THE CHALLENGES OF TECHNOLOGY AND ECONOMIC CATCH-UP IN EMERGING ECONOMIES

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PRAISE FOR *THE CHALLENGES OF TECHNOLOGY AND ECONOMIC CATCH-UP IN EMERGING ECONOMIES*

"This book pushes ahead our frontier of knowledge about technology upgrading and economic catch-up. It combines a solid analytical approach with illustrative case studies. A must-read for all who want to understand what it takes for an emerging market economy to keep climbing the income ladder."

Otaviano Canuto, former vice-president at the World Bank and author of *Climbing an Income Ladder: Development in the Global Economy*

"This book represents a state-of-the-art understanding of the various and complex issues regarding technology upgrading and economic catch-up in emerging economies at the country, sector, and firm level. It is a very useful contribution for a full understanding of the wide range of challenges, successful experiences, and policy dimensions."

Franco Malerba, Professor of Applied Economics, Bocconi University

"Policy makers in countries under income traps have much to learn from this great book. With a broad scope, it analyses successful catch-up cases, from different regions and sectors. It highlights new challenges: catch-up with sustainability. With strong theoretical foundations this book brings forward a powerful message: underdevelopment can be overcome."

Eduardo da Motta e Albuquerque, Professor, Universidade Federal de Minas Gerais, Brazil

"A unique and inspiring synthesis of facts, thoughts, ideas, and advice on how technology upgrading could boost emerging economies."

Robert Tijssen, Professor, Stellenbosch University

"This book provides a valuable and timely discussion of technology catch-up and upgrading, which are indispensable strategic objectives for middle-income countries striving to escape the middle-income trap as well as low-income countries attempting to get on a trajectory of inclusive, sustainable development."

Alfred Watkins, Founder, Global Solutions Summit

"This book unlocks the secret of catch-up through technology upgrading with successful cases and sound analysis. It is a major contribution to the field of innovation studies that should be read by all who care about the intricate relationship between technology upgrading and economic catch-up."

Lan Xue, Dean, Schwarzman College, Tsinghua University

Preface

Studies of economic growth have shown that the patterns and rates of long-term growth are strongly driven by innovation and technological capabilities. This linkage from innovation to growth also means that if the process of technology capability accumulation is not effective, then long-run economic growth itself will be at peril. This book starts from the recognition that this is the case for some emerging economies and other countries in the global south, and that the phenomenon of the so-called middle-income trap is real and important. We argue that the ineffectiveness of technology upgrading is key in understanding the nature of growth and challenges facing countries at the middle-income stage.

The basic idea for this book emerged in October 2016 during a friendly meeting among three of the editors in Moscow in October 2016 in the aftermath of the Higher School of Economics conference "Foresight and STI Policy." In his presentation on the so-called "middle innovation trap", Jeong-Dong Lee had argued that in order for developing countries to get unstuck and move from the early stage of catching-up (the "sweat" stage) to the more advanced sustainable growth stage (the "design" stage), they actually needed to modify the whole structure innovation system, that is the nature of and incentives to the actors, the networks, and the institutions to enable ideation of solutions and world-level innovation. While the topic has attracted a lot of attention over the decades, with deep scholarship going at least as far back as the mid-twentieth century, the three of us (also including Dirk Meissner and Nick Vonortas) thought that the possibilities for better understanding were far from exhausted. Especially so given the rapidly evolving socio-technological environment of the early twenty-first century with the ascent of half of the planet's population and the increasing speed of technology diffusion. The landscape seemed to us ripe for re-examination.

The next question arose fast. Who would be other experts to invite in order to enable such an intellectually ambitious project to lift off the ground? It took little time and effort to think of two: Professor Keun Lee from Seoul National University, who has written extensively on catching up in a Schumpeterian perspective, and Professor Slavo Radosevic, an authority on the process of technology upgrading, especially in transition countries. It did help a lot that both were already good colleagues and professional friends. They both graciously accepted our invitation.

The group of five editors proved quite suitable for the task. Their affiliations spanned the globe—timewise if nothing else, which made simultaneous communication a challenge—from East Asia, to Eastern Europe, to Western Europe, to North and South America. In addition to their home institutions, each had affiliations with other major universities and editorial services in major field journals that gave them privileged knowledge of what, why, how, and who in this field. They assembled a superb team of global experts who, despite their very busy schedules and obligations, graciously agreed to write chapters for this tome. Just about everyone who was invited agreed to write a chapter. We have no words to thank them for their generosity and the care they took in preparing and revising several drafts of individual chapters.

The next stepstone in the process was to organize a major international event in an emerging country, Brazil, early July 2019. It was hosted by the Department for International Science and Technology Policy on the main campus of the University of Campinas and, more specifically, the São Paulo Excellence Chair in Innovation Systems, Strategies and Policy (InSySPo). A large group of post-doctoral researchers and doctoral candidates affiliated with InSySPo worked tirelessly under the oversight of Nick Vonortas for about nine months to make the conference happen. The conference was organized around the first complete drafts of the book chapters. A very strong group of high calibre discussants were given the difficult task of commenting in some detail. Again, just about everyone invited agreed to join us in Campinas. By our standards, at least, we ended up with one of the most intellectually interesting events and one of the largest: a good chunks of the world's top academic expertise on the subject physically congregated for three productive days in an emerging economy.

Following another year of revisions and interchange, the next step involved the presentation of the advanced versions of the chapters in a series of five international workshops (online) during November and December 2020 and, subsequently, February, March, and April 2021. While SPEC InSySPo was the organizational hub, this time all five home universities of the five co-editors actively co-sponsored the workshops, including (alphabetically) the George Washington University (Washington, D.C., USA), the National Research University Higher School of Economics (Moscow, Russia), Seoul National University (Seoul, Korea), the University of Campinas (Campinas, Brazil), and the University College London (London, UK). Chapters were presented by the authors and a new set of external expert discussants were invited to comment and ask difficult questions—now regarding implementation. Large attendance of the workshops adding up to several hundred people and excellent commentary produced again very rich discussion environments.

Both the UNICAMP conference (2019) and the series of five workshops (2020–21) have been recorded and are available online.

The result of this multi-year effort is now in front of you in the form of a volume with sixteen chapters in which the editors are proudly joined by some of the academic world's best in dealing with contemporary challenges and opportunities of socio-technical catching-up facing the emerging world. This is no small feat given that this emerging world consists of no less than half the human population. We are fully aware that we are stepping on moving sand—this was the original motivation for the book, anyway—and that the discussion is based on past experiences, some of which may soon become obsolete. Thus, we would advise the reader to think through critically. The editors do underline this important point in the introductory chapter.

The book is being released in the midst of a global health disaster unprecedented in living memory. None of it was anticipated when we started this endeavour. Since then, it has become trite to argue that the world will never look the same again even after the end of the COVID-19 pandemic. Trends that were already visibly clear to experts—the problems with globalization; the reorganization of international business due to geopolitical struggles as well as the rapid introduction of fundamental technological advancements in information and communication technologies, biomedical sciences, and advanced materials; the major concerns over environmental degradation and climate change; and the consequences on development models—have become obvious for larger numbers of the general population and policy decision makers. We do agree, there will be no full come-back. This again calls for caution in drawing definite lessons for the future from examples of the past.

The COVID-19 global crisis has demonstrated the importance of 'system resilience', meaning the economy's ability to withstand social, financial, environmental, or other shocks without catastrophic and system-wide effects. It has also re-iterated the importance of structural change and the ability of reorienting innovation systems to better meet society's pressing needs. We see that this re-orientation is consistent with the emphasis in this book on capabilities broadly defined. Building and enhancing a new and broad spectrum of capabilities by emerging economies should proceed in the context of a 'new global shift' which represents interaction among path-dependent processes of the past driven by globalization and a new phase of digitalization, on the one hand, and new challenges driven by the concerns like sustainable development and biological resilience of human and natural ecosystems, on the other.

In a nutshell, this is a tome full of great ideas which also represent the state-of-the-art in this field. We are personally exhilarated with the result, as well as feeling humble for being able to work alongside leading scholars in the field. We have learned a whole lot next to them! In order to spread the lessons as far and wide as possible, we have also been blessed with a good publisher who has agreed to turn this volume into an open-access book starting in about a year from publication. Difficult to imagine otherwise when one's intended audience is largely in countries with few resources!

The Editors in Campinas, London, Moscow, Seoul, and Washington, DC
May 1, 2021

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An effort of this size requires the involvement of large numbers of people. First and foremost, special thanks go to the book chapter authors who worked tirelessly over the years. Their deep experience and scholarly virtuosity have been invaluable. So has been their patience to work through various drafts. Special thanks also go to the various expert discussants we have used in six international events—one in Campinas and five online—who read drafts of the material carefully, prepared excellent comments and posed critical questions to the chapter authors and to the audiences. Altogether, something like seven hundred people have attended these six events which makes us particularly happy and proud. The discussants include (in alphabetical order): Eduardo Albuquerque, Anwar Aridi, Ron Boschma, Yannis Caloghirou, Otaviano Canuto dos Santos Filho, Reda Cherif, Bruno Brandão Fischer, André Tosi Furtado, Alessandro Golombiewski-Teixeira, Fuad Hasanov, Jongsuk Jang, Sérgio Robles Reis de Queiroz, Márcia Rapini, Janaina Ruffoni, Sérgio Luiz Monteiro Salles Filho, Robert Tijssen, and Al Watkins.

A strong hand of applause goes to all the young researchers affiliated with the São Paulo Excellence Chair "Innovation Systems, Strategies and Policy" (InSySPo)—doctoral candidates and postdocs—who worked to stage the very successful international conference at the University of Campinas in 2019. They include Paola Rücker Schaeffer, Rafaella Marcelly de Andrade, Vinicius Muraro da Silva, Irineu de Souza Lima Júnior, Suelene Mascarini de Souza Rom, Alireza Ilbeigi, and Fernando Mesquita. Guilherme Cavalcante Silva played a critical role in organizing and supporting the five online workshops.

We are appreciative of the receptivity and clear guidance by Adam Swallow, the OUP's commissioning book editor, who led the initial negotiations with the editors and placed the volume into a steady state as well as the multiple staff members of the publishing house who oversaw the transformation of the material into a coherent and flawless tome. Together with our colleague, Prof. Sira Maliphol of Stony Brook University, Korea, they did all of the heavy lifting of communication, individual contracting, and production. We were very happy with the early decision to turn the book to open access a year following the first release which we considered essential since a large share of the expected audience is in developing countries.

Last, but by no means least, we thank our sponsors and home institutions.

The Research Foundation of the State of São Paulo (FAPESP) has been a key player through its long-term funding of the SPEC InSySPo and affiliated graduate students and researchers, also including the big international conference at UNICAMP in July 2019. Professor Carlos Henrique de Brito Cruz, FAPESP's ex-Scientific Director, has played a very important role over the years as cheerleader and supporter of InSySPo. The Department of Science and Technology Policy at the University of Campinas, and especially the colleagues and InSySPo investigators Professors Sérgio Queiroz, Sérgio Salles, and André Furtado, have been generous hosts over the years.

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Seoul National University has also been a key supporting institution as two editors of this volume are affiliated with it. In particular, we acknowledge the support by the Laboratory Program for Korean Studies through the Ministry of Education of the Republic of Korea and the Korean Studies Promotion Service of the Academy of Korean Studies (AKS-2018LAB-1250001), as well as the CIFAR's IEP Program Grant housed at the Center for Comparative Economic Studies of the University. Support from the National Research Foundation of Korea (NRF) grant (No. NRF-2017R1A2B4009376) and the Innovation Policy Center of the Engineering Research Center of Seoul National University are much appreciated.

All five academic institutions represented by the editors of this volume have provided productive, intellectually vibrant homes, and contributed equally to the cost of open access. They include (alphabetically) the George Washington University (Washington, DC, USA), the National Research University Higher School of Economics (Moscow and St Petersburg, Russia), Seoul National University (Seoul, Korea), the University of Campinas (Campinas, Brazil), and the University College London (London, UK).

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1
Technology Upgrading and Economic Catch-Up

Context, Overview, and Conclusions

Jeong-Dong Lee, Keun Lee, Dirk Meissner, Slavo Radosevic, and Nicholas S. Vonortas

1.1 Introduction

Studies of economic growth have shown that the patterns and rates of long-term economic growth are strongly driven by innovation (Nelson and Winter 1982). Accumulation of technological capabilities driven by innovation activities leads to further growth by deepening and diversifying industrial activities, propelling and fundamentally enhancing growth potential (Abramovitz 1986; Fagerberg 1995; Kim and Nelson 2000; Fagerberg et al. 2007). This linkage from innovation to growth also means that if the process of building technological capabilities is not effective, long-run economic growth itself will be derailed or slow. This book starts from the recognition that this is the case for some emerging economies and many countries in the global south, and thus the phenomenon of the so-called middle-income trap (MIT) is important (Felipe 2012; Aiyar et al. 2013; Eichengreen et al. 2013; Lee 2013a; Paus 2017). In other words, we argue that the failure or ineffectiveness of technology upgrading is the key issue in understanding the nature and problem of economic growth at middle-income stage.

Technology upgrading is the process of enhancing the technological capabilities of firms, sectors, regions, or countries. The early literature has explored technological capabilities at different development stages and identified the characteristics of each stage. For example, Kim (1997) divides technology upgrading in developing countries into the stages of adoption, assimilation, and innovation. Along a similar vein, Hobday (1994) discussed upgrading along the stages of OEM (own equipment manufacturing), ODM (own design manufacturing), and OBM (own brand manufacturing). Lee (2005, 2013) linked these stages to different objects of learning, such as operational skills, process technology, design technology, and finally new product development technology. Discussion of diverse technologies can also be linked to diverse modes of learning and international technology transfer, including foreign

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direct investment (FDI), export, technology licensing, import of capital goods, and exchange of personnel. It also includes the necessary absorptive capacity required for successful technology upgrading (Amsden 2001).

Any remaining doubt about the importance of technological advancement on economic growth has been blown away in the era of artificial intelligence, robotics, and bioscience (Agrawal et al. 2020; Bloom et al. 2019; TEConomy and BIO 2020; WEF 2019; WIPO 2019). Basically all major international multilateral organizations tout the criticality of this link and prescribe courses for policy action across the board and across both leaders and followers (Cicera and Maloney 2017; Cicera et al. 2020; Crespi et al. 2014; EU 2020; OECD 2018; WIPO 2020; IEL 2018; World Bank 2010). The relationship between technological upgrading and economic growth is not a new topic in economics. It has been explored through various theoretical frameworks including evolutionary economics, technology accumulation studies, and the resource-based view or capability theory (Nelson and Winter 1982; Lall 1992; Cimoli et al. 2009; Hall and Rosenberg 2010; Rosenberg 1976). The range of empirical innovation studies has improved our understanding of patterns of technology upgrading across firms, sectors, and countries (Cohen 2010; Fagerberg et al. 2005; Freeman and Soete 1997; Gallouj and Djellal 2010; Kamien and Schwartz 1982; Link and Vonortas 2013; Malerba and McKelvey 2019; Malerba and Vonortas 2009; Tassey 2007). In particular, firm-level studies undertaken during the 1980s and 1990s have demonstrated country and sector-specific paths of technology upgrading. These were followed by sector studies during the 1990s and 2000s which have enriched our understanding of a variety of sector-specific technology paths. They have shown that technology upgrading is a crucial distinction between the countries that successfully overcame the growth slowdown of middle-income countries like East Asian countries and those that are still stalled like Latin American countries and thus stuck in the so-called middle-income trap (Lee 2013a; Paus 2017). Countries may reach middle income by leveraging latecomers' advantages, such as shifting resources to more productive sectors and importing capital from developed countries.

However, growth and technology upgrading are non-linear processes with sometimes significant timelag between technology upgrade and resulting growth, and the failure of countries to deepen and diversify the industrial structure and technological knowledge (Lee 2016; Vivarelli 2016) limits their transition to high-income status. Related to the non-linearity of the process is the issue of whether the latecomers should follow the same/similar path/trajectories of the forerunners or skip some stages along the path or even create a new path (Lee and Lim 2001). Lee (2013a, 2019) finds that successful latecomers do not necessarily follow the older paths but often create a new path so as to leapfrog into the next generation of technologies ahead of incumbents. Important further literature discussing technology upgrade and growth performance has appeared, especially focusing on cases of middle-income countries (Radosevic and Yoruk 2016, 2017; Vivarelli 2016). Needed is not only a better understanding of the paths to technology upgrading in emerging economies but also new conceptual and theoretical understanding of these issues in the changing socio-economic context.

The market opening of previous "Second" and "Third World" countries including China has led to new dynamics of technology accumulation and interaction among emerging and developed economies. The acceleration of globalization which was driven to a large extent by the proliferation of global value chains (GVC), has led to significant changes in patterns of technology upgrading and especially to new modes of interaction between domestic technology efforts and external sources of technological knowledge. However, the path of increasing role globalization of emerging economies has been interrupted by the global financial crisis 2008/09 and the 2020 COVID-19 pandemic in the last ten years but also in other related crises like the dotcom bubble in the early 2000s. Although very different in nature, the former two crises have both led to the deceleration of globalization. This has further reinforced the need to better understand the major challenges facing managers and policymakers in emerging economies in what seems to be a new stage of (de)globalization.

At policy and management levels, the issues of nearshoring or reshoring of the value chains have become new concerns. The sudden retreat of globalization and recognition of the risk of the efficiency-driven GVC have been calling for recalibration of the role of governments. Global climate change and digitization of the world economy have emerged as additional layers of complexity which may dramatically change not only opportunities but also the nature of catching-up for emerging economies. Recent re-examinations of past experiences have shown that successful technology upgrading is not a passive and autonomous process but rather involves active and coordinated activity orchestrated by a variety of state and non-state actors. Several studies have appeared discussing the rationale, extent, scope, and method of policy intervention (Cimoli et al. 2009; Mazzucato 2013). Whether these new situations and dynamics will lead to so-called "Shifting Wealth II" (OECD 2014) and continuing increase in the economic importance of emerging economies will ultimately depend on whether their productivity growth will be driven by technology upgrading.

Compared to the old and new challenges and uncertainties facing emerging economies, our understanding of the technology upgrading of emerging economies is sparse, unsystematic, and scattered. While our understanding of these issues from the 1980s and 1990s is relatively more systematized, the changes that took place during the globalization and proliferation of GVCs and the effects of the post-2008 events on technology upgrading have not been explored and compared synthetically. Moreover, the recent growth slowdown in many emerging economies, often known as a middle-income trap (MIT), has reinforced the importance of understanding of the technology upgrading challenges of catching-up economies.

If we are to understand the dynamics of "Shifting Wealth" we must comprehend better the patterns of technology upgrading of the emerging economies and the main challenges that they are facing in this process. We believe that the time is ripe for "taking stock of the area" which would systematize and evaluate the existing knowledge of the processes of technology upgrading of emerging economies at the firm, sector, and international levels and which would make further inroads in research on this issue. This volume aims to significantly contribute towards this end.

1.2 Setting the Stage

1.2.1 Definition of Technology Capability and Upgrading Patterns

Technology capability is the ability to use technology and technical knowledge to create useful goods and services. Specifically, it means the ability to digest and absorb existing knowledge and create new technologies, including those related to production, investment, and innovation (Westphal, Kim and Dahlman 1985; Katz 1987; Kim 1997). Much of technology capability is firm specific: it is difficult to make and not easy to transfer. Thus, it is part of the core competencies in the resource-based theory of firm. Teece (1998) suggested the concept of dynamic capability, which refers to the firm's ability to capture and realize the new opportunity and appropriate the returns of innovative investment in a changing environment. Dynamic capabilities are rooted in the resource-based theory of the firm, adding the dynamic dimension which makes the concept very relevant to research on technology upgrading.

As a firm's core resource, technology capability consists of production capability, investment capability, and innovation capability (Kim 1997; Dahlman, Ross-Larsen, and Westphal 1987). Lee et al. (this volume) and Bell (2009) distinguish between implementation and design capabilities, while Choung and Hwang (Chapter 9, this volume) also differentiate between technical and non-technical capabilities. The technology capability of a firm is determined by the firm's human resources, technology level, and management of an organizational system (Bell and Pavitt 1993; Leonard-Barton 1995; Teece 2012).

