical evidence needed to examine the revealed capabilities of 4IR firms; to develop detailed profiles of firms along the six technological or organizational functions identified; to evaluate the level of technological capability accumulation over time; to elaborate maps that help firms ignite strategies to move up the 4IR readiness to maturity spectrum. The outcome of such future research will be valuable for policymakers who are wrestling with issues concerning the required interventions for fostering firm-level technological upgrade and readiness to endorse the 4IR. The testing and further adaptation of the framework can also lead to the creation of a practical tool needed by both international organizations and government policymakers to make decisions about such firms.

Future studies will undoubtedly improve our 4IR framework, fine-tune it by reviewing the nature, breadth and depth of these capabilities across different manufacturing industries that prevail now within developing countries, e.g. textiles – low tech; semiconductors – medium tech, and AI and robotics – high tech. These studies can focus on the level of skills, knowledge, experience and resources that firms have accumulated across the firm or within specific technological or organizational functions necessary for closing the digitalization gaps and for endorsing and realizing the 4IR, as well as the role of domestic and foreign systemic actors in this process.
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EDB. 2017. The Singapore Smart Industry Readiness Index: Catalysing the transformation of manufacturing. Singapore Economic Development Board In partnership with global testing, inspection, certification and training company TÜV SÜD Validated by an advisory panel of industry and academic experts Supported by Singapore Government agencies.


UNIDO. Forthcoming. “UNIDO Survey on the Adoption of Digital Production Technologies by Industrial Firms.” UNIDO.


## Appendix 1: Adapted representation of Lall (1992) and Bell and Pavitt’s (1995) framework of technological capabilities

<table>
<thead>
<tr>
<th>Levels of technological capabilities &amp; description</th>
<th>Technological and/or organizational functions</th>
<th>Illustrative examples of refined sets of human and organizational activities, skills, experiences, knowledge and resources that constitute the capabilities of the firm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level 6: Advanced</strong></td>
<td>Investment function</td>
<td>Developing new production systems and components.</td>
</tr>
<tr>
<td>Capability to conduct advanced, structured, ‘blue-sky’ R&amp;D and engineering in technologies, production systems and products; either intra-firm and standalone or inter-firm through collaborations with other actors.</td>
<td>Decision making and control</td>
<td>Process design and related R&amp;D.</td>
</tr>
<tr>
<td>Production function</td>
<td>Project preparation and implementation</td>
<td>Process innovation and related R&amp;D. Radical innovation in organization.</td>
</tr>
<tr>
<td>Supporting function</td>
<td>Processes and production organization</td>
<td>Product innovation and related R&amp;D.</td>
</tr>
<tr>
<td></td>
<td>Product-centred</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Capital goods supply</td>
<td>R&amp;D for designs and specifications of new plant and machinery.</td>
</tr>
<tr>
<td><strong>Level 5: Intermediate</strong></td>
<td>Investment function</td>
<td>Search, evaluation and selection of technology sources. Tenders or negotiation. Overall project management.</td>
</tr>
<tr>
<td>Capability to implement complex changes in existing/dominant technologies, and/or to engage in incipient R&amp;D for the systematic exploratory experimentation, search, and tests related to a novel technology, either intra-firm and standalone or inter-firm through collaborations with other actors.</td>
<td>Decision making and control</td>
<td>Detailed engineering, Plant procurement, Environment assessment, Project scheduling and management.</td>
</tr>
<tr>
<td>Production function</td>
<td>Project preparation and implementation</td>
<td>Commissioning, Training and recruitment.</td>
</tr>
<tr>
<td></td>
<td>Processes and production organization</td>
<td>Process improvement, Licensing new technology, Introducing production organizational changes.</td>
</tr>
<tr>
<td></td>
<td>Product-centred</td>
<td>Licensing new product technology and/or reverse engineering, Incremental new product designs.</td>
</tr>
<tr>
<td>Supporting function</td>
<td>Capital goods supply</td>
<td>Incrementally innovative reverse engineering and original design of plant and machinery.</td>
</tr>
<tr>
<td><strong>Level 4: Basic</strong></td>
<td>Investment function</td>
<td>Active monitoring and control of feasibility study, technology choice/sourcing and project scheduling.</td>
</tr>
<tr>
<td>Capability to implement minor adaptations in existing/dominant technologies, and/or to engage in informal exploratory experimentation, search, and tests related to a novel technology, either intra-firm and standalone or inter-firm through collaborations with other actors.</td>
<td>Decision making and control</td>
<td>Feasibility studies. Outline planning, Standard equipment procurement, Simple ancillaries engineering.</td>
</tr>
<tr>
<td>Production function</td>
<td>Project preparation and implementation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Processes and production organization</td>
<td>Improving layout, scheduling, maintenance and minor process adaptation.</td>
</tr>
<tr>
<td></td>
<td>Product-centred</td>
<td>Minor adaptations to market needs, and incremental improvement in product quality.</td>
</tr>
<tr>
<td>Supporting function</td>
<td>Capital goods supply</td>
<td>Copying new types of plants and machinery. Simple adaptation of existing designs and specifications.</td>
</tr>
<tr>
<td><strong>Level 3: Production/operational capability</strong></td>
<td>Investment function</td>
<td>Engaging primary contractor, Securing and disbursing finance. Officiating at opening ceremonies.</td>
</tr>
<tr>
<td>Capability to produce goods at given levels of efficiency and given input requirements. The firm’s capability is mainly in technology using skills and knowledge and in simple organization arrangements for routine production.</td>
<td>Decision making and control</td>
<td>Preparation of initial project outline, Construction of basic civil works, Simple plant erection.</td>
</tr>
<tr>
<td>Production function</td>
<td>Project preparation and implementation</td>
<td>Routine operation and basic maintenance. Efficiency improvement from experience in existing tasks.</td>
</tr>
<tr>
<td></td>
<td>Processes and production organization</td>
<td>Replication of product specifications and designs. QC to maintain existing standards and specifications.</td>
</tr>
<tr>
<td></td>
<td>Product-centred</td>
<td></td>
</tr>
<tr>
<td>Supporting function</td>
<td>Capital goods supply</td>
<td>Replication of unchanging items of plant and machinery.</td>
</tr>
</tbody>
</table>
Appendix 2: Supplemental information on the systematic literature review process

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inclusion</strong></td>
<td>English documents from 2000 to 2020 only. Peer-reviewed journal articles, conference proceedings and book chapters. International organizations’ papers and reports and governmental reports.</td>
</tr>
<tr>
<td><strong>Exclusion</strong></td>
<td>Non-refereed publications. Documents prior to 2000.</td>
</tr>
<tr>
<td><strong>Scope of the publications</strong></td>
<td>Engineering, Manufacturing, Management, Policies</td>
</tr>
</tbody>
</table>