While defined at the firm level, the concept of technology capability is also applied at the country level (Lall 1992). At the country level, technology capability can be expressed as the sum of all players' (including firms') capabilities and the environmental factors affecting those. Relatedly, the concept of social capability is also mentioned in the literature, which is also an effort to express the technology capability of society as a whole (Fagerberg and Srholec 2008; Cimoli and Porcile 2011; Castelacci and Natera 2013, 2016). This is more recognizable by the concept of a national innovation system which points at the role of the institutional characteristics of a country as a factor affecting the technology capability of firms (Freeman 1987; Lundvall 1992; Nelson 1993). The ability to diffuse new technologies, create new ones and, consequently, create new firms and industries can be expressed at the level of the national innovation system.

The process of technology capability upgrading is long and arduous. According to Kim (1997) and Lall (1998) emerging economy firms start the catching-up process by adopting more advanced technology than currently available and, concurrently, by accumulating production-related capabilities. They build new facilities and begin to accumulate know-how for feasibility testing, technology selection, finance, and organization. As these experiences accumulate, they inch closer to starting to create their own technology by mastering the ability to innovate. Specifically addressing the mode of manufacturing production across the GVC, it has been noted that the path of technology upgrading evolves from OEM (Original Equipment Manufacturing), to ODM (Original Design Manufacturing), and to OBM (Original Brand Manufacturing) stage (Hobday 1995). Surveying the scale and scope of available concepts, Radosevic et al. (2016) argue that the dynamic upgrading pattern of technology capability is not uniform but rather multifaceted in terms of depth and breadth.

The catch-up of the latecomers is not an automatic process. It is possible when the strategic intention of catch-up is accompanied by a well-designed plan for leapfrogging (Lee and Malerba 2017). Just as catch-up is not easy, the upgrading of technology capability does not happen spontaneously over time from production capability to innovation capability or from simple technology adoption to innovation.

In this regard, Lee (2016) notes that the capability transition is often difficult, especially the great leap forward from implementation capability to design capability. Failure in this transition results from the fact that implementation capability is embedded within the firm and the country and is solidified in some form of rigid routine or paradigm. However, the institutional arrangement that is effectively organized around the implementation capability is dramatically different from those surrounding the design capability. Failure to transition successfully causes many latecomers that have been able to catch up at least to middle-income level to be unable to move to higher income levels.

1.2.2 Economic Growth, Catch-Up, and Technological Capability

Economic growth is conventionally represented by the growth of gross domestic product (GDP) per capita. From a production point of view, such growth can be achieved by capital deepening leading to increased levels of productivity. Scholars have long viewed economic growth as a result of deepening and diversification of economic activities. Diversification can be looked at as the enhancement of export portfolio (Rodrik 2004; Hausmann and Rodrik 2003, 2006; Hausmann et al. 2007).

Whether deepening or diversification or both, the result is structural change. A prominent way of looking at the process of structural change can be the Schumpeterian concept of "creative destruction" through which less productive activities are abandoned in favor of more productive ones. What drives this "creative destruction"?

In addition to capital deepening, traditional neoclassical models of growth saw it driven by exogenous technological development (Solow 1956) or other factors such as the discovery of natural resources. However, with time came more sophisticated arguments regarding the capability to digest external knowledge and create new technology (Abramovitz 1984; Lall 1994; Bell and Pavitt 1995; Kim 1998). In addition to technological capability, Abramovitz (1984) emphasized the ability of the society at large and its institutions to adopt and combine skills and to manage organizational and financial resources, called "social capability".[1] Technology and social capability are pre-requisites of "creative destruction" resulting in structural change and economic growth.

Whether latecomers can catch up with developed countries and reach similar levels of GDP per capita is one of the oldest questions in economics. Neoclassical economists saw this convergence as inevitable in free markets. Their argument was based on the simplification that knowledge is a public good and anyone can access the same pool of knowledge. On the other hand, economic historians and institutionalists have gained a lot of insights from examining real cases, especially from the successful catch-up cases like Germany in the nineteenth century (Gerschenkron 1962, 1963) The term, "latecomer's advantage", was coined to describe how latecomers can achieve growth much faster than developed countries by accepting professionals and machines embodying advanced knowledge from them (Veblen 1915). These advantages are more prominent in periods of radical technological change which abound with potential "windows of opportunities" (Perez and Soete 1988). Unfortunately, successful catch-up is a relatively rare phenomenon in only a few cases, including Germany, Japan, and some East Asian countries. Since the 1980s, the gap between most emerging economies and advanced countries was maintained or even widened (Gill and Kharas 2015). Most latecomers have remained at low- or middle-income levels, and many countries, especially those out of the low-income level, have no longer been able to grow beyond the income level of $5,000 to $10,000 GDP per capita. This observation has been named the middle-income trap by the World Bank (2012).

This, of course, raises the question why only a few countries are successful in catching-up. Technology capability and its dynamic upgrading patterns are key. The lack of many successful catch-up cases suggests that the stylized processes offered in the literature are easier to describe than replicate. Is there a generally proven and successful way to gain technology capability? The answer is probably not.

[1] Abramovitz expanded the argument further by pointing to the relationship between "technological congruence" and "social congruence".

1.2.3 Contemporary Challenges

1.2.3.1 Global Value Chain Complexity

GVCs have become increasingly complex across most sectors of economic activity. The number and types of participating firms and countries have increased greatly. Beyond simply securing markets or resources or securing a production base built on low-wage labor, international investment is now seeking collaborative efforts for technological development and operates under principles of open innovation. The degree of GVC participation and the technology capability of a country tend to be closely interrelated and to coevolve. Latecomers generally begin participating by providing access to natural resources or low-wage production bases. In return, they seek to secure basic production capabilities and gradually increase their technological capabilities as they advance to higher value-added activities.

The mode and intensity of participating in the GVCs are not uniform. Countries follow different strategies. Strategies also vary according to the development stages. A stylized process has been characterized recently as the in-out-in approach (Lee et al. 2018). According to this, countries that have achieved successful catch-up actively participate in the early stages, but once they have made some progress, they begin to reduce GVC participation to focus on building internal technological capabilities. They again shift towards active participation later and from a different perspective, now based on the capability to create high value-added innovation.

Latecomer participation in GVCs raises expectations of upgrading capability through technology transfer and learning. Hitherto experience, however, indicates that GVC participation does not guarantee the upgrading of technological capabilities. Frequently, firms in developing countries subordinate to the strategy of multinational corporations that dominate GVCs, making them unable to escape the OEM level. Such observations suggest the importance of strategy for both firms and countries to increase their technological capabilities while participating in GVCs (Hansen and Okwell 2014).

1.2.3.2 Emerging Technological Paradigm

General purpose technology (GPT) refers to a collective platform of complementary technologies centering on core technologies such as microchips or artificial intelligence today, and at the same time, the set of rules governing innovation. This was the case with the steam engine of the Industrial Revolution, and the mass production system in the second industrial revolution. These GPTs change and the emergence of new GPTs can disrupt industry leadership across countries. Computing and digital technologies underlined the third industrial revolution. The fourth industrial revolution is arguably represented by artificial intelligence, big data, technology virtualization, and robotics.

To date, while the new alleged wave of technological advancement change is still in its early stages and its potential impact insufficiently understood, it has ushered arguments of new windows of opportunity for latecomers to catch up and leapfrog. At the same time, incumbent developed countries and lead companies may fall victims to big legacy investments and technology capabilities better attuned to the older paradigm. The important role of public policy decision makers has been called forward in order to facilitate the transition and avoid coordination failures.

1.2.3.3 Sustainable Growth

The burden on the environment brought about by the fossil-fuels-based growth has worsened an already problematic situation. Advancing climate change due to human activity has invited calls for reconsidering traditional concepts of economic growth. In addition, as the limits of natural resources and bio limits of the Earth become apparent, questions have been raised about the sustainability of resource-intensive growth models. The result has been proposals for a green growth view that also takes into account the negative effects on the natural environment.

Another important concept to consider when discussing sustainability is income inequality. The recent increase in global income inequality has raised serious questions about growth model effectiveness. Health, education, and gender equality are additional factors to consider in the realm of sustainability. The United Nations' Sustainable Development Goals (SDGs) can be seen as examples of multifaceted factors that must be considered for the sustainable growth of people and societies.

1.2.4 This Volume

The contributions in this volume are framed within the Schumpeterian or neo-Schumpeterian perspective on growth and structural change. This perspective stands in sharp contrast to neo-classical perspective on growth as it is based on evolutionary theory of economic change (Nelson and Winter 1982) and conceptualizes growth as a historical and institutionally driven process which takes place in the interaction of micro and macro determinants in the context of innovation systems (Nelson 1993; Lundvall 1992). While the neo-classical framework operates in a world of incentives and partly in the world of institutions as optimizing allocation mechanisms, the neo-Schumpeterian perspective adds the important missing dimension of capabilities and systems, with its core concepts like systemic or capability failure (Lee 2013b; Woolthuisa et al. 2005), rather than just market failure. Capabilities are the property not only of individuals and organizations but also of innovation systems. Capabilities are also institutionally embedded, and their acquisition represents the core of the technology upgrading and catching-up process.

Within this broadly defined context the book focuses on four major themes. The first theme explores the relationship between technology capability and economic growth from new methodological angles including that of the middle-income trap. The second theme addresses technology capability upgrading from structural, sectoral, and micro-level perspectives. The third theme is on the emerging paradigm of technology capability upgrading which is about sustainability, green growth, inclusiveness, and socio-economic and political determinants of technology capability building. The fourth theme is about several dimensions of innovation policy (large state programs, GVCs, and new industrial policy) which reflect a state of transition or changing policy philosophies. In the following we guide the reader through different chapters and explain how they relate to these four broad themes. A concluding section synthesizes key messages and outlines the emerging research program in this area.

1.3 Main Themes of the Book

1.3.1 Technology Capability and Growth Performance at the Country Level

The first major theme of the volume is a macro-perspective on growth, technology, and catching-up. Usual macroeconomic accounts are rooted in growth accounting using aggregate production functions and aggregate productivity measures. Although useful, growth accounting does not shed light on the underlying facets of technology and does not in any way capture technology capabilities. The neo-Schumpeterian perspective takes a much more differentiated notion of technological capabilities as a departing point and is able to capture many more factors that facilitate or hinder their accumulation. Five chapters in this section all share this underlying perspective in exploring different facets of the relationship between technology and economic growth. They approach technology as broader capability embodied in technology changing activities, in firm production activities, and in the innovation systems in which firms operate. Technology capability development is dynamic and structurally changing, driven by the co-evolution of a country's technological and socio-economic capabilities.

Based on this understanding of the technology upgrading, Fagerberg and Srholec in Chapter 2 of this volume, "Capabilities, Competitiveness, Nations", explore the role of broadly defined capabilities such as "Technology," "Education," "Governance," and "Empowerment." They explore these factors on a large sample of countries in the 1995–2013 period and show that there has been a strong tendency towards divergence in technological capabilities but convergence in education and governance. A second part of their analysis is based on testing a growth model which shows that differences in the scope for imitation followed by changing technological capabilities are crucial for explaining differences in growth. Increases in education and improvements in governance also mattered, but less.

Their analysis shows differences in the significance of different factors of growth across different world regions. For example, imitation gaps fail to account for the very rapid growth of the catching-up economies in Asia (e.g., China), but technology capabilities are the major reason why the Asian Tigers outperformed the other developed countries during this period. The "former socialist countries" growth rates declined due to deteriorating education, while the countries which joined the EU recorded increased growth due to improved governance. Among technological capability variables they show the major contribution of diffusion of ICTs for the "former socialist countries," the Latin American countries, and the countries in the Middle East and North Africa. Growing "innovation capabilities" as reflected by increases in science, research and development (R&D), and patenting play a significant role in the growth of "Asian Tigers." Finally, their results show the significant role of external demand in contrast to price-linked factors like exchange rates.

Overall, their contribution shows that capabilities and the technology capability perspective are relevant frameworks for understanding the growth and technology upgrading of countries. Their research also indicates the relevance of institutions for technology capability building, an issue further addressed in the chapter by Dutrenit et al. (Chapter 13, this volume). In particular, this applies to inconclusive results reported for the "Empowerment" variable which reflects the role of political, institutional, and social factors. Last but not least, they point to the need to improve indicators of basic technological capabilities associated with production, distribution, and (incremental) learning, or "production capabilities".

This latter topic has been taken on board in the chapter by Lee et al. (see Chapter 4, this volume) and Chapter 3 in this volume by Bruno, Osaulenko, and Radosevic titled, "Technology Upgrading in Emerging Economies: A New Approach to its Measurement, Results, and Relationship to Mainstream Measures." Bruno et al. apply a new conceptual framework to the measurement of technology upgrading developed by Radosevic and Yoruk (2016, 2017). They base their approach on the idea that technological transformation is not about the simple accumulation of capital or productivity improvements at the existing technological level, rather, it is about the accumulation of a range of diverse capabilities (production, technology, R&D, etc.), their structural transformation, and the coupling of domestic technology efforts to technology transfer.

Based on a sample of sixteen mostly emerging economies in the period 2002–16, Bruno et al. tested the components of the index of technology upgrading (ITU) (scale and scope) and their correlation to country income levels. To test the relevance of the technology upgrading framework compared to conventional macroeconomic approaches, they explored the relationship between the ITU, its individual components and subcomponents, and changes to total factor productivity (TFP) and labor productivity. The ITU explains changes to both TFP and labor productivity. Technology exchange has no explanatory power, which suggests that openness to technology exchange, unless complemented by own technology accumulation activities, does not contribute to increased TFP and labor productivity. Among the individual components of the ITU, only production capability contributes significantly to variations in TFP.

The analysis demonstrates the need to broaden the scope of innovation policy to include production (manufacturing) capabilities in policy framing (Kim 1997). Also, the results suggest that coordination among the components of technology upgrading is crucial and requires systemic policies that cut across conventional policy areas.

Lee, Baek, and Yeon in Chapter 4 of this volume, "Middle Innovation Trap: Capability Transition Failure and Stalled Economic Growth" depart from the position that technological transformation is about the accumulation of a range of diverse capabilities. They explore economic growth, especially the middle-income trap, from the perspective of "capability transition failure." Based on the analytical framework developed by Lee (2016), they address growth through two types of technological capabilities, namely, implementation capability and design capability. They explore transformation from implementation to design capability, proxying each of the capabilities by several indicators and testing their relationships with economic growth over the 1996–2016 period. Their results show that development of implementation capability precedes that of design capability. Moreover, they show that there is a non-linear relationship between technological capabilities and income levels due to transition challenges between two stages. Countries like Thailand and Mexico have failed in this transition while Korea has undergone a much smoother transition from implementation to design capability stage.

Transition failures are caused by path dependencies and failures of countries to restructure their innovation systems around the concept of design capabilities. A transformation from implementation based to a design capability based innovation system is a system-wide change incorporating not only R&D but also education, finance, industry structure, trade regime, and industrial and innovation policies. Their argument is that this change is non-trivial as it requires a simultaneous, rather than piecemeal and sequential, change in different sub-systems. All in all, their analysis represents an empirically grounded, policy-relevant perspective on the middle-income trap.

Technology upgrading beyond the middle-income trap is considered in Chapter 5 in this volume by Keun Lee, "Economics of Technological Leapfrogging." The chapter builds on the key insight of Lee (2013a, 2019) that latecomers do not simply follow advanced countries' path of technological upgrading but either skip certain stages or create their own path which differs from that of the forerunners. Lee defines leapfrogging as "latecomers doing something different ahead of incumbents" that may put latecomers at the technology frontier. Catching-up based on imitation eventually reaches diminishing returns and cannot be the basis for achieving technology leadership. Instead of pursuing a path-following strategy by adopting the current established technology, leapfrogging calls for one of two alternative strategies. The first alternative is skipping the established stages of technology deployment by adopting the latest generation of technology (for instance, mobile instead of fixed telephony), while the second is a path-creating strategy of adopting the emerging generation technology.

These paths require detours, referring to strategies which do not conform to mainstream views. A first detour is about promoting imitative innovation under a loose intellectual property (IPR) regime in the form of petit patents and trademarks, rather than promoting and strengthening patent rights. The second detour is about being plugged into GVCs in the initial stages of catching-up, subsequently reducing dependence on foreign GVCs in the more advanced stages by building domestic value chains.

The probability for leapfrogging success is much higher in periods and under conditions when latecomers can exploit three types of opportunities. First, technological opportunities are higher in periods of disruptive technological change such as the current period of the fourth industrial revolution. Second, leapfrogging is more likely in periods of market disruption or increasing market opportunities, either external or domestic demand. Finally, leapfrogging is more likely when the exploitation of market and technological opportunities is facilitated by appropriate activities of the government in transforming the national innovation system. This latter issue is also addressed in Chapter 4 in this volume by Lee, Baek and Yeon and in Chapter 9 by Choung and Hwang.

Finally, Lee draws rich policy and management-relevant insights for different groups of emerging economies as well as for different types of emerging economies' firm strategies. Overall, this chapter establishes the economics of leapfrogging as a new research area. The chapter presents a new framework to explore and interpret cases of "forging ahead" at sectoral level which are much more frequent in emerging economies. Several cases of technology upgrading at sectoral level are explored.

The issue of innovation upgrading through innovation surveys' evidence is explored in this volume in Chapter 6 by Roud, "Innovation Surveys as Evidence for Technological Upgrading and Catch-Up Studies." Macro studies as well as sectoral studies of technology upgrading hide the crucial feature of innovation capabilities which is their high heterogeneity across firms. Roud uses the OECD (2009) taxonomy of innovation sophistication levels which differentiates between: non-innovation companies, technology adopters, national imitators, international imitators, national innovators, and international innovators. The methodological novelty of research is that it applies this taxonomy over a sixteen-year period (2000–15) at both national as well as sectoral levels. This enables him to show changing morphology of technology or innovation upgrading which is not detectable when only firm or sectoral averages are used.

This approach has generated major insights. First, there is strong path dependency and inertia which shows the limited scale of transformation processes within the national innovation system of Russia. Second, there is striking evidence on the stable share of firms across different groups which are insensitive to periods of economic growth or downturns. Third, there is an overall tendency towards simplification of innovation strategies, that is, the increasing share of enterprises that follow the technology adoption strategy with no in-house capability building.

In the second step, this taxonomy is applied across sectors which are then clustered on the basis of firms' innovation capabilities. Results show that only a fraction of sectors focus on proactive innovation and successfully compete on the global markets. However, the most notable and encouraging tendency is the migration of industries from the non-innovative to a somewhat more capable category. The analysis shows that policies that are focused only on advanced innovators will have marginal macroeconomic effects. Instead, policy could target much more the growing number of firms with baseline innovation capabilities which will have positive effects on their productivity levels. As pointed out "the logic of policies should move away from 'supporting the best' to the idea of promoting mass innovation in all the industries in order to stimulate the processes of accumulating a basic level of innovation capabilities" (Roud, Chapter 6, this volume).

1.3.2 Technology Capability Upgrade and Sectoral Catch-Up

A second major theme in the volume is about technology upgrading at the sector level. Neo-Schumpeterian economics goes beyond macro/micro distinction and opens up a rich array of insights into multilevel dynamics of interaction between the market, institutions, and their co-evolution with technological capabilities. Within this perspective the macro outcomes are being driven by firm-specific paths of technology upgrading as well as inter-firm interaction and competition, and are molded by the institutional context. Three chapters in this section explore why technology upgrading is a complex, historically contingent process where outcomes are dependent on a variety of mutually interrelated factors whose outcomes are far from certain.

Cherubini Alves, Vonortas, and Zawislak in Chapter 7 of this volume, "Macro and Micro Foundations for Technology Upgrading and Innovation: The Case of Shipbuilding and Offshore Industry Missed Window of Opportunity in Brazil" explore the case of the semi-failure of the entry of Brazil into the deep-oil drilling industry following the discovery of large oil reserves in the offshore areas, mainly of the states of Sao Paulo and Rio de Janeiro. Seemingly, Brazil had the potential to exploit all three windows of opportunity for catching-up in this industry: extensive technological knowledge in deep sea drilling by its leading oil producer Petrobras; strong market demand also supported by public demand-side policies; and public supply-side policies to support stakeholders in this mission-driven project. The state through its public company Petrobras had the opportunity to shape the market and to coordinate the activities of a large number of stakeholders towards a clearly defined goal: the challenge of extracting huge quantities of oil from the most difficult physical conditions of 4 kilometers depth (2 kilometers of sea water and 2 kilometers of salt and rock) as a spearhead to promote the development of other manufacturing sectors and especially shipbuilding to manufacture the necessary oil-producing platforms and sea-faring tankers. This goal was supported by "local content policies, tax incentives, trade-barriers, special funding by the Brazilian Development Bank, and the commitment of Petrobras to be the ultimate buyer of technology and vessels developed and assembled in Brazil" (Cherubini Alves et al., Chapter 7, this volume). The authors show that "windows of opportunity" are only a favorable structural precondition whose exploitation is dependent on network-specific alignment of individual strategies and stakeholders' activities.

The major mechanism of implementation was to set up a policy arrangement to create the institutional conditions and incentives for the shipbuilding industry to flourish in Brazil. Petrobras played a major role as the lead firm coordinating some of the main technological and contractual interfaces, establishing the links "between the policy goals (which aimed at catching up and upgrading) and the concrete industry agents responsible for leveraging and building capabilities" (Cherubibi Alves et al., Chapter 7, this volume). Their analysis shows that the policy set up to build national industrial capabilities was done without a strong mechanism for rapid technological transfer. Lacking core-technological capabilities required high capability building costs that surpassed the cost advantages produced by the policy incentives. That is to say, the lack of pre-existing national capabilities has hindered the possibilities of catching-up. This is in line with Lee, Baek, and Yeon's Chapter 4 in this volume, who argue that implementation capabilities focused on the efficient production and operational experience is the very first step before actually catching up. Moreover, in the analyzed case, industrial policies dealt with a vast number of contractual interfaces that proved to be very hard to coordinate. Opportunistic behavior of agents under severe time pressures led to bribery and corruption which jeopardized the continuation of the operation.

Continuing with the same country (Brazil) and the same general field of economic activity (primary resource extraction), Figueiredo and Piana explore how domestic mining firms have successfully exploited the changing windows of opportunity. In Chapter 8 of this volume, "Technology Upgrading in Natural Resource-Intensive Industries: Evidence from the Brazilian Mining Industry," they report on a very detailed longitudinal study which looks at technology upgrading activities of two major Brazilian mining firms, now internationally leading companies—and their surrounding ecosystem. Their research depicts three major stages of development of the industry: (i) emergence phase/early 1940s–mid-1960s; (ii) gradual catch-up phase/late 1960s–late 1990s; and (iii) forging ahead phase/early 2000s–mid-2010s). For each stage they outline changing windows of opportunities in terms of demand, technological opportunities and challenges, and institutional factors. Their especially valuable contribution is that in each of the stages they depict at very detailed level both science and technology (STI) activities and production-related improvements and innovation in the so-called "doing-using-innovating" (DUI) activities. The case illustrates how required knowledge was either internally generated or externally acquired through a variety of learning mechanisms across the different stages. It is clearly demonstrated that these two modes of knowledge generation and acquisition are complementary.

The study shows that firms' technological learning strategies that emerge as strategic responses to changing windows of opportunity, "vary from imitative and defensive to offensive, involving various DUI and STI learning mechanisms, whose use are qualitatively changed over time, affecting firms' technology upgrading process across its emergence, gradual catch-up, and forging ahead phases" (Figueiredo and Piana, Chapter 8, this volume). Their case can be considered a "success story" both in terms of technology upgrading and in terms of economic growth. It shows that external market opportunities, stability of ownership, and willingness to change and compete internationally have enabled firms to engage in a continuous process of learning and innovating, moving from imitators to world leaders. However, the process of upgrading has been gradual and has evolved over time, based on the acquisition of both technological and organizational capabilities. When compared to the Cherubini Alves et al. case of Brazilian deep oil drilling industry (Chapter 7, this volume) it shows the advantages of bottom-up processes which can be facilitated by external factors and policies but not necessarily entirely pushed in a top-down manner. It shows an evolutionary process which has not been interrupted—due to scandals and mismanagement in the excruciating effort to produce results very fast—and which has led to a durable innovation ecosystem. A comparison of these two cases shows that technological upgrading is not only about successful coupling of technological learning and market opportunities but also about the institutional stability which facilitates coupling among different types of opportunities.

Last but not least, the Figueiredo and Piana study in Chapter 8 shows that technology upgrading processes cannot be fully captured by focusing only on explicit R&D-based activities. In that respect, their study provides a good benchmarking reference to the range of activities which would need to be captured by any set of indicators to be a fair reflection of the diversity of technology upgrading activities (as previously argued by Bruno et al., Chapter 3, and Lee et al., Chapter 4, in this volume).

The issue of complexity and the uncertain nature of technology upgrading so much present in the chapter by Cherubini Alves et al. (Chapter 7, this volume) is also the focus of Choung and Hwang in Chapter 9, "Upgrading Non-technological Capabilities: Evidence From Korean Firms." They explore three complex product development projects: small nuclear reactors, nuclear power plant construction, and high-speed trains. These are cases of post-catch up development as they are new world frontier technologies developed and deployed in an economy which throughout its modern history has been one of the world paragons of "catching-up" with the global technological frontier through technological imitation and assimilation based on mass production systems. Their concluding assumption is that the institutional and organizational setup at both firm, interfirm, and policy levels favorable to catching up may not be "fit" for post-catch-up purposes.

Choung and Hwang frame this issue by drawing on the product life cycle and on Utterback and Abernathy's (1975) three-stage innovation model which differentiates between fluid, transition, and specific stage. They then explore the three cases by looking at intra-firm, inter-firm, and public research institutes' relations and how they are shaped by the overall policy context. Their cases show that the system geared towards catching up where technological and institutional trajectories are largely externally given faces significant challenges in the deployment of technologies at the frontier, and especially of complex product system technologies. Mastery and deployment of new technologies is faced with both technological, institutional (regulatory), and market uncertainties. A policy regime which operated well during the initial stages does not have the required flexibility to promote standardization of new technologies as well as capacity to finance (commercialize) this type of development. Required capabilities are not any more confined to intra-firm capabilities but require systems engineering knowledge as well as system integration for complex products, which calls for a new role of public research institutes to support the coordination of collective learning.

Moreover, the critical roles of different stakeholders change over product life cycle. In the fluid stage, key actors are technology developers and regulatory agencies; in the transition stage it is close links between users and component suppliers in cooperative product development. Finally, in the specific stage, it is the ability to build a business ecosystem and the ability to manage the capabilities of component supplier networks. Choung and Hwang's main conclusion is that in the post-catch up stage the role of non-technological (organizational and inter-organizational and institutional capabilities) is critical to shift the emerging economy sectors from catch-up to post-catch-up stage. Their cases offer a wealth of strategic and policy implications of relevance for other emerging economies sectors, firms, and countries.

1.3.3 Emerging Paradigm on Technology Capability Upgrading

Traditionally, technology upgrading of emerging economies has been framed within the catching-up and economic growth perspective. The dominant paradigm of research focused on exploring firm-specific patterns of technology accumulation and on the external environment surrounding firms was framed most often through the systems of innovation perspective. The ultimate criteria for assessing firm or sector or country technology upgrading was profitability or economic growth. The neo-Schumpeterian perspective with its focus on the cumulative and differentiated nature of technology has been the natural habitat for this research. This approach will continue to remain as the dominant research program but probably in a significantly modified form to reflect new developments in terms of environmental factors and greener models of growth as well as concerns of inclusion, poverty, and other social factors.

A major new development is the changing nature of technology through the ongoing increasing application of artificial intelligence algorithms and so-called Industry 4.0 related technologies. Its application is systemic technological change, which is not only technical but also organizational, social, and political, and which profoundly changes the nature of the capitalist system. This is the type of process explored by Perez (2015) and Freeman (2019), termed as change in techno-economic paradigm.

A second major development is the demise of the fossil-fuel-based growth regime which has hit at the limits of biosphere, threatening the very idea of economic growth and, with it, the traditional approach to innovation as primarily a tool of economic growth. Concern has been further reinforced by climate change pointing out that economic activity at contemporary scale must be considered as an integral component of Earth's adaptive and complex network of its bio-physical systems (Raworth 2017). For innovation studies on emerging economies this means a shift of focus from growth towards a sustainable technological regime which will respect planetary boundaries while also promoting the growth, welfare, and resilience of emerging economies.

The chapters in this section are contributions towards this emerging paradigm of research and policy thinking on technology capability. Tilman Altenburg frames the issue in stark and binary way as "Catching Up or Developing Differently? Techno-Institutional Learning with a Sustainable Planet in Mind." He rightly points out that catching-up has in earlier times been seen as imitation of the established techno-economic patterns which would mean that catching-up economies do not have much option but to adopt fossil-fuel-based and energy-intensive technologies. If this were to be the case, the world economy would be unable to achieve absolute decoupling between economic performance, on the one hand, and resource consumption and environmental impact, on the other. This leads him to discuss to what extent the notion of catching-up is still useful in a situation where a radical departure from environmentally unsustainable patterns is inescapable.

The argument is that "the normal transition from imitation to innovation may therefore delay the adoption of sustainable alternatives, which is particularly problematic when looming environmental crises require fast turnaround, as is the case of decarbonization" (Altenburg, Chapter 10, this volume). If catching up is just about technology adoption and imitation, then replication of energy-intensive paths of development will lead to further lock-in into outdated and climate change harmful technologies.

Some of the answers to Altenburg's questions are given in chapters by Lee and Mathew in this volume. Lee, like Altenburg, also points out that catching-up based on imitation eventually reaches diminishing returns and cannot be the basis for achieving technology leadership. Lee points out that successful latecomers do not simply follow advanced countries' paths of technological upgrading but either skip certain stages or create their own path which differs from that of the forerunners. Mathews (this volume, Chapter 11) argues that, given the country's resource scarcity, the emerging growth regime of China is increasingly based on green activities and technologies as the only alternative. Nonetheless, Altenburg's argument remains very relevant for the majority of catching-up economies that do not have strategic capacities to skip what in the short term seem to be cheaper energy-intensive stages and/or are not dramatically resource constrained as is China. Whether these economies will embark on imitating technologies of a carbon-based industrial era will depend on the global pricing of carbon as well as on opportunities for diffusion of new green technologies. So, the extent to which these economies will be able to imitate new technologies of the green economy will depend on whether the green technologies frontier is moving fast enough that there is scope for imitation and diffusion.

From the perspective of this volume, the very objective of catching up—level of economic development as expressed in GDP per capita—has been increasingly redefined. The new objective of catching-up includes sustainable development and green growth which is about economic growth and development but also ensures that natural assets continue to provide the resources and environmental services on which human well-being relies (OECD 2011). The emerging issues and solutions in this new context for catching-up economies are the core of the new research paradigm on technology upgrading. Altenburg's chapter thus represents a strong point of departure for further thinking and research on technology upgrading in the context of sustainable development and green growth.

Mathews in his chapter (this volume, Chapter 11), "Leapfrogging on Steroids: China's Green Growth Strategies," forcefully argues that China is the most vivid example of the shift from the techno-economic regime based on fossil fuels towards the regime based on green growth. His main point is that this shift is the result of the necessity faced by China, given its huge energy needs and resource scarcity as well as the geo-political limits by which it can substitute for the missing energy and mineral resources. China "discovers" green growth as the only viable strategy for catching up and forging ahead.

This shift means a large-scale switch to an energy trajectory based on renewables, and a resource trajectory based on new strategies like the circular economy (urban mining). Mathews illustrates his argument with several Chinese success stories like electric power grid modernization through utilization of Ultra High Voltage (UHV) technology, Permanent Magnet Direct Drive (PMDD) technology in wind turbines, and the rapid introduction of high-speed rail (HSR) inter-city transport.

Another major insight from this evidence (though not explicitly explored by Mathews in this chapter) is that China has combined multiple paths of technology upgrading. It has followed both an imitative path well described by Lin (2012) but has also embarked on alternative leapfrogging paths as argued by Mathews and also discussed broadly by Lee in this volume. Mathews points out that the Chinese alternative paths are not entirely market driven but are also very strongly driven by the state and state-owned enterprises. This issue is further explored by Gao in his chapter on Chinese large-scale modernization programs (Chapter 14, this volume).

Chapter 12 by Ciarli, Savona, and Thorpe on "Innovation for Inclusive Structural Change" establishes a new research agenda on the issue of inclusivity. The authors depart from the widely recognized stylized fact in Schumpeterian economics that innovation through "creative destruction" entails structural change which might have exclusionary outcomes. However, they recognize that innovation may also be inclusive, thus generating inclusive structural change. There are various trade-offs between innovation, structural change, and their inclusiveness or exclusiveness.

This issue has emerged as policy relevant with the recognition of income-polarizing effects of technical change (for example, digitalization) in developed economies. While the chapter by Ciarli et al. focuses on low and medium-income economies, their analysis is also applicable to developed economies. Their motivation is to explore what are the conditions, actors, and interactions under which innovation leads to both structural change and inclusion, and reinforce each other in a virtuous circle.

In a state-of-the-art review of the relationship between innovation, structural change, and inclusion, Ciarli et al. ask which innovations lead to upgrading and further structural change. Which innovations are inclusive? How does inclusion influence innovation and structural change? How does structural change affect inclusion and innovation? Besides analytically exploring all these relationships, the authors discuss the ensuing trade-offs between inclusion, structural change, and innovation on the examples of the south–south trade and investments, grassroots innovation in low-middle-income economies, and on the agglomeration economies of clusters and cities in such countries.

The analysis concludes that the industrial and innovation policy in these contexts should aim to identify relevant opportunities for indigenous innovation and its diffusion. However, it is recognized that, for this, market incentives would need to be complemented by incentives "beneficial to inclusion" and by supporting the effective demand of "local communities" and "more diffuse groups" for novel products or services "which might (or might not) then lead to better social and economic outcomes." Ultimately, the outcome will depend on "the political economy of value creation and redistribution which will ensure whether or not innovation capacity is made sustainable in the long run to redirect pathways of innovation towards inclusive structural change" (Ciarli et al., Chapter 12, this volume).

Dutrénit, Natera, Puchet, and Vera-Cruz in Chapter 13, "Evolutionary Spheres that Condition the Technological Capabilities Accumulation in Latin America," develop a new agenda which could be labeled as a political economy of technology accumulation. They apply it to the context of Latin American economies where they also address among others the issues of inequalities tackled in the chapter by Ciarli et al. They argue that technology capability accumulation is inextricably linked to political, social, and environmental factors. This leads to framing the technology capability accumulation processes at firm and national levels as being shaped by the co-evolution of two subsystems: the techno-economic and environmental (TEE) sphere and the socio-political (SP) sphere. The interaction between these two spheres leads to country-specific development profiles.

The analysis is quantitative, based on thirty indicators grouped into TEES indicators of economic performance, STI inputs and outputs, and the environmental impact of economic activities, on the one hand, and SPS indicators of quality of life and of the socio-political environment in the 1980–2015 period, on the other . Based on the cointegration relationships between income per capita and individual components of TEES and SPS, the authors are able to identify three development profiles among eighteen Latin American countries: (i) countries whose systems are biased towards TEE while lacking in SP development; (ii) countries whose systems are biased towards SP while lacking in TEE; and (iii) countries with a more balanced relationship between TEE and SP systems. The analysis suggests that the constraints to technology upgrading are not confined on a narrow S&T system but are broader and are located in both TEE and SP systems. Consequently, different policy foci are suggested stemming from different countries' profiles. In all cases countries need to strengthen the firms' technology capability accumulation "in accordance with the country's development profiles."

The main conclusions of this chapter support views that middle-income traps are due to politics as much as they are due to economics (Doner and Schneider 2016).

1.3.4 Innovation Policy for Technology Upgrading

A last section of the volume explores facets of innovation policies for technology upgrading. The selected policy issues in the volume should be seen in the context of significantly changing policy philosophies evolving from the mid-twentieth century until today.

In emerging economies, the period from the 1960 to 1970s had been characterized by import substitution industrial policy and so-called vertical industrial policies. During the 1980s and 1990s and until the first decade of the twenty-first century the dominant policy philosophy in many emerging economies was the so-called "Washington Consensus" or market-friendly policies, where technology-upgrading activities were submersed within the horizontal or sectorally neutral innovation policies. Re-examination of these policies started with the failure of the Washington consensus and the high growth of China and Vietnam which resisted this approach (see on this World Bank 2005 *mea culpa* study). The current period could have been until recently characterized as a post-Washington period or a period of search for new policy alternatives. The current health crisis has further speeded up changes of policy thinking in this area driven also by the reassertion of nation states in the global economy and the rise of strategic industrial innovation policies. Three chapters in this volume reflect this current transitory stage of policy thinking.

The powerful role of industrial and innovation policy to overcome latecomer advantages is very vividly presented in Chapter 14 by Gao entitled, "Using Large-Scale Programs to Help Develop Technological Capabilities: Cases in China." This is a summary description of eight success stories of technological catching-up and forging ahead which stand in contrast to some other Chinese experiences like automotive and airplane jets. Several factors are present in all the successful cases pointing to the main ingredients of Chinese technology upgrading. First, Gao points to the strategic intent led by individual leaders in their positions long enough to ensure stability of the modernization process. Such champions were crucial for enforcing a strategizing approach in contrast to an economizing approach, especially when stakeholders were faced with the high costs of local developments and the initial inferiority of local firms. Second, the key was not only in accumulating capabilities in individual firms but in reshaping the nature of the existing value chains and innovation networks, initially dominated by foreign multinational enterprises (MNEs), and providing more opportunities for local firms to catch up. The major actors in this process were state-owned enterprises (a point also highlighted by Mathews) with capabilities to mobilize networks of suppliers and lead innovation ecosystems. Finally, the upgrading of the emerging domestically controlled network relied heavily on levers of state policy which was in a position to trade access to the Chinese market with transfer of technology, especially in the case of large-scale public procurement programs like high-speed rail network or high voltage transmission network. This *quid pro quo* policy has been supplemented by an explicit local content requirements policy. Chinese upgrading came about as favorable interaction among three groups of factors, none of which individually would have sufficed.

Given the huge size of the Chinese market we should be aware that some of these elements are difficult to implement in other emerging economies. The size of the technology gap is also an important factor which can explain some of the Chinese failures in automotive and in jet planes. However, the issues regarding how to induce strategic behavior in local firms, mobilize local supply chains, and form constituencies for technology upgrading are very powerful lessons from the Chinese experience, valid for a large number of emerging economies.

Gao's chapter argues that no technology upgrading can take place without restructuring relations with MNEs. This is even more important for emerging economies that do not have Chinese bargaining power in the international economy. How these economies can technologically upgrade is very much about their policies towards GVCs. Pietrobelli's chapter (Chapter 15, this volume), "Industrial and Innovation Policies in a World of Global Value Chains," provides a state-of-the-art understanding of research on policies in this area, ranging from policies to "attract" or "join" value chains to policies to "upgrade through GVC." The range of instruments involves a variety of public inputs and market interventions of both horizontal and vertical nature.

In the past few decades we have lived in a "value chain world" where "GVC-oriented policies", that is, policies targeting production and technology upgrading through GVCs, have gained ground. Unlike traditional old-style industrial policy thinking which was about sectors, GVC oriented policies target much narrower business activities. The policy challenge becomes to identify critical "GVC gaps" in technological capabilities whose accumulation cannot be resolved through conventional market failure logic but require close interaction between value chain coordinator firms, local firms, and public stakeholders.

The challenge for laggard economies is also to manage a learning process whereby their domestic players keep stepping up in positions of higher value-added in existing GVCs and ultimately setting up their own. How to set initiatives and programs to use GVCs as levers for local technology accumulation is still poorly understood, and Pietrobelli gives us several examples of challenges and successes in this area. He also implicitly argues that GVCs are not a panacea for technology upgrading as their effects on technology upgrading essentially depend on interaction with the local innovation systems. The key message that emerges is that the outcomes strongly depend on the co-evolution of GVC and innovation systems where, in the long term, countries may change the degree and nature of their reliance on GVC and on local innovation systems.

Finally, the chapter by Kuznetsov titled "Experimentalist Governance for Technology Upgrading: New Industrial Policy Process" (Chapter 16, this volume), addresses a question rarely explored in research on innovation policy: how policymakers should go about implementing new policy. That shifts attention from probing *what* the issue is to *how* to design and implement programs which will recognize danger of failure and vested interests as well as low policy capacity, which is endemic to emerging economies. The approach that Kuznetsov develops based on a rich policy experience is part of so called "new industrial policy" thinking, valuing experimentation (see also Rodrik 2004; Sabel and Zeitlin 2011; Dutz et al. 2014; Foray 2014; Radosevic 2017; and Breznitz and Ornston 2018). The main idea is that policymakers cannot act as principals but have to embark on the policy experimentation process to "discover" constraints and opportunities. The challenge is to establish governance mechanisms for "diagnostic monitoring" which can ensure early "error-detection and error-correction of the continuously shifting and erring choices." Industrial policy then effectively becomes the outcome of "a series of bets along an uncertain and rapidly evolving technological frontier, dropping unprofitable projects and offloading successful ones to create space for new initiatives."

As would be expected, this approach contradicts the conventional Weberian public-sector logic where failure is not tolerated. This raises the issue of "accountable experimentation" (Kanellou et al. 2019); it also de facto limits the widespread use of this type of policy across the public sector. Kuznetsov provides an overview of many examples of successful new industrial policy which have been emulated with much success across the world (like Israeli Yosma Fund and Foundacion Chile) and points out unknown "hidden gems" of successful programs in emerging economies. He accounts for the political economy dynamics of the process and cycles through which such cases evolved.

It could be argued that the alternatives to the proposed experimental industrial policy are either vertical industrial policy programs which rest on unrealistic assumptions of "enlightened" policymakers who can pick winners or horizontal policies which are broad based and only implicitly somewhat selective. New industrial policy programs may emerge as alternative "spaces of novelty" whenever there are windows of opportunity from habitual rent seeking captured by local "policy entrepreneurs."

1.4 Key Findings

Overall, the contributions in the volume represent state-of-the-art understanding of the issues around technology upgrading and economic catch-up in emerging economies. They address country-, sector-, and firm-level issues based on a variety of country experiences; explore the newly emerging research issues on green economy, sustainability, and inclusiveness, and their relationship to technology upgrading. They examine major current policy issues in the context of past policy experiences and outline new policy avenues. Several key lessons emerge:

First, one important concept brought about in this book is that of transition (or upgrading) failure which refers to difficulties facing middle-income countries in their effort to make a transition from imitation to innovation stages. This difficulty has also been discussed in Lee (2019) in terms of a narrow passage between the middle-income and the high-income stages. In this book, the chapter by Fagerberg and Srholec (Chapter 2) observes that while imitation gaps alone fail to account for the very rapid growth of the catching-up economies in East Asia, technology capabilities are the major reason. In the chapter by Lee, Baek, and Yeon (Chapter 4), such transition failure is analyzed in a more specific manner in terms of making a hard transition from implementation to design capability.

Transition failure can be partly attributed to the fact that the next stage often involves more direct competition with incumbents and thus requires new kinds of capabilities which are mostly difficult to acquire. For instance, the chapters by Figueiredo and Piana and by Choung and Hwang (Chapters 8 and 9) commonly discuss the importance of science and technology-based innovation activities as well as production-related improvements and innovation, or so-called "doing–using–innovating" activities. The latter chapter, in particular, validates the importance of non-technological factors (organizational and inter-organizational and institutional capabilities) in advancing to and succeeding in the more advanced stage.

This idea of transition failure is consistent with the concept of non-linearity. The chapter by Bruno, Osaulenko, and Radosevic (Chapter 3) finds that simple openness to technology exchange, unless complemented by own technology accumulation activities, does not contribute to increased TFP and labor productivity required for the next stage. This non-linearity may be one reason for the need to take some strategic risk in the form of leapfrogging and detours, which is different from the mainstream views oriented toward a linear view. As discussed in the chapter by K. Lee (Chapter 5), leapfrogging makes more sense as the latecomer gets close to the frontier and finds that technology transfer becomes more difficult or costly. Although risky, leapfrogging is a way to overcome the barriers associated with IPR protection by incumbents as latecomers leap forward towards new generations of technology ahead of incumbents who often tend to stay longer with the existing technologies where they are superior.

Second, this book underscores the importance of interaction between firm-level capability and the surrounding innovation systems. For instance, the case of mixed success (or failure) in the shipbuilding sector in Brazil shows that individual firm capabilities are not enough for catching-up unless there is a network which can generate synergies and create a new dynamic of technology upgrading. This shipbuilding case is quite a contrast with the successes in other sectors (mining) in Brazil and those in China (large infrastructure). The latter cases clearly depict how technology upgrading has proceeded effectively as interaction of firm-level responses and their surrounding ecosystem exploiting the exogenous windows of opportunities (Lee and Malerba 2017). The importance of interaction is one of the cases for the frequent transition failures because the transition is a system-wide change, not only in applied and developmental research but also in education, finance, industry structure, trade regime, and industrial and innovation policies. Such recognition is also consistent with technology upgrading being shaped by co-evolution of two subsystems (spheres): techno-economic and environmental and the socio-political spheres, as discussed in the chapter by Dutrénit, Natera, Puchet, and Vera-Cruz (Chapter 13).

Third, this volume emphasizes the importance of managing strategically the local–foreign interface (indigenous firms vs. MNEs) to induce the eventual rise of local ownership and local value chains as one of the critical factors for successful upgrading of technologies and economies in the longer term. Successful cases of upgrading discussed in this volume, such as those in China, suggest that the key is not just accumulating capabilities in firms but reshaping the nature of the existing value chains initially dominated by MNEs, and providing eventually more opportunities for local firms. In Gao's study on Chinese cases, the major actors in this process were state-owned enterprises, also echoed by Mathews in his chapter on China (Chapter 11).

The critical importance of stable or local ownership has to do with the nature of process of technology upgrading, which is a fundamentally uncertain and long-term process subject to diverse factors. The chapter by Figueiredo and Piana (Chapter 8) on the success in the mining sector in Brazil also shows that the process is affected by strategic responses to changing external windows of opportunity, while the effective responses themselves keep changing qualitatively over time. Thus, given inherent uncertainties, stability of ownership (domestic ownership) is advantageous in terms of enabling firms to engage in a continuous process of learning and experimentation in the effort to innovate their way from imitators to world leaders. Thus, Gao concludes that no technology upgrading can take place without restructuring relations with MNEs.

Even more challenging for other emerging economies that lack the Chinese bargaining power is the discovery that the technological upgrading of their economies depends very much on their policies towards GVCs. One emerging idea in this regard is the so-called "in-out-in again" strategies as discussed in the chapter by Carlo Pietrobelli (Chapter 15) as well as in Lee et al. (2018) and Lebdioui et al. (2020). At the initial stage of growth by a latecomer, increased participation in GVCs is necessary to absorb foreign knowledge and production skills. In the effort to functionally upgrade at the middle-income stage, countries must seek separation and independence from foreign-dominated GVCs to increase domestic value-added. Finally, after establishing their local value chains, latecomer firms and economies may seek reintegration into the GVC system, often leading the chains themselves. Broadly speaking, this is one of the many possible ways GVCs and their governance coevolve with innovation systems (Lema et al. 2019).

Fourth, this volume emphasizes the need for yet newer avenues of thinking about policy. The impossibility of development and growth the old-fashioned way is emphasized by Mathews. Greener paths to growth have become necessary in an era when more than half of humanity—that is, several billion souls—is progressing fast simultaneously. More inclusive paths to innovation, structural change, and growth are also becoming imperative given the current experiences with rapidly diverging incomes and capabilities across the masses. Ciarli, Savona, and Thorpe propose that more inclusive paths are possible. Kuznetsov points out yet another interesting idea: policy approaches that reward risk-taking are flexible, and are based on experimentation. This is something that the public sector has generally failed to do outside the contexts of exceptional dashes to technology upgrading and growth such as the United States, Germany, and Japan in the late nineteenth and early twentieth centuries, the Soviet Union in the mid-twentieth century, Japan and Korea in the second half of the twentieth century, and China during the past few decades. New policy thinking evolves towards the "process" view of development where focus is not confined to the technological, institutional, or natural endowments but extends to the processes through which successful local cases of sustainable growth diffuse, propagate, and coalesce.

1.5 The New Global Context and the Road Ahead

The technology upgrading of middle-income countries in the first half of the twenty-first century takes place in the context of several major economic and technological transformation processes, coupled with the several events which can be considered as "tipping points." By this we mean events that represent shifts in the structural transformation processes observed since the end of the twentieth century. The global financial crisis of 2008/09 and the 2020 COVID-19 global crisis, though of very different nature, represent such "tipping points," that is, events that have either shifted systems trajectories towards new directions or accelerated transformations along already established trajectories. For example, the diffusion of digital technologies has been accelerated by the COVID-19 crisis; the post-COVID-19 period may see the outright retreat of or a new stage of globalization.

Globalization of the late twentieth and early twenty-first century which has led to the rise of emerging economies, and in particular China, currently seems to have slowed down or halted altogether. Meanwhile, catching-up characterized primarily as economic growth has led to extensive environmental degradation, thus making present growth patterns of a large share of humanity unsustainable in the long term. The COVID-19 global crisis has demonstrated the importance of "system resilience," meaning the economy's ability to withstand social, financial, environmental, or other shocks without catastrophic and system-wide effects. It has also re-iterated the question of whether countries can reorient innovation systems to better meet society's pressing needs. Consequently, instead of being focused only on economic growth, challenges in technology upgrading have partly shifted towards green growth, inclusive development, and environmental and human resilience.

The book emerges in the period of a "new global shift" which represents interaction among path-dependent processes of the past driven by globalization, an increased global middle class, and proliferation of ICT as general purpose technology, on the one hand, and new challenges driven by the concerns like those mentioned above regarding sustainable development, environmental degradation, and biological resilience of human and natural ecosystems, on the other. From the perspective of emerging economies, the challenges induced by globalization, the proliferation of GVCs, and their increased dependence on technology upgrading through global supply chains still remain the major concerns. The contested nature of globalization by its losers and winners, the increasing role of China in the global economy, and the differentiation among the BRICS countries and other emerging economies raise the issue of how to balance the needs for openness with the need for autonomy of national spaces.

The past has shown that mere openness does not suffice for catching-up, while a closed economy is also not a viable route to technology upgrading. How to couple endogenous technology efforts with the need for accessing foreign markets and foreign knowledge have become even more pressing in the contemporary context where the majority of national challenges are global in nature (e.g., trade, foreign direct investment (FDI), security, access to energy resources, environment, global health). Deindustrialization of many middle-income economies is linked not only to globalization but also to differences in opportunities to capture the benefits of digitalization or technological transformation and the increasing inequalities that stem from these processes. This increasing differentiation poses challenges as well as opportunities for green and inclusive development in the context of ongoing digital technological transformation. The COVID-19 global crisis has accelerated these patterns and added resilience as the important challenge for future development and human welfare.

Popular policies might be affected. Let's think for a moment of an example of a policy area high on the agenda: *smart specialization*. Born in the era of unfettered globalization, it becomes vulnerable in the current shake-up of GVCs. Smart specialization-based regional profiles makes a region more vulnerable to external shocks like the recent COVID-19 event and other shocks imposed by interventions of different kinds such as geopolitical struggles.[2] A paradigm shift in priority setting from focusing on most promising fields towards sustainable economy may be more appealing. The smart specialization approach until recently more or less took the external environment for granted. Managerial responses to minimize value chain vulnerability and restructuring priming diversification will require new approaches to smart specialization and regional positioning to capitalize on the emerging opportunities.

Having discussed earlier several key findings from the book, we can conclude this Introduction with reference to the remaining issues and new challenges associated with the new global context. One of them is how to make technology upgrading and such induced growth more inclusive and environmentally sustainable. These issues are dealt with in several chapters of the book but require further treatment. The goal would be to find out what are the conditions, actors, and interactions under which innovation leads to growth-enhancing, sustainable, and inclusive environments, and how to make them reinforce each other in a virtuous circle. Solutions can be sought in the concept of leapfrogging in the chapter by Mathews, as he discusses China's leapfrogging into a new energy trajectory based on renewables, consistent with the concept of a circular economy (urban mining). Solutions for inclusive innovation can also be sought by referring to the idea that choice of technologies is closely intertwined with socio-political spheres as discussed in the chapters by Ciarli, Savona, and Thorpe and by Dutrénit, Natera, Puchet, and Vera-Cruz (Chapters 12 and 13).

Also, disruption of GVCs in the post-pandemic era poses both additional difficulties and new opportunities for emerging countries seeking new modes of technology upgrading and catch-up, possibly in a renewed recognition of the role of the government.

Whatever alternative modes are possible, one point of agreement would be a need to rely more on domestic resources for a more resilient pattern of development. Further, given that high-end manufacturing sectors mean a high entry barrier for most emerging economies at middle-income stage, exploration of the possibility of high-value addition in resource-based sectors should be tried out. For instance, Lebdioui et al. (2020) observed that Malaysia and Chile are showing signs of growth beyond the middle-income trap owing to their success, not in manufacturing, but in several resource-based sectors (such as petroleum, rubber, and palm oil sectors in Malaysia, and salmon, fruits, wine, and forestry in Chile).

Last but not least, the volume points out the need to examine trade-offs between conventional forms of technology upgrading driving efficiency and productivity and more modern concepts of technology upgrading, mindful of the "greening" of economies, inclusion, and societal resilience. The period since 2008 has shown the limits

[2] The argument is reminiscent of the old debate in economics about national specialization on the basis of natural endowments, an idea that catching-up countries of the past (in East Asia and Latin America) rejected wholesale.

of focus on unfettered markets and growth as the ultimate solution to inequality accompanied by policies which ex post can cure all the ills of fast growth. Instead, the focus should be on balancing trade-offs of high productivity and GVC efficiencies, and of social and environmental costs of growth, with requirements for the green transition, sustainability, biological resilience of the economy and society, and inclusive technological diffusion. This increasing multiplicity of objectives poses considerable new challenges for scholars in exploring and assessing as well as for policymakers in directing the technology upgrading of emerging economies. This new research agenda is increasingly interdisciplinary and shifts considerably boundaries of inquiry towards social and political determinants of technology upgrading. We hope that contributions in this volume indicate the direction of desirable new research and policy agenda which reflects the changing global context of the first half of the twenty-first century.

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PART I

TECHNOLOGY CAPABILITY AND GROWTH PERFORMANCE AT THE COUNTRY LEVEL

2

Capabilities, Competitiveness, Nations

Jan Fagerberg and Martin Srholec

2.1 Introduction

One of the most challenging questions in economics is this: Why do some countries perform so much better economically than others over long periods of time? This is of course a matter of great theoretical and practical importance, and for this reason, it has attracted interest from economists for centuries. In fact, Adam Smith had already struggled with this question. And, as the following quotation from Friedrich List—in a rebuttal to Smith's reasoning about the subject—shows, the idea that this has something to do with a country's capability to absorb, exploit, and create knowledge has been around for a long time:

> The present state of the nations is the result of the accumulation of all discoveries, inventions, improvements, perfections and exertions of all generations which have lived before us: (…) every separate nation is productive only in the proportion in which it has known how to appropriate those attainments of former generations and to increase them by its own acquirements. (List 1841, p. 113)[1]

Nevertheless, the issue continues to be surrounded by controversy. One of the reasons has to do with resistance by many economists to the use of concepts such as knowledge, capabilities, and competitiveness in connection with analyses of how countries perform. Such factors, it is commonly argued, are attributes of individuals, not collectives. What economists should do, following this view, is to analyze economic development as the result of interaction between individuals that seek to maximize their own welfare. However, whatever the merits of this approach, what seems clear is that it substantially reduces the range of phenomena that the analyst can meaningfully say something about (and hence influence). Arguably, many if not most issues that policymakers are concerned about simply slip under the radar of analysts basing themselves solely on this individualist approach.

Policymakers' need for advice is instead met by a more practically oriented literature, often related to the consultancy industry, based on the exploration of popular

[1] Cited after Soete et al. (2010), p. 1161.

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concepts, frameworks and exemplars considered to be relevant for decision-making in organizations at various levels. With respect to nations a typical example is the construction of composite indicators of competitiveness ranking countries according to how competitive (successful) they are (IMD 2012, WEF 2011). By taking into account the various dimensions that go into such indicators and how they are weighted together, analysts may derive conclusions about the sources of a country's success—or a lack of such—relative to others, and hence what might be done about it. Although the construction of these indicators is often almost void of theory (and based on very simple empirical methods), the interpretation of reality they convey and the advice this leads to receive much attention both in the media and among policymakers.

Arguably, economists should be able to do better when it comes to providing relevant policy advice. While the individualist approach may be useful for analyzing certain issues, it should also be recognized that a collective cannot always be reduced to the sum of the attributes of the individuals joining it. Collectives such as firms, organizations, and nations are more than the mere sum of their parts. They are also repositories of knowledge, institutions, and resources that significantly influence the actions—including interactions—of their members in efforts to create and exploit economic value.

Nevertheless, it is often argued that use of concepts such as capabilities and competitiveness at the country level implies wrongly applying firm-level theories to the analysis of entire nations. This is so, the argument goes, because firms and nations are altogether different entities, and, hence, require different theoretical approaches to be adequately understood. However, while it is certainly true that there are differences between firms and nations that should not be overlooked, there are also similarities that ought to be taken into account.[2] Both firms and countries are organized entities in which populations, based on their skills and resources, interact to create value, which is then distributed across the population according to certain criteria. Moreover, they both have systems of governance which significantly influence the creation and distribution of economic value and that affect their performance.

Hence, although there are important differences between countries and firms, the economic environment in which these entities operate, with its capitalist, knowledge-based dynamics, is essentially the same, and so are many of the factors that influence their performance. Using related concepts and understandings to analyze these challenges should therefore not be regarded as a deadly sin but on the contrary as quite natural. Doing so may also have the added arguably non-trivial benefit that it provides

[2] A common argument is that firms can go bankrupt (and eventually be forced out of business) while nations cannot. However, history is replete with examples of nations that did not survive, often because they were less efficient than others economically. The Soviet Union and the previously socialist countries in Eastern Europe come to mind as relevant examples. More recently, the governments of Greece, Portugal, Spain and others have been exposed to a lot of pressure for not governing their economies in a sufficiently good way.

policymakers and managers with a common language for dealing with some of the challenges and opportunities they are facing.

The structure of the chapter is as follows: Section 2.2 discusses the part played by knowledge in economic growth, and the role of technological and social capabilities for the successful exploitation of knowledge towards this aim. How such capabilities can be measured is the topic under consideration in Section 2.3. Section 2.4 presents a model linking capabilities with growth and competitiveness. The subsequent section contains results from estimating the model on cross-country data from the two last decades. Finally, Section 2.6 presents conclusions and points to topics for future research.

2.2 Knowledge, Economic Development, and Capabilities[3]

Most people today would easily accept the view that knowledge and development are two sides of the same coin. But this is not the way growth and development normally have been analyzed in economics. Rather, from the classical political economists onwards, growth and development have been seen as arising from accumulation of (physical) capital. One possible explanation for this may be the close connection that existed during the so-called Industrial Revolution between the introduction of new machinery and economic growth. Since new technology entered the economic sphere through investments (in machinery) it was the latter that was seen as the constraining (or enabling) factor and that hence merited most attention.

This tendency to reduce technology to machinery (or knowledge to artifacts) was something that not only affected economic orthodoxy. Even a highly heterodox economist such as Torstein Veblen argued along these lines in what may have been the first scholarly attempt to analyze catch-up processes in the world economy (Veblen 1915). In earlier times, Veblen argued, the diffusion of technology had been hampered by the fact that technology was mostly embodied in persons, so that migration of skilled workers was a necessary prerequisite for its spread across different locations. However, according to Veblen, the advent of "machine technology" changed this logic completely (ibid. 191). In contrast to the conditions that had prevailed previously, he argued, this new type of knowledge "can be held and transmitted . . . and the acquisition of it by such transfer is no laborious or uncertain matter" (ibid.). Hence, because of these changes, catch-up should be expected to be relatively easy and was under "otherwise suitable circumstances," largely "a question of the pecuniary inducement and . . . opportunities offered" (ibid. 192).

This optimistic mood with respect to what could be obtained through participating in technology diffusion came to be shared by most neoclassical economists in the

[3] The issues covered in this section are surveyed in greater depth in Fagerberg and Srholec (2009) and Fagerberg, Srholec, and Verspagen (2010).

early post-war period. According to Robert Solow, the most famous contributor to the development of the neoclassical theory of economic growth (Solow 1956), knowledge—or technology—should be regarded as a public good freely available to anyone with a desire to share it, independent of their background or location. It follows that it should be expected to benefit everybody to the same extent. This was also the assumption adopted in subsequent applied research based on this perspective. Edward Denison, the leading researcher of cross-country differences in economic growth in the Western world in the early post-war period, put it as follows: "Because knowledge is an international commodity, I should expect the contribution of advances of knowledge (…) to be of about the same size in all the countries" (Denison 1967, p. 282). To the extent that differences in income and productivity across countries remained, these would largely be explained by differential rates of capital accumulation in the past, related differences in saving behavior, and demographic trends.

However, these optimistic predictions have not always been confirmed in reality (Fagerberg and Srholec 2005; Milanovic 2009). For example, during the 1980s and 1990s, what were called the "lost decades" for development (Easterly 2001), the difference between the poor and the rich part of the world was hardly reduced at all. One important reason for the failure of these predictions, we shall argue, has to do with how technology and its contribution to economic development were conceived by those who made them. Arguably, there is no such thing as a worldwide stock of homogenous knowledge that flows across the globe at the speed of light and which everybody can exploit as much as they like. Rather there are many different types of knowledge and knowledge holders. Not all knowledge is scientific, as Friedrich von Hayek pointed out long ago (Hayek 1945). Much knowledge is practical and context specific (which does not make it less useful economically of course). Knowledge is also widely distributed across actors and contexts. As Hayek repeatedly stressed it is totally impossible for any actor, being a person or a firm (or a government for that sake), to know "everything" that may be relevant for the solution of an economic problem (what is often called "perfect knowledge"). In fact, just to identify what the relevant areas of knowledge are and how these can usefully be approached may be quite challenging.

Even in the case when the relevant knowledge can be identified, is codified and easily accessible, there is no guarantee that it will be successfully transferred. The knowledge may for example be difficult to understand and absorb. Higher education—even a doctorate or a whole group of people with such qualifications—may be required. Hence, it not sufficient to have access to knowledge, you must also have the necessary capabilities to understand, absorb, and exploit it. Building such capabilities may be demanding, costly, and time-consuming. Moreover, firms cannot rely on only one type of knowledge. They need to be able to access, absorb, combine, and use many different types related to, for example, finance, logistics, products, markets, production, etc. Access to necessary resources, such as ICTs, means of transport and skilled labor, and knowledge about how to access, keep, and exploit those, is also crucial. It is of little help, say, to be aware of some promising knowledge if you cannot get hold of the resources necessary to reap the potential benefits from its exploitation.

Hence, if economic development primarily is about knowledge, then it must also be about the abilities of social actors to engage in the process of accessing, absorbing, and using knowledge, so that income and welfare grow. Under capitalist conditions the most important social actor in this respect is the firm. From this perspective the gradual enhancements of a firm's capabilities in accessing, absorbing, and using knowledge must be regarded as a crucial factor in economic development. The Korean development scholar Linsu Kim suggested the term "technological capability" for this phenomenon. He defined it as "the ability to make effective use of technological knowledge in efforts to assimilate, use, adapt, and change existing technologies, (…) to create new technologies and to develop new products and processes" (Kim 1997, p. 4).[4]

Kim's analyses were based on lessons from how Korean electronics firms, such as Samsung, gradually upgraded from a passive role of implementing imported technology, to a more active role of introducing incremental improvements, and eventually ventured into the forefront of innovation-based competition. He therefore distinguished between different layers of technological capability depending of the complexity of the challenge: production capability, investment capability, and innovation capability. Production capability—the most basic requirement—is needed to operate productive facilities efficiently. Investment capability is required for the arguably more challenging task of establishing new productive ventures. Finally, innovation capability is seen as necessary for the development of new goods or services that better meet the requirements of the market. Kim expected the requirements to become more stringent, in particular with respect to innovation capabilities, as countries climb up the development ladder. Thus, following his view, for a firm or country in the process of catching-up, the appropriate level of technological capability is a moving target.

Having pointed out the important role that firm-level technological capabilities play in the process of development we now turn to the question of how the development of such capabilities depends on the firm's environment. Firms are not isolated islands and their performances are also influenced by the characteristics of the environment in which they operate. That the social, institutional, and political characteristics of the environment in which a firm operates influence its performance, is not a new insight. In fact, in the 1960s Irma Adelman and Cynthia Morris had already pointed out, on the basis of an in-depth study of a number of indicators on development for a large number of countries, that "the purely economic performance of a community is strongly conditioned by the social and political setting in which economic activity takes place" (Adelman and Morris 1965, p. 578). This was also emphasized

[4] To the best of our knowledge the first to use this concept in print was Kim in an article in *Research Policy* (Kim 1980). It quickly became widely used, see for example Fransman and King (1984) and Lall (1987). For a survey and an application to the national level see Lall (1992).

by the economic historian Moses Abramowitz, who used the term "social capability" for this aspect (Abramovitz 1986). He defined it as "countries' levels of general education and technical competence, the commercial, industrial and financial institutions that bear on the abilities to finance and operate modern, large-scale business, and the political and social characteristics that influence the risks, the incentives and the personal rewards of economic activity" (Abramovitz 1994a, p. 25).

Many of the concerns that led Adelman and Morris and Abramovitz to focus on the role of social, institutional, and political aspects in development are also central in the more recent literature on "national innovation systems" (NIS). The NIS concept first appeared in work by Christopher Freeman (Freeman 1987), Bengt Åke Lundvall (Lundvall 1992), and Richard Nelson (Nelson 1993), and this analytic framework has since been extensively used in both scholarly and policy-analytic work (Sharif 2006). The concept may be used in a narrow as well as a broader sense (Edquist 2004). The narrower definition of the national innovation system includes innovative firms and the public research infrastructure with which they interact in varying degrees (Nelson 1993). The broader definition, which arguably is closer to Abramovitz' reasoning, extends this to all learning and innovation activities in a country regardless of where these take place (Lundvall 1992, Edquist 2004).

The discussion so far leads to two propositions: 1) that generation of technological capabilities is a must for countries that wish to catch up and 2) that the degree of success in this aim to a large extent depends on wider economic, social, institutional, and political factors. While many would sympathize with these propositions, they might perhaps have doubts about the possibility to explore these through empirical research, the issue to which we now turn.

2.3 (How) Can Capabilities be Measured?

The approach that will be pursued here is to assemble a set of indicators considered relevant for the phenomenon we wish to capture, and construct a composite variable. In this respect, the underlying assumption is that indicators reflecting the same dimension of reality should be expected to be strongly correlated so that we can use factor analysis for this purpose.[5]

A challenge in empirical analyses of this type is to get high-quality information on all the dimensions of reality that we wish to take into account for a sufficiently large number of countries and long enough time span. Typically, there is a trade-off between availability of high quality information and the size and composition of the sample. Indeed, many potentially interesting indicators only exist for a small number of (mostly) developed economies. Annual data may also be problematic, since many countries do not supply the type of information we wish to use on a yearly basis (and

[5] See Adelman and Morris (1965), Temple (1998), Temple and Johnson (1998) and Fagerberg and Srholec (2008) for earlier applications of factor analysis to cross-sections of countries.

the years for which data exists may differ across countries). Balancing the quest for high-quality of information on the one hand against sample size and time period on the other hand led to the choice of a cross-section sample of 114 countries on different levels of development between 1995 and 2013 (or the nearest year available).

The indicators of technological and social capabilities used in the study are listed in Table 2.1, while further information on definitions and sources can be found in the Appendix.[6] In the case of technological capability the indicators taken into account here include the quality of a country's research system (as reflected in scientific publications), invention and innovation (as measured by patent applications and R&D expenditure), and development of the ICT infrastructure (proxied by internet users). While the two former dimensions may come close to what Kim had in mind with his concept "innovation capability", the latter may also be relevant for what he called "production" capability, since access to state-of-the-art ICT is very important for firms' ability to produce and market goods and services and compete in global markets. With respect to social, institutional factors, or social capability, we were able to include three broad dimensions, the first of which is the skill level of the population (as reflected in tertiary attainment, enrolment in (all forms of) education, and literacy). A second dimension refers to the quality of the governance in a country. Indicators taken into account in this case include measures of how effective the government is, the extent to which corruption is a problem and, finally, whether law and order prevails.[7] Third, we included a range of indicators reflecting the possibility of a nation's population engaging in political and social activities, and (to some extent) economic activities.

Although the indicators taken into account cover many relevant dimensions, there were also certain aspects that we were not able to measure as well as we ideally would have liked. For example, both Kim and Abramovitz emphasized the importance of managerial capacity and supporting sources of finance. We are, however, not aware of any source of information that can be used to measure managerial capacity, apart from perhaps the availability of highly qualified labor (tertiary attainment, included in education), which is arguably much broader than what Kim and Abramovitz had in mind. The same goes for supporting sources of finance. For instance, with respect to the ability of organizing and financing new ventures, what Kim called "investment capability," supply of venture capital might perhaps have been a relevant indicator. But unfortunately such information was only available for some of the countries included in our dataset and could therefore not be taken into account. Failing to do so, we considered broader measures of financial development, such as the size of a country's financial market, but eventually sided against their

[6] In some cases observations were lacking and had to be estimated with the help of the other indicators in the data set. See the Appendix for more information.

[7] Note that when it comes to measuring the quality of a country's governance, we have several sources of relevant information for each of the "sub-dimensions" taken into account here. Following Srholec and Verspagen (2012), therefore, a two-stage hierarchical approach to factor analysis was used. In the first stage, information for each sub-dimension was synthesized into a common factor, which was then used in the second stage. See the Appendix Tables 2A.2-2A.4 for results of the first-stage factor analysis.

inclusion because we considered their relationship to a country's capability to exploit knowledge commercially to be problematic. Indeed, excessive "financialization" may also be a burden for the real economy of country rather than a capability. Finally, as emphasized by Abramovitz, it would have been interesting to be able to include the prevalence of culturally embedded norms, for example social capital, of importance for economic development, but again lack of available data for a sample of the present size precluded this.[8]

The factor analysis (Table 2.1) led to the identification of four (for the most part) quite different capabilities, labeled "Technology," "Education," "Governance," and "Empowerment," respectively. Technological capability is highly correlated with R&D, patenting and scientific publication but also, to a lesser extent, with advanced skills (tertiary attainment), and the proliferation of the internet. The analysis suggests that there are three different aspects of social capability. The first, Education, loads particularly highly on the two most basic education indicators, literacy and enrolment (in all types of education), but also on tertiary attainment and internet. The second, associated with quality of governance, is highly correlated with government effectiveness, (lack of) corruption, the prevalence of law and order and, to some degree, the related "physical integrity rights." Finally, the analysis suggests a

Table 2.1 Capabilities: Results of the factor analysis

	Factor loadings			
	Technology	**Education**	**Governance**	**Empowerment**
Scientific and engineering articles	0.51	0.05	0.44	0.06
USPTO patent applications	0.89	−0.02	−0.02	0.02
R&D expenditures	0.70	0.06	0.21	0.08
Internet users	0.39	0.48	−0.14	−0.02
Tertiary attainment	0.32	0.56	0.00	0.13
Literacy	−0.13	0.84	0.06	0.04
Education enrolment	0.05	0.83	0.13	0.00
Government effectiveness	0.05	0.08	0.86	0.02
(Lack of) corruption	0.02	−0.03	0.92	0.08
Law and order	0.02	0.09	0.91	−0.01
Civil liberties	0.08	0.13	0.03	0.83
Freedom of the press	0.06	−0.13	0.23	0.80
Empowerment rights	−0.06	−0.02	−0.08	0.99
Women's rights	0.10	0.27	0.03	0.60
Physical integrity rights	−0.08	0.06	0.45	0.40

Note: 78.2 percent of total variance explained, the extraction method is principal factors, oblique oblimin rotation, based on pooled data in 114 countries in 1995 and 2013, hence 228 observations in total.

[8] See Fagerberg and Srholec (2009) for a discussion of how such factors may be explored (for a more limited set of countries).

third type of social capability, reflecting the possibility of the population taking an active part in society; we called this "Empowerment."

Figure 2.1 plots the development of a country's technological capability over the period 1995–2013 against its initial level in 1995. In this way four quadrants appear. Up to the left, in the quadrant labeled "losing momentum," we find countries with a high but stagnating (or declining) technological capability. Very few countries appear in this category (Ukraine is the most obvious example). In contrast, the countries in the top-right quadrant combine a high initial capability-level with an above average capability-increase. Hence, these are countries that are "moving ahead" technologically. Korea, Taiwan, Singapore, Israel, and Finland are countries that particularly excel in this regard, but many other developed countries are also to be found in this category. Another group of countries with above average performance can be found down to the right. These countries, a mixed crowd of Asian (China for instance) and European countries (from the southern and eastern parts of the continent), are "catching up" technologically from a relatively low initial level. Finally, in the quadrant down to the left we find countries that are "falling behind" technologically, that is, countries that combine a low initial level with below average performance. Many countries in Africa, Latin-America, and Asia belong to this category, as do some previously socialist countries (i.e., countries once dominated by the former Soviet Union).

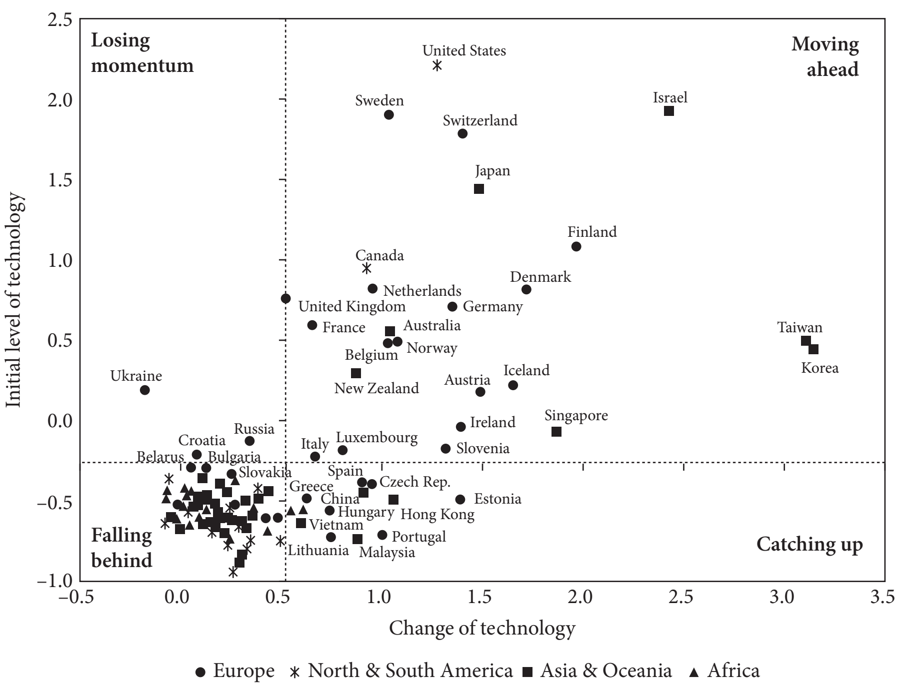

Figure 2.1 Technology (1995–2013)

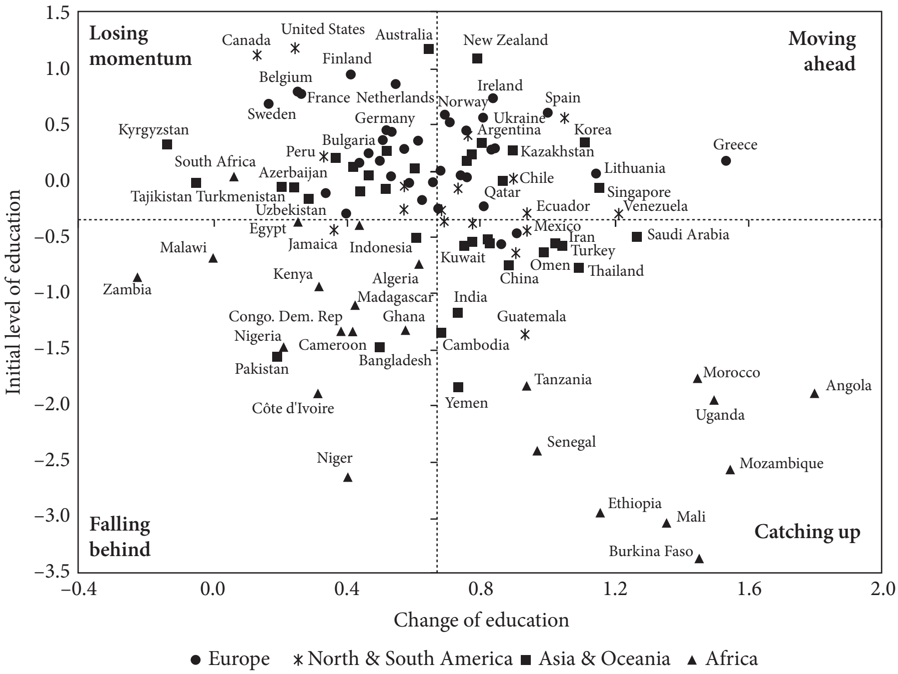

Figure 2.2 Education (1995–2013)

For technological capability what can be observed is a strong tendency towards divergence, with the great majority of countries either moving ahead or falling behind. However, when it comes to education (Figure 2.2) there is clearly more convergence going on, with many highly developed and previously Socialist countries in the "losing momentum category" and a number of developing countries, particularly from Africa, "catching up". However, there are also many African countries in the "falling behind" category, so the performance of this continent in the educational area is far from uniform. Among the countries that are "moving ahead" on the educational front we find among others some of the Asian Tigers (Korea, Singapore, and Taiwan) and Spain, Greece, and Ireland.

The tendency towards convergence in capability levels, which could be observed in the case of education, is even more pronounced for governance (Figure 2.3). In particular, many African, Asian and Eastern European countries improved their governance over this period, while it was the other way around for some developed countries (with already very high quality levels at the outset). However, a number of previous Soviet republics, now independent, saw their governance deteriorate over the period. With respect to the degree of "Empowerment" (see Figure 2.4), all quadrants are relatively well populated, indicating a lot of variation across countries, both in the levels and trends.

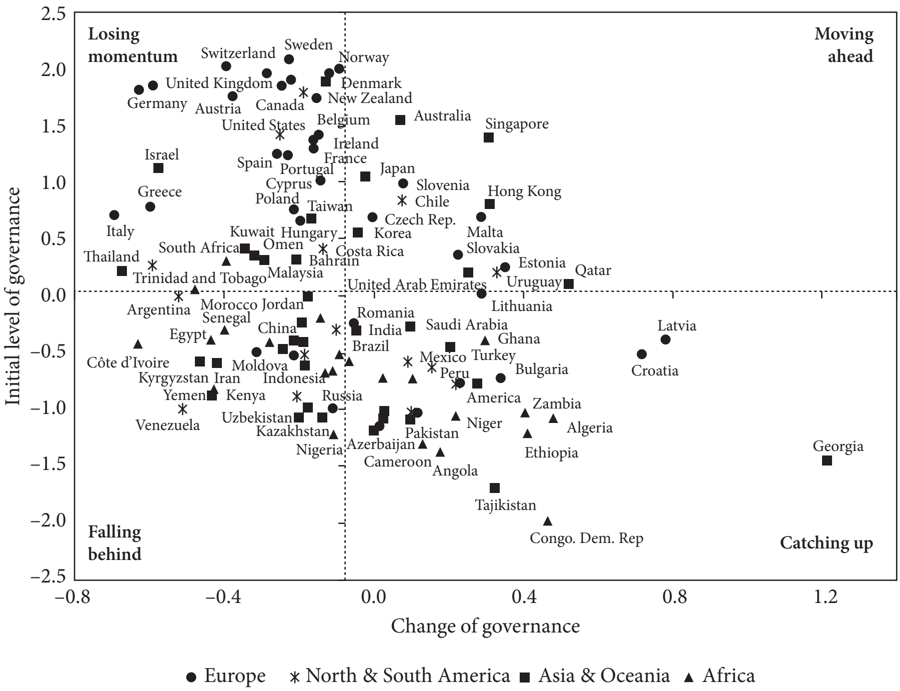

Figure 2.3 Governance (1995–2013)

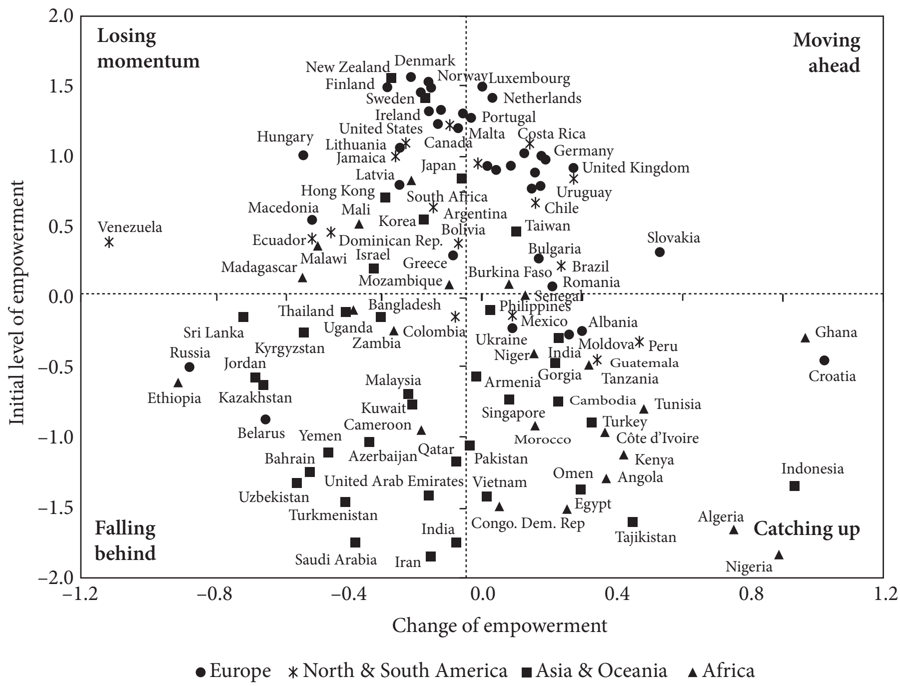

Figure 2.4 Empowerment (1995–2013)

2.4 Capabilities, Growth, and Competitiveness: A Model

In the previous section it was discussed how technological and social capabilities can be measured, and the distributions and dynamics of these capabilities were examined. However, our primary interest is in the relationship between these capabilities and economic growth. As a step towards analyzing that issue we will in this section, following earlier work on the subject by Fagerberg (1988a,b) and Fagerberg et al. (2007), go deeper into the relationships between capabilities and economic growth with the help of a formal model based on Schumpeterian logic. In the model, growth is assumed to be the outcome of innovation and diffusion of technology and capabilities necessary for their economic exploitation.

Consider that the (volume of) GDP in a country (*Y*) is a function of its technological knowledge (*T*) and its social capacity for exploiting the benefits of knowledge (*C*):

$$Y = f\left(T, C\right), \tag{1}$$

where *T* is a function of knowledge (or innovation) created in the country (*N*) and knowledge diffused to the region from outside (*D*):

$$T = h(N, D). \tag{2}$$

Assume further that the diffusion of external knowledge follows a logistic curve (Metcalfe 1988). This implies that the contribution of diffusion of externally available knowledge to economic growth is an increasing function of the distance between the level of knowledge appropriated in the country and that of the country on the technological frontier. Hence, for the frontier country, this contribution will be zero by definition. Let the total amount of knowledge, adjusted for differences in size of countries (e.g., per capita, hence the *cap* superscript), in the frontier country and the country under consideration, be T_*^{cap} and T_i^{cap} respectively and let *d* be the rate of growth of knowledge diffused to the region from outside (*D*):

$$d = \gamma - \gamma T^{gap}, where T^{gap} = \frac{T_i^{cap}}{T_*^{cap}} \tag{3}$$

By differentiation and substitution we arrive at the following solution for growth of GDP, using small case letters for growth rates (e.g., $y = \mathrm{d}Y/Y$ etc.):

$$y = \gamma \varepsilon_{YT} \varepsilon_{TD} - \gamma \varepsilon_{YT} \varepsilon_{TD} T^{gap} + \varepsilon_{YT} \varepsilon_{TN} n + \varepsilon_{YC} c \tag{4}$$

where $\varepsilon_{YT} = \frac{\partial Y}{\partial T} \frac{T}{Y}$ refers to the partial elasticity of GDP with respect to technology (similar for other variables).

In the model, three sets of factors determine the rate of growth of a country: (1) The potential for exploiting knowledge developed elsewhere; (2) the creation of new knowledge within the country; and (3) the growth in the social capacity to exploit (or "absorb") knowledge (independently of where it is created). The model encompasses many of the empirical models found in the literature on catching-up and differences in economic growth across countries. For instance, many if not most empirical models used in the "catching-up" literature are variants of equation (4) when we drop the innovation term (see, for example, Baumol et al. 1989). Focusing more explicitly on the role of innovation for catch-up, Fagerberg (1987, 1988a) showed that countries that caught up very fast also had very rapid growth of innovative activity. The analysis suggested that superior growth in innovative activity was the prime factor behind the huge difference in performance between newly industrialized countries (NICs) in Asia and Latin America in the 1970s and early 1980s. Fagerberg and Verspagen (2002) have shown that the rapid increase in its innovative performance was the primary cause of the continuing rapid growth of the Asian NICs relative to other country groupings in the decade that followed. The research (Fagerberg 1987; Fagerberg and Verspagen, 2002) also indicates that innovation may have become more important for economic growth over time (while imitation has become more demanding).

The above model abstracts from trade, but to get a more complete understanding of the role played by competitiveness[9] we will in a second step include trade as well. To see how this may be done consider a two-economy model, in which one "country" interacts with the rest of the "world." Let exports be X, imports be M and W be world demand, all measured in terms of volume. In addition to the two explanatory factors already taken into account, that is, (1) The country's technological competitiveness (its knowledge assets relative to competitors) and (2) Its social capacity to exploit technology commercially (again relative to competitors), we now also include (3) Its price competitiveness (relative prices on tradeables in common currency); and (4) World demand. The two first factors, technology and social capacity, are the same as earlier but measured relative to the world average. Consider exports as:

$$X = f\left(T, C, P, W\right), \tag{5}$$

where T, C, P is technology, capacity and price competitiveness in country i, relative to the world: $T = \frac{T_i}{T_{world}}, C = \frac{C_i}{C_{world}}, P = \frac{P_i}{P_{world}}$

Since imports in this model are the "world's" exports, we can model imports in the same way, noting that the competitiveness variables in this case are the inverse of those in equation (5) and that domestic demand (Y) replaces world demand:

[9] A common definition of competitiveness is: "the degree to which, under open market competition, a country can produce goods and services that meet the test of foreign competition while simultaneously maintaining and expanding domestic real income" (OECD 1992, p. 237).

$$M = g\left(\frac{1}{T}, \frac{1}{C}, \frac{1}{P}, Y\right) \tag{6}$$

If we—for the time being—take world demand and technology, social capacity, and price competitiveness as given, equations (5)–(6) give us two relationships between three endogenous variables (*Y*, *X* and *M*).[10] To solve the open economy model for, say, GDP growth we need an additional constraint linking growth to trade. It is common to assume in the literature that there exist economic mechanisms that prevent a country from continuing on paths that would not be sustainable in the long run, such as accumulating ever-increasing debts or claims on a grand scale vis-à-vis the rest of the world. This may occur through adjustments of the fiscal and monetary policy stance, but it may also be the result of working of markets, such as the capital, labor, and currency markets. Fagerberg (1988b) and Meliciani (2001) tested this restriction on evidence from developed economies and found that it was supported by the data. Formally, following earlier contributions by Thirlwall (1979) and Fagerberg (1988b), what we assume is balanced trade (equation (7) below) which is equivalent with balancing savings and investments. Note that an alternative way to formulate this restriction that would be consistent with the model is to assume that the surplus (deficit) used to service foreign debts (financed from foreign assets) is a constant fraction of exports (or imports).[11] Thus, the analysis presented here is consistent with a world in which countries have foreign debts or assets.

$$XP = M \tag{7}$$

We assume as before (equations (2)–(3)) that technology depends on both national sources (*N*) and diffusion (*D*) from abroad, and that the latter follows a logistic curve. By totally differentiating (2)–(3) and (5)–(7), substituting and rearranging, the following solution for growth of GDP follows:

$$y = \gamma\varepsilon_{TD}\frac{\varepsilon_{XT}+\varepsilon_{MT}}{\varepsilon_{MY}} - \gamma\varepsilon_{TD}\frac{\varepsilon_{XT}+\varepsilon_{MT}}{\varepsilon_{MY}}T^{gap} + \varepsilon_{TN}\frac{\varepsilon_{XT}+\varepsilon_{MT}}{\varepsilon_{MY}}n + \frac{\varepsilon_{XC}+\varepsilon_{MC}}{\varepsilon_{MY}}c + \frac{\varepsilon_{XP}+\varepsilon_{MP}+1}{\varepsilon_{MY}}p + \frac{\varepsilon_{XW}}{\varepsilon_{MY}}w \tag{8}$$

We see that the growth of a country now depends on five factors: (1) The potential for exploiting knowledge developed elsewhere, which depends on the country's level of technological development relative to the world frontier; (2) Creation of new

[10] A feedback from the endogenous variables (growth and trade) on capabilities and prices cannot be excluded a priori but we have at the present stage of the analysis chosen to regard capabilities and prices as exogenous (see Fagerberg et al. (2007) for an extended discussion).
[11] As is easily verified, we may multiply the left- or right-hand side of (7) below with a scalar without any consequence for the subsequent deductions.

knowledge (technology) in the country relative to that of competitors; (3) Growth in the social capacity to exploit knowledge, independently of where it is created, relative to that of competitors; (4) Change in relative prices in common currency and (5) Growth of world demand weighted by the ratio between the income elasticity for exports and that of imports.

By comparing equation (8) with the reduced form of the simple growth model considered previously (equation 4), we see that, apart from the two last terms on the right-hand side, the model has the same structure. The only difference is that the coefficients of the growth equation (the reduced form) now are sums of coefficients for the similar variables in the equations for exports and imports divided by the income elasticity of imports. Hence, the higher the income elasticity for imports is, the lower the effect on growth of all other factors will be. Moreover, the two last terms in (8) resemble the open-economy growth model suggested by Thirlwall (1979). The first of these two terms is the familiar Marshall–Lerner condition, which states that the sum of the price elasticities for exports and imports (when measured in absolute value) has to be higher than one if deteriorating price competitiveness is going to harm the external balance (and—in this case—the rate of growth of GDP). The second reflects the argument put forward by Thirlwall (1979) and Kaldor (1981) that the extent to which a country is specialized in industries that are in high (low) demand at home and abroad may be of vital importance for its economic growth. Thus, the simple growth model outlined previously and the Kaldor–Thirlwall model may be seen as special cases of the more general Schumpeterian open economy model presented above.

2.5 The Competitiveness of Nations: An Empirical Analysis

In this section we will, following Fagerberg et al. (2007), exploit the reduced form of the above model (equation 8) to explain growth performance for a cross section of 114 countries between 1995 and 2013. The analysis that follows extends earlier work on the subject in various ways. First, we are going to consider a more recent time period.[12] Second, we aim for a richer treatment of technological and social capabilities (and their impacts) than what was possible previously. This allows us, for example, to include ICT infrastructure in a more satisfactory way than before. However, the biggest difference compared with earlier work regards the treatment of social capabilities, which instead of being summarized into a single variable,[13] are included here as three different dimensions, each with its own distribution and dynamics. Third, to better take into account the role played by global demand for economic

[12] The earlier analysis of Fagerberg et al. (2007) covered the time period 1980–2002.

[13] Fagerberg et al. (2007) used the term "capacity competitiveness" for what we here, following Abramovitz (1986, 1994a,b) and Fagerberg and Srholec (2008), call "social capabilities."

growth we allow for differences in export specialization with respect to goods and services as well as markets (trading-partners).[14]

Hence, the empirical model to be estimated contains the following variables:

Dependent variable:
- GDP growth 1995–2013(log difference)
Explanatory variables:
- Gap: Log of the ratio of initial GDP per capita to the frontier country in 1995
- Capabilities: Change of technological and social capabilities 1995–2013
- Price: Growth of the real effective exchange rate 1995–2013 (log difference)
- Demand: Growth in world demand 1995–2013 (log difference) weighted by the initial commodity and market composition of each country's exports in 1995

For more information on sources and definitions, see Appendix.

Table 2.2 contains the results. Four different regressions are reported. The first column contains ordinary-least-squares (OLS) estimates of the basic model, while the second and third columns repeat the same exercise with methods that adjust for the possible impact of outliers, using the iteratively-reweighted-least-squares estimator suggested by Li (1985) and OLS excluding outliers,[15] respectively. The results are very similar across the three different specifications and the explanatory power is quite respectable, around 50 percent. In all cases the economic growth of a country is positively related to a large scope for imitation, growing technological capability, increased education, improved governance and high demand for the goods and services the country produces (and to some extent the markets it sells to as well). However, neither (change in) empowerment nor price competitiveness seems to matter much.

To test for the robustness of these results to the inclusion of other exogenous variables, reflecting differences in history, geography and nature, we add in the third column a battery of such indicators to the model and eliminate these variables one by one using a backward search, applying the 10 percent level of significance as criterion

[14] Demand (w_i) is computed by weighting the growth of world demand by product or market (g_j) (i.e., the log difference) with the initial composition (specialization) of each country's exports (s_{ij}):

$$w_i = \sum_{j=1}^{m}\left(g_j \times s_{ij}\right), \text{with } s_{ij} = \frac{X_{ij}^{t-1}}{\sum_{j=1}^{m} X_{ij}^{t-1}} \text{ and } g_j = \ln\left(\sum_{i=1}^{n} X_{ij}^{t}\right) - \ln\left(\sum_{i=1}^{n} X_{ij}^{t-1}\right),$$

where *i* is the exporting country and j is either a product or a market. X_{ij} denotes the country's *(i = 1 . . . n)* exports of a product/to a market *(j = 1 . . . m)* while *t–1* and *t* are two points in time. A high score indicates favorable demand conditions for a country's exports. Both merchandise trade and trade in services are included in the computation of demand by product, while only the former is available for demand by market. Demand by product is based on data for merchandise trade at 3-digit level of SITC, rev. 3, with 255 product categories and trade in services distinguished in three categories (transport, travel and other services). Demand by market is based on data for merchandise trade by 215 partner countries.

[15] The countries identified as outliers on the base of Cook's distance and excluded from the third column are Algeria, Azerbaijan, Democratic Rep. of Congo, Qatar, and Venezuela.

Table 2.2 Explaining GDP growth: Regression results, various estimators, 1995–2013

	OLS	Iteratively re-weighted least squares	OLS Excluding outliers	OLS Excluding outliers
Gap	**−0.59*****	**-0.64*****	**−0.75*****	**−0.74*****
	(5.38)	(7.64)	(8.42)	(7.22)
Δ technology	0.20***	0.19**	0.24***	0.25***
	(2.67)	(2.21)	(3.24)	(3.56)
Δ education	0.16***	0.17**	0.18***	0.18***
	(2.65)	(2.57)	(2.86)	(2.86)
Δ governance	0.22**	0.17**	0.20***	0.21***
	(2.15)	(2.46)	(2.97)	(2.98)
Δ empowerment	−0.07	−0.04	−0.06	−0.06
	(0.97)	(0.53)	(0.97)	(0.97)
Δ price	0.00	−0.05	−0.04	−0.04
	(0.03)	(0.77)	(0.55)	(0.51)
Demand by product	0.33***	0.24***	0.31***	0.30***
	(3.01)	(3.43)	(4.36)	(4.51)
Demand by market	0.17**	0.14*	0.10	0.11
	(1.99)	(1.94)	(1.38)	(1.55)
Tropics				0.15*
				(1.73)
Natural disasters				−0.12**
				(2.01)
F-test	14.49***	13.69***	22.94***	26.16***
R^2	0.47	0.43	0.58	0.61
Number of observations	114	114	109	109

Note: Absolute value of robust t-statistics in parentheses. *, **, *** denote significance at the 10, 5 and 1 percent levels. Cook's distance used to exclude outliers with the conventional cut-off point at 5/number of observations. Beta values reported.

for whether to retain a variable or not. The exogenous variables included in this robustness test were: ethnic, linguistic and cultural fractionalization, size of domestic market, oil and gas endowments, access to ocean, natural disasters, climate (tropics or subtropics), and malaria ecology drawn from Alesina et al. (2003), Fearon (2003), Gallup et al. (1999), Kiszewksi et al. (2004) and Université catholique de Louvain (2014). As shown in the fourth column of Table 2.2, only two such variables were retained, but with minimal influence on the estimates of the other variables included in the model, which hence may be deemed reasonably robust.[16]

An interesting question on which there is little evidence so far concerns the extent to which countries that increase one capability in tandem with other capabilities get

[16] Being a tropical country is positive for growth, which may seem surprising given the challenges that many of these countries face. However, many of the potentially negative effects of being a tropical country, related to extreme weather for instance, are also covered by the "natural disaster" variable. So the positive effect of being a tropical country may be interpreted as being conditional on accounting for some other effects in the model.

an extra bonus (i.e., if there is a "complementarity" effect). This was tested by adding interaction terms between the capability variables one by one to the regression in the fourth column. However, in no case did the interaction effect turn up significantly different from zero at the 10 percent level. We also tested for the possibility of longer lags for the capability variables by including the initial level alongside the change of the variable. However, this was not supported either, except for the empowerment variable, which came out with the opposite sign (negative) of what should be expected.

To explore the implications of the main findings in more detail we provide in Table 2.3 below a decomposition of how the model explains the relative growth performance of groups of countries with similar characteristics (with respect to their geographical location, history, and level of development). The prediction is based on the fourth model reported in Table 2.2 (with control variables, subsumed under "Other" in Table 2.3). The various country groupings in the table are mostly self-explanatory except, perhaps, for "other former socialist countries" which consist of countries once belonging to—or dominated by—the then Soviet Union and which have not later joined the European Union (see Appendix Table 2A.5 for more details).

Table 2.3 reveals that the prediction is reasonable for most country groupings, confirming that the model explains the growth pattern of the last two decades rather well. Nevertheless, the model fails to fully account for the very rapid growth of the catching-up economies in Asia (e.g., China) during this period. The analysis confirms that differences in the scope for imitation (the Gap) are crucial for explaining differences in growth. According to the decomposition, the developed countries should for this reason alone be expected to grow about 3.3 percent less per year than the countries of Sub-Saharan Africa (the poorest country group in the sample), which is not far from what actually happened.

Besides the scope for imitation, the most powerful factor for "why growth rates differ" appears to be changing technological capability. For example, this is the major reason why the Asian Tigers outperformed the other developed countries during this period. The failure of many poorer countries to improve their technological capabilities (relative to the countries in the developed part of the world) also goes some way in explaining why opportunities for growth were not fully exploited. However, increases in education and improvements in governance also mattered, although less. For example, improved skills added about 0.2 percent per year for the Asian Tigers, while a similar reduction in growth occurred for the "former socialist countries" due to deteriorating education there. Improved quality of governance was of greatest importance for the countries which joined the European Union after the dissolution of the Soviet empire: the decomposition attributes about one third of their catch-up vis-à-vis the developed countries to this factor.

The important role played by changes in technological capability may merit a more detailed analysis. Figure 2.5 reports the contributions from the various indicators that make up the composite technological capability variable. It is interesting to note the different roles that the various indicators play for country groups at different levels of development. In many countries on a medium to low level of development

Table 2.3 Explaining annual GDP growth: A decomposition, 1995–2013

	N	Actual growth	Estimated Growth	Contribution of the explanatory factors to difference from the world average								
				Gap	Δ techno-logy	Δ edu-cation	Δ govern-ance	Δ empower-ment	Δ price	Demand by product	Demand by market	Other (geo, etc.)
Developed countries	26	2.12	2.21	−1.45	0.40	−0.06	−0.19	0.01	0.02	−0.13	−0.13	−0.15
East Europe (new EU members)	11	3.15	3.50	−0.41	0.03	0.05	0.34	−0.05	−0.06	−0.18	0.01	−0.12
Other former socialist countries	13	4.82	4.62	0.73	−0.31	−0.19	0.15	0.05	0.01	0.01	0.31	−0.01
Latin America	14	3.56	3.82	−0.14	−0.22	0.04	0.02	−0.02	−0.01	0.05	−0.07	0.28
Asian Tigers	4	4.17	4.15	−1.30	1.24	0.19	0.21	0.01	0.04	−0.28	0.05	0.08
East Asia	7	5.54	4.36	0.76	−0.05	0.07	−0.19	−0.03	0.00	−0.24	−0.04	0.20
South Asia	4	5.43	4.45	1.34	−0.25	−0.11	0.07	0.05	−0.01	−0.40	−0.06	−0.06
Middle East and North Africa	12	4.31	4.12	−0.32	−0.18	0.10	−0.13	0.01	0.00	0.72	0.09	−0.06
Sub-Saharan Africa	18	5.10	5.52	1.83	−0.29	0.05	0.05	−0.02	0.00	0.01	−0.03	0.03

Note: Based on column 4 in Table 2.2. Average annual GDP growth in the world, i.e. the intercept, is estimated at 3.88 percent. N is number of observations.

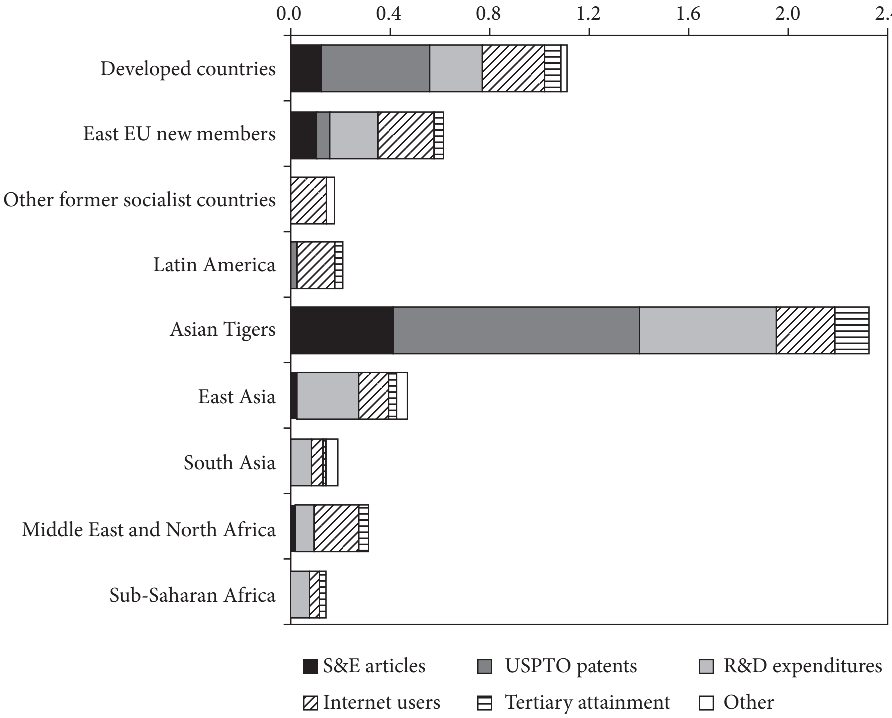

Figure 2.5 Contribution to growth of technological capability
Note: Based on the factor analysis reported in Table 2.1.

the major contribution to growth of technological capability tends to come from diffusion of ICTs. This is particularly notable for the "former socialist countries," the Latin American countries, and the countries in the Middle East and North Africa. At a higher level of development, however, growing "innovation capabilities" as reflected by increases in science, R&D, and patenting are of much larger significance. This pattern is especially evident for the "Asian Tigers" for which more than three-quarters of their (exceptionally high) capability growth come from such advanced sources. Moreover, among the countries in the developing part of the world, the countries of East Asia stand out by having both the fastest growth of technological capability and the largest share of this growth coming from R&D investments, indicating—perhaps—that the innovation-based growth model spearheaded by the Asian Tigers is spreading to other countries in East Asia.

2.6 Conclusions

This chapter has argued that concepts such as capabilities and competitiveness are not only relevant for firms (Teece 2010) but also for nations. Countries are more than mere sums of the characteristics of the individuals that happen to live there. They are also repositories of knowledge, institutions, and resources that underpin the economic activities within their respective borders. Such country-level characteristics influence the economic activities of its firms and citizens.

Previous research has identified two main types of capabilities, technological and social. Technological capabilities refer to the ability to create and exploit knowledge to produce goods and services. Such capabilities are often firm specific but are also influenced by environments in which firms operate, as firms increasingly depend on external sources for developing and improving their capabilities. Technological capability also has an important national dimension as countries regularly devote large resources to develop and maintain such capabilities.

While technological capabilities largely are attributes of firms, social capabilities are characteristics of the social environment that firms share, and that influence firm's operations in various ways, from being a source of much needed resources, such as skills, to for example providing an institutional and legal framework for firms' activities. Although politicians may influence the development of technological capability, and many examples—not the least from the emergence of the Asian Tigers as technological and economic powerhouses in the world economy—testify to that, their say is probably even larger when it comes to social capabilities.

The formal model and its application to data for a large number of countries highlight the important roles played by technological and social capabilities for competitiveness. The main argument put forward here is that both technological and social capabilities are required. While technological capability provides a basis for competitiveness, social capability is a prerequisite for successful economic exploitation of technology. The empirical results presented here indicate that such capability building may be vastly more important economically than so-called price-competitiveness, which traditionally has been the major focus of economists.

However, the research reported in this chapter also points to several issues that deserve to be explored further in future work on the role of capabilities for competitiveness and economic growth. For example, there is a need to improve indicators to better measure aspects of technological and social capabilities that have not been measured adequately so far. This relates, for example, to relatively basic technological capabilities associated with production, distribution, and (incremental) learning, what Kim called "production capabilities", that are generally taken for granted in developed economies but that may vary a lot in the developing part of the world. It also holds for the impact of more informal institutions such as beliefs, norms and routines for which relevant indicators for large, cross-country samples have been hard to come by. The inconclusive results reported in this chapter for the "Empowerment" variable also calls for more conceptual work on the role of political, institutional and social factors for growth and competitiveness. Moreover, as noted, existing research has not come very far in measuring the impact of capabilities in management and finance of new ventures. Related to this is also the broader issue of the role of the financial sector for the performance of the real economy, and hence growth and competitiveness, on which both conceptual and empirical work should be welcomed.

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Appendix (data and sources)

A brief overview of definitions and sources of the indicators is given in Table 2A.1 below. The main source of data is the Conference Board (2014), UNESCO (2014), World Bank (2014), PRS Group (2014), National Science Board (2012 and 2014), USPTO (2014), Barro and Lee (2010), Kaufmann et al. (2014), Cingranelli et al. (2014), Freedom House (2014a,b), Darvas (2012), UNCTAD (2014), Gallup et al. (1999) and Université catholique de Louvain (2014). The database has been complemented by international data from other sources such as Castellacci and Natera (2011) and OECD (2014), while national sources were only used for Taiwan if necessary.

Sample size and composition was given by the availability of data. GDP, price and demand data were fully available for all countries in both periods. For the indicators of technological and social capabilities we used data from the nearest available year to 1995 and 2013. Although the selected indicators have broad coverage, in some cases there were missing values that had to be dealt with. A number of the advanced countries do not monitor literacy any more. We assumed that all of these countries maintain 99.5 percent literacy. The remaining missing data were estimated using the *impute* procedure in Stata 11.2 (see the Stata 11.2 Manual for details). We based the estimation on data for the other indicators used to construct the capability measures. The number of observations (in both periods) estimated by the procedure is given in the last column of Table 2A.1.

Table 2A.1 Definitions and Sources of the Indicators

Indicator & definition	Scaling	Source	Estimated observations
GDP: Gross Domestic Product (GDP) converted to 2013 price level with updated 2005 EKS PPPs.	USD	Conference Board (2014)	0
Scientific and engineering articles: Counts of articles published in journals covered by Science Citation Index (SCI) and Social Sciences Citation Index (SSCI).	per mil. people	National Science Board (2012 and 2014)	0
USPTO patent applications: Counts of applications for utility patents filed in the United States Patent and Trademark Office (USPTO) classified by country of residence of the first named inventor.	per mil. people	USPTO (2014)	0
R&D expenditures: Intramural expenditure on research and experimental development (R&D) performed on the national territory.	% of GDP	UNESCO (2014), OECD (2014), Castellacci and Natera, (2011) and national sources	34
Internet users: Internet users are individuals who have access to the internet (from any location or device).	per 100 people	World Bank (2014)	0
Tertiary attainment: People aged 25 and over whose highest schooling level attained is tertiary.	%	Barro and Lee (2010)	24

Literacy rate: People aged 15 and over who can read, understand and write a short, simple statement on their everyday life.	%	World Bank (2014)	1
Education enrolment: Primary, secondary and tertiary education enrolment, regardless of age (gross), expressed as a percentage of the total population of primary and secondary school age and the five-year age group following on from secondary school leaving.	%	World Bank (2014)	37
Bureaucracy quality: An assessment of the institutional strength and quality of the bureaucracy, which represents a shock absorber that tends to limit revisions of policy when governments change.	index	PRS Group (2014)	14
Corruption: An assessment of corruption within the political system not only in the form of financial corruption but also excessive patronage, nepotism, job reservations and "favor-for-favors", secret party funding, and suspiciously close ties between politics and business.	index	PRS Group (2014)	14
Law and order: An assessment of the "Law" element, in which the strength and impartiality of the legal system are considered, and the "Order" element, which is an assessment of popular observance of the law.	index	PRS Group (2014)	14
Bureaucracy and policy consistency: An assessment of the quality of the country's bureaucracy, how confident businesses can be of the continuity of economic policy stance and the extent to which policymaking is far sighted, or conversely aimed at short-term economic advantage.	index	Global Insight Business Risk and Conditions (WMO)—data retrieved from Kaufmann, et al. (2014)	1
Corruption: An assessment of the intrusiveness of the country's bureaucracy. The amount of red tape likely to be countered is assessed, as is the likelihood of encountering corrupt officials and other groups.	index	Global Insight Business Risk and Conditions (WMO)—data retrieved from Kaufmann et al. (2014)	1
Judicial independence and crime: An assessment of how far the state and other outside actors can influence and distort the legal system and how much of a threat businesses face from crime.	index	Global Insight Business Risk and Conditions (WMO)—data retrieved from Kaufmann et al. (2014)	1
Quality and excessiveness of bureaucracy: An assessment of institutional effectiveness and the extent of red tape.	index	Economic Intelligence Unit (EIU)—data retrieved from Kaufmann et al. (2014)	15
Corruption: An assessment of corruption among public officials.	index	Economic Intelligence Unit (EIU)—data retrieved from Kaufmann et al. (2014)	15

Continued

Table 2A.1 Continued

Indicator & definition	Scaling	Source	Estimated observations
Rule of law: An assessment of the legal system in terms of fairness of judicial process, enforceability of contracts, speediness of judicial process, the risk of confiscation and expropriation, intellectual property rights protection, private property protection and the extent of violent and organized crime.	index	Economic Intelligence Unit (EIU)—data retrieved from Kaufmann et al. (2014)	15
Civil liberties: An assessment of the degree of the freedoms of expression, assembly, association, education, and religion and personal autonomy without interference from the state. The scale of the indicator has been reversed into increasing order, while keeping its original range.	index	Freedom House (2014a)	2
Freedom of the press: An assessment of legal, political and economic environment for the media. The scale of the indicator has been reversed into increasing order, while keeping its original range.	index	Freedom House (2014b)	0
Empowerment rights: An assessment of the degree of the freedoms of foreign movement, domestic movement, speech, assembly and association, workers' rights, electoral self-determination and freedom of religion.	index	Cingranelli et al. (2014)	2
Women's rights: An assessment of adherence to women's economic, political and social rights.	index	Cingranelli et al. (2014)	2
Physical integrity rights: An assessment of adherence to a group of four rights known as the "physical integrity rights": rights to freedom from extrajudicial killing, disappearance, torture, and political imprisonment.	index	Cingranelli et al. (2014)	2
Price: Real effective exchange rate	index	Darvas (2012)	0
Demand by product: Growth in world demand weighted by the initial commodity composition of each country's exports.	index	UNCTAD (2014)	0
Demand by market: Growth in world demand weighted by the initial market composition of each country's exports.	index	UNCTAD (2014)	0
Tropics: Land in Koeppen-Geiger tropical climate (Af+Am+Aw) as the proportion of total land area.	%	Gallup et al. (1999)	0
Natural disasters: Log of people killed in natural disasters (earthquake, volcano, storm, drought, flood, extreme temperature, wildfire, landslide and epidemic) per total population.	per mil. people	Université catholique de Louvain (2014)	0

Table 2A.2 Government effectiveness: Results of the factor analysis

	Factor loadings
Bureaucracy quality (PRS)	0.84
Bureaucracy and policy consistency (WMO)	0.90
Quality and excessiveness of bureaucracy (EIU)	0.91

Note: 78.1 percent of total variance explained, the extraction method is principal factors, oblique oblimin rotation, based on pooled data in 114 countries in 1995 and 2013, hence 228 observations in total.

Table 2A.3 (Lack of) corruption: Results of the factor analysis

	Factor loadings
Corruption (PRS)	0.79
Corruption (WMO)	0.89
Corruption (EIU)	0.93

Note: 76.2 percent of total variance explained, the extraction method is principal factors, oblique oblimin rotation, based on pooled data in 114 countries in 1995 and 2013, hence 228 observations in total.

Table 2A.4 Law and order: Results of the factor analysis

	Factor loadings
Law and order (PRS)	0.79
Judicial independence and crime (WMO)	0.95
Rule of law (EIU)	0.94

Note: 79.8 percent of total variance explained, the extraction method is principal factors, oblique oblimin rotation, based on pooled data in 114 countries in 1995 and 2013, hence 228 observations in total.

Table 2A.5 Regional groups of countries

Developed countries	Australia, Austria, Belgium, Canada, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Japan, Luxembourg, Malta, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States
East Europe (new EU members)	Bulgaria, Croatia, Czech Rep., Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia
Other former socialist countries	Albania, Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Macedonia, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
Latin America	Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Dominican Rep., Ecuador, Guatemala, Jamaica, Mexico, Peru, Trinidad and Tobago, Uruguay, Venezuela
Asian Tigers	Hong Kong, Korea, Singapore, Taiwan
East Asia	Cambodia, China, Indonesia, Malaysia, Philippines, Thailand, Vietnam
South Asia	Bangladesh, India, Pakistan, Sri Lanka
Middle East and North Africa	Algeria, Bahrain, Egypt, Iran, Jordan, Kuwait, Morocco, Oman, Qatar, Saudi Arabia, Tunisia, Turkey, United Arab Emirates, Yemen
Sub-Saharan Africa	Angola, Burkina Faso, Cameroon, Cote d'Ivoire, Democratic Rep. of Congo, Ethiopia, Ghana, Kenya, Madagascar, Malawi, Mali, Mozambique, Niger, Nigeria, Senegal, South Africa, Tanzania, Uganda, Zambia

3
Technology Upgrading in Emerging Economies

A New Approach to its Measurement, Results, and Relationship to Mainstream Measures

Randolph Luca Bruno, Kirill Osaulenko, and Slavo Radosevic

3.1 Introduction

Technology upgrading of emerging economies is a process of transformation from production and investment-driven growth to innovation-based growth (Acemoglou et al. 2006). It is a process that is fraught with difficulties that have been defined recently as "the middle-income trap" (OECD 2014). The problem is that this transformation is not about the simple accumulation of stock of capital or productivity improvements at the existing technological level; rather, it is about the accumulation of a range of diverse capabilities (production, technology, R&D, etc.), their structural transformation, and the coupling of domestic technology efforts to technology transfer (Lall 1992). In other words, this process, which we term *technology upgrading,* is multidimensional and, therefore, its conceptualization and measurement are non-trivial issues (Radosevic and Yoruk 2016, 2018).

The conventional approach would be to reduce technology upgrading to a single indicator, such as Total Factor Productivity (TFP) or labor productivity, or to use R&D and patents as indicators (Syverson 2011). Although such approaches would capture some aspects of the transformation of technological capabilities, they remain either rather uninformative or not relevant to emerging economies and countries that can be defined, broadly, as middle- or upper-middle-income economies. An alternative method involves use of a wide range of indicators and a composite indicator, such as the global innovation index (https://www.globalinnovationindex.org), to proxy for the multi-dimensional nature of this process. However, these metrics cover the entire spectrum of countries that form the global economy and are neither theoretically nor empirically grounded in the type of technological capabilities specific to emerging economies (see Radosevic and Yoruk 2016, 2018).

In this chapter, we apply the technology upgrading framework developed in Radosevic and Yoruk (2016, 2018) to explore the dynamics and morphology of

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technological upgrading in sixteen—mostly emerging—economies. The technology upgrading framework is located between aggregate theories of economic growth and micro/meso accounts, and represents new metrics appropriate for emerging economies catching up to the technology frontier. The paths to technology upgrading are explored in a three-dimensional space that includes: A) the intensity and types of technology upgrading; B) the breadth of technology upgrading; and C) technology transfer (technology exchange) with the global economy.

These three components (and sub-components) of technology upgrading are relatively autonomous, but, also, are mutually dependent, with different degrees of substitutability and complementarity. These properties allow us to track the routes to technology upgrading, understand the trade-offs between different components and explore differences in the potential for long-term growth. The underlying idea is to explore the mutual interactions among three dimensions of technology upgrading and the relationship between this upgrading and growth and levels of productivity. In other words, the technology upgrading index proxies for long-term growth *potential*, and our analysis provides new insights into the differential potentials for further long-term growth in emerging economies.

Section 3.2 presents our conceptual framework and analytical approach. Section 3.3 describes technology upgrading capabilities and the relationships among the three components of technology upgrading. Section 3.4 explores the dynamics of technology upgrading, based on data for the period 2002–16, and identifies the different routes to technology upgrading taken by the sample economies. Section 3.5 investigates the empirical relations between our indexes and conventional macro-indicators of technology upgrading, that is, TFP and labor productivity. This tests the robustness and relevance of our framework and highlights those framework components that are strongly correlated to conventional measures of countries' performance. Section 3.6 concludes the chapter.

3.2 Measuring Technology Upgrading: Conceptual Approach and Methodology

Technology is too complex to be encompassed by a single indicator, such as TFP or labor productivity. TFP refers to efficiency in general, not necessarily the accumulation of technology capability (Prescott 1998). It is a convenient proxy for growth whether driven by capital accumulation, increased employment, or broadly defined "efficiencies," but does not provide much information (Felipe and McCombie 2014).

Labor productivity is a simpler to calculate and easier to interpret measure. However, higher value-added per employed might reflect higher capital intensity rather than more productive use of labor. Hence, productivity tends to be higher in capital-intensive industries and industries with monopoly power (Cusolito and Maloney 2018).

It would seem clear that an alternative indicator is needed which would more directly measure the accumulation, transformation and adoption of technological capabilities. The value of direct indicators, such as *patents,* is limited for emerging economies whose technology activities are mainly behind the technology frontier (Acemoglu et al. 2006). We prefer a composite indicator which is conceptually adjusted to the specificities of the technology upgrading process in emerging economies.

Firstly, technology upgrading is a multidimensional process based on an understanding of innovation that includes not only R&D and technology generation capabilities but also production (manufacturing) capabilities (Bell and Pavitt 1993). Second, technology upgrading is about structural change, along various dimensions—infrastructure, technology, industry, and organization (this last being an intangible asset). Countries can improve, although the technology, industry, and organizational structure may remain mostly unchanged. However, sustained growth is linked to within-sector structural upgrading of infrastructure and skills, knowledge diversification, and firm growth based on transfer of resources from traditional to new industries. Third, technology upgrading is shaped by interaction with the global economy via international trade, knowledge, and investment flows (Mowery and Oxley 1995).

Technology upgrading is about different capabilities and we are interested in the institutional setups in which capabilities accumulation takes place. Our primary focus is on the outcomes of technology accumulation, that is, technology upgrading activities. Technology upgrading refers to changes to both technology intensity and technology structure, which need to be considered within the broader context of integration in global value chains.

Drawing on Radosevic and Yoruk (2018, 2016), we conceptualize technology upgrading as an outcome of the interactions among more intensive technology activities, structural upgrading, and the changes mediated by the relations between the focal economy and the global economy.

Although the aggregate technology upgrading indicator has three dimensions, which means it can be calculated statistically, we argue (see Radosevic and Yoruk 2018) that it makes sense to aggregate only components A (intensity) and B (breadth). The third component (C) (interaction with the global economy) is a moderating dimension, that is, it amplifies or reduces the effects of technology upgrading depending on the intensity and modes of the interaction with the global economy.

Table 3.1 presents the elements (components) of our technology upgrading framework. The individual indicators (Index A technology intensity plus Index B structural features) are used to construct the latent variables for a composite Indicator of Technology Upgrading (ITU) and its sub-indexes. Index C (interaction with the global economy) is calculated similarly, but is considered a standalone index.

Based on this analytical framework, the ITU includes intensity/type of technology upgrading and breadth or structural features of technology upgrading. The first category includes production capability, R&D and knowledge intensity and technology

Table 3.1 Components of technology upgrading

Index A: Technology Intensity (scale)
Production capabilities
R&D capabilities
Technology capabilities
Index B: Structural Features (scope/breadth)
Infrastructure (IT, human, physical, organisational)
Knowledge diversification and changes to supply of and demand for technology
Organisational capabilities
Index C: Interactions with the Global Economy
Exchanges of technology and knowledge

capabilities, which are based on sixteen indicators. The second category includes human capital and physical infrastructure, structural change/knowledge diversification, and organizational capabilities, which are based on thirteen indicators. Index C—interaction with the global economy—is separate from the aggregate ITU index and is based on five sub-indicators. The extent of integration with the global economy is not a measure of the economy's degree of technology accumulation. Whether knowledge interactions lead to technology accumulation depends on whether the acquired (foreign) knowledge complements or substitutes for domestic technology accumulation. We consider our three indexes to be autonomous and to reflect the three dimensions of technology upgrading.

Appendix Table 3A.1 presents the sources, availability and weights of each index and their indicators.[1] All the indexes and sub-indexes are computed on a standardised 0-100 scale, that is, a weighted average of each component on a common support.

ITU intensity (A) goes beyond technology generation and includes production capability and R&D capability, which proxy for knowledge absorption and knowledge generation capacity. ITU scope and breadth (B) includes the broad infrastructure, knowledge diversification and demand for and supply of technology, and upgrading of organisational capabilities. It refers to the structural dimensions of the upgrading process. Index C—exchanges of knowledge and technology with the global economy—is proxied by five indicators: net inflows/outflows of Foreign Direct Investment (FDI), receipts/payments for technology, and technology exports. Although intensive inflows of capital and knowledge may enable sophisticated exports, without generation, adoption, and absorption of technology, they are unlikely to increase productivity or domestic technology upgrading (Rojec and Knell 2017; Bruno and Cipollina 2017; Bruno et al. 2018). Hence, we consider exchange of knowledge and technology with the global economy as a stand-alone component of technology upgrading.

[1] We tested statistical consistency using Cronbach's alpha.

3.3 Capacity for Technology Upgrading: A Descriptive Analysis of Countries' Relative Positions

Our framework is appropriate for middle-income economies, in different geographic locations, with different levels of success in technology upgrading. Since we use a relatively large number (36) of indicators, we chose to analyse only sixteen economies; this allows us to trace the origins of individual countries' aggregate positions to individual groups of indicators.

Some might question our country selection; however, our aim is to explore the diversity of technology upgrading paths, not to provide a representative sample of broadly defined middle-income economies.

Our sample of countries was chosen as follows. The first three countries were China, India, and South Africa, which belong to the so-called BRICS (Brazil, Russia, India, China, South Africa) group. China and India were chosen based on their global importance and fast economic growth. The Central and East European economies (CEE), the Union State plus Ukraine account for the largest set of countries in our sample—Poland, Czechia, Hungary, Romania, Russia, Ukraine, and Belarus—chosen based on our expertise in this world region and their two different growth models. The CEE economies generally are examples of what we would call "foreign-led" modernization or economies where, over the past thirty years, FDI and openness have played central roles. However, we would describe Russia, Belarus, and Ukraine as examples of "domestic-led" modernization, or economies where the role of internal control of the economy has been much more critical (Radosevic 2011). Also, some of these countries are European Union (EU) members, which has essential effects on access to technology and FDI.

Although Eastern Europe and Latin America have some developmental and structural features in common, comparisons among them are quite rare. For this reason, we chose two resource-based economies (Brazil, Argentina) as comparators for Russia and Ukraine. South Korea was chosen as the model of catch-up among the emerging economies. Israel is sometimes considered a contemporary prototype of high-tech upgrading, although its productivity levels show that high tech does not lead automatically to high productivity in the overall economy. Germany was chosen as an example of a developed country and a relevant reference for the CEE economies and, also, for China. Finally, Spain, a southern European economy, is an example of a successful "intermediate economy" (Molero 1995), caught in the middle-income trap of the technology and cost drivers of growth.

Our period of analysis is 2002–16, which is the longest period for which we had consistent data.[2] We constructed a dataset based on World Bank Development Indicators, the World Economic Forum Global Competitiveness Index, World

[2] To construct a balanced dataset, 3.32% of the sample was extrapolated either by taking the average of the two closest observations or the last available observation in the time series. The Appendix Table 1 provides more detail on the individual countries and the variables.

Intellectual Property data, the Scopus database, and the International Organization for Standardization, United Nations Educational, Scientific and Cultural Organization, Barro-Lee, Forbes, and UNComtrade databases (see Appendix Table 3A.1).

We explore the relative rankings of our sample of economies, based on the technology upgrading indexes. First, we compare countries' relative positions on the ITU (A + B) according to per capita income. The variables are expressed in standardized values, that is, within the range 0-1 (0-100%). Figure 3.1 shows broad correspondence between relative income and technology upgrading level ($R^2 = 0.69$). However, the distribution of countries along the ITU is more concentrated compared to the income level distribution. This suggests that income differences are driven by a range of non-technological factors, such as natural resources or past innovation rents, or industries, such as tourism, where technology is less important. Also, a country's ITU ranking may be higher than is reflected by its current income level. Among our sample countries, China, Korea, and Israel would seem to have a greater capacity for technology-driven growth than it is reflected by their current income levels.

In terms of technology upgrading capacity, our sample countries fall into three groups. The largest group of eleven countries (South Africa, Brazil, Belarus, Argentina, Russia, Ukraine, Romania, China, India, Poland, and Hungary) have ITUs between 0.2 and 0.35 on the standardized range while Germany, Israel, and Korea have the highest index values in the range 0.53 to 0.57. Spain and the Czechia are an intermediate group. There are three points worth emphasizing. First, the homogeneity or relative concentration among the bottom group; second, the similar rankings among Germany, Korea, and Israel, which might be related to our conceptual framework being geared towards the technological activities of middle-income rather than technology frontier economies; and third, the relatively large gap, populated by two intermediate economies (Spain and Czechia), between the bottom eleven and top three economies.

The intensity (A) and scope (B) of technology upgrading comprise the ITU. Figure 3.2 depicts a positive and highly correlated relationship between these two components ($R^2 = 0.89$). However, the intensity of technology upgrading (scale) distribution is twice as dispersed as the breadth of technology upgrading distribution. This suggests that the primary source of the differences among countries is not their structural features or breadth of technology upgrading, but rather the intensity or scale of their technology activities. This is in line with the literature on structural change, which suggests that the main influence on productivity is within-sector productivity changes (Peneder 2004).

Finally, we compare the ITU (A + B) to the index of technology and knowledge exchange (C). It is generally assumed that openness of the economy to knowledge exchange is essential for technology upgrading. However, such openness does not lead automatically to technology upgrading unless inflows of knowledge are linked to domestic technological activities. Radosevic and Yoruk (2018) show that increased exchanges of technology and knowledge with the global economy, do not necessarily

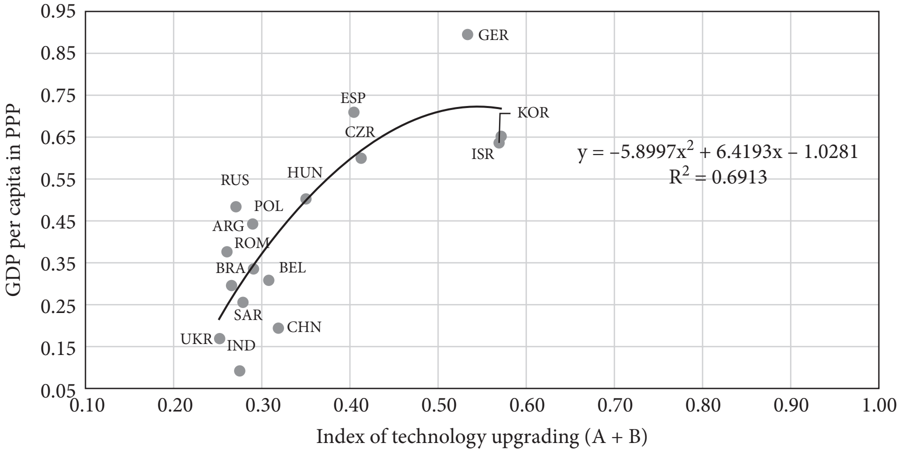

Figure 3.1 Relationship between GDP per capita and "Index of Technology Upgrading (A + B), average 2002–16 (in standardized values)"

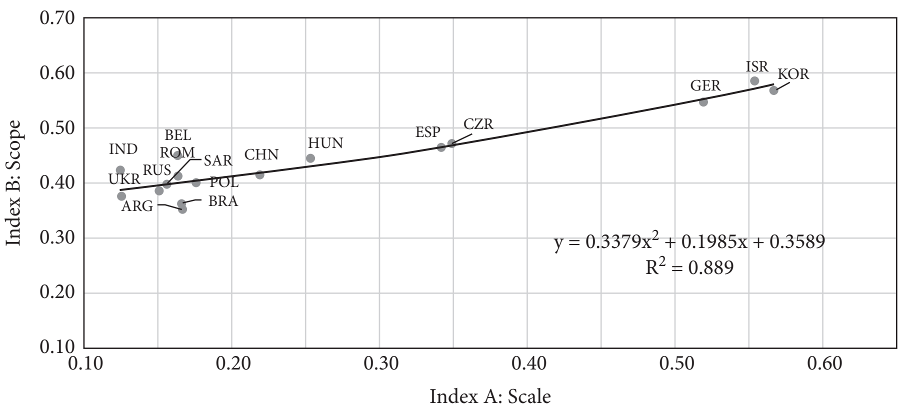

Figure 3.2 Position of countries on indexes of A (scale/intensity) and B (scope/breadth), average 2002–16 (based on standardized values)

increase the potential for technology-based growth. Figure 3.3 depicts a strong correlation between the aggregate ITU and the index of technology and knowledge exchange for fifteen out of the sixteen economies in our sample.[3] We could treat Hungary as an outlier and assume a positive and significant relationship, but that would mean ignoring the fact that Hungary is described as an assembly economy, which enjoys strong inflows of FDI and whose knowledge transfer is influenced more by multinational firms' transfer pricing than absorption of disembodied

[3] R^2 is 0.277 for the 16 economies and 0.75 for the 15 minus Hungary.

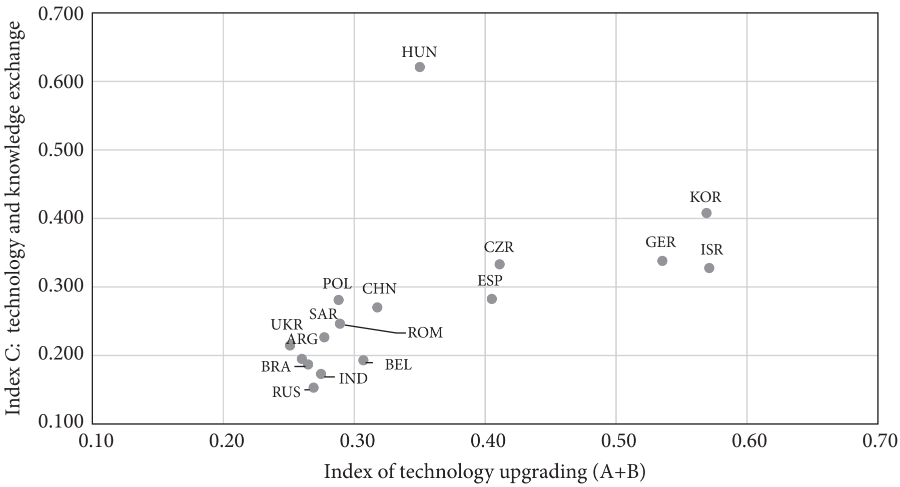

Figure 3.3 Position of countries on index of technology upgrading (A + B) and C (technology/knowledge exchange), average 2002–16 (in standardized values)

foreign knowledge. Similar to technology upgrading breadth, the distribution of economies along index C (technology exchange) is more concentrated than the ITU distribution. This suggests that countries with similar degrees of openness to foreign technology and knowledge show quite different outcomes, as reflected in their ITU.

In the rest of this section, we examine the sub-indexes that drive country differences in intensity (A) and breadth (B) of technology upgrading. Figure 3.4 shows that the most significant differences are related to technology capabilities, where, on a 0–1 scale, three countries (Germany, Israel, and Korea) register ten times more intensive knowledge generation activities than the sample average. This is as expected since the index refers to technology generation not manufacturing (production) capability or R&D capability, which are a mixture of knowledge generation and knowledge absorption activities. The gap between these three leaders and the rest of the sample is significant, but relatively less so for R&D capability. In the case of production (manufacturing) capability, five countries are ranked top—Korea, Germany and Israel, and the Czechia and Spain, which are equal to or higher than the first three.

Thus, we can assume that differences in technology upgrading intensity are driven by differences in technology capability, R&D and, then, production (manufacturing) capability. This is related to the nature of technology upgrading, which begins with production capability improvements, involves R&D and both absorptive and knowledge generation capacity, and leads to differences in the generation of new knowledge including frontier knowledge (Cohen and Levinthal 1989, 1990).

The breadth of technology upgrading index tries to capture three dimensions of structural transformation: infrastructure and human capital upgrading; upgrading

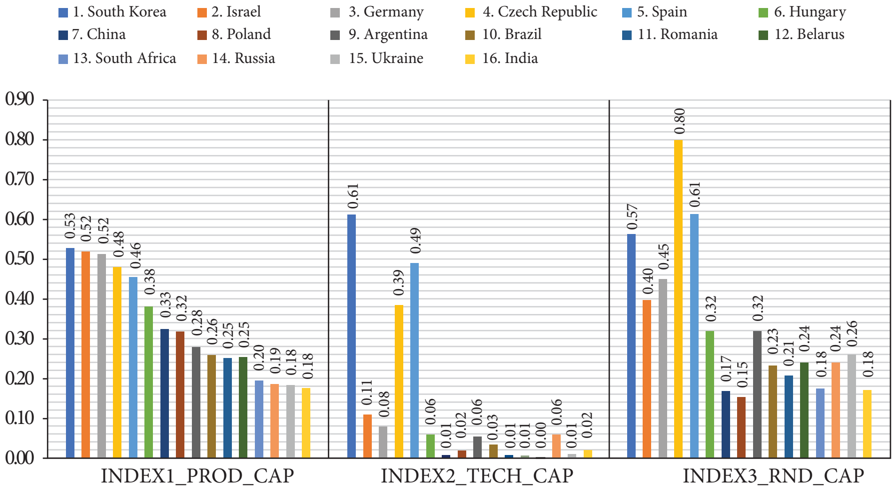

Figure 3.4 Sub-indexes of intensity of technology upgrading (A): Production (1), Technology (2) and R&D upgrading (3), average 2002–16

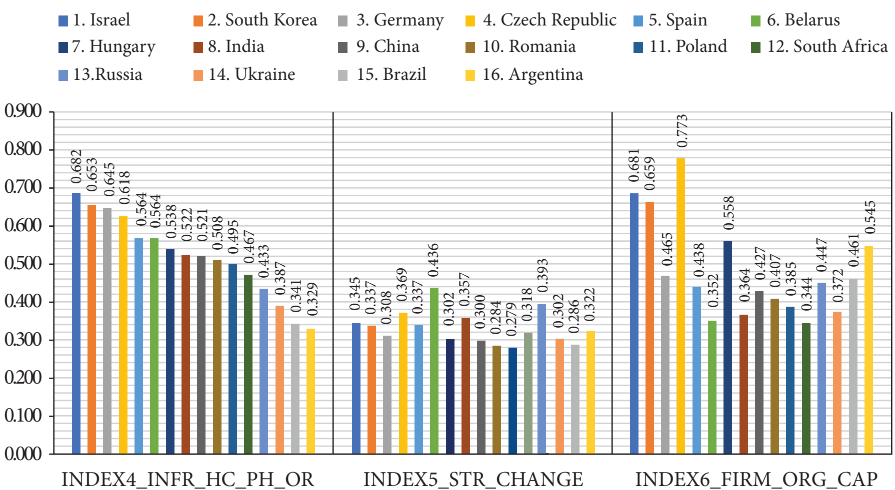

Figure 3.5 Sub-indexes of Index B (breadth): Infrastructure (4), Structural change (5) and Organizational capabilities (6), average 2002–16

of supply and demand for and diversification of knowledge; and upgrading of organisational capabilities. Figure 3.5 shows that the most significant differences among countries are related to organisational capabilities (Index 6) and the least significant are related to structural changes (Index 5). The top three economies (Germany, Korea, and Israel) have similar intensity of structural changes as other economies.

On the other hand, organisational capabilities are significantly more developed in the top three economies and differences in broadly defined infrastructure upgrading are also substantial. In summary, differences in technology upgrading breadth are driven primarily by differences in organizational capabilities and then by infrastructure upgrading and there are no significant differences between the top-ranked and the other countries regarding level or scale of structural changes.

3.4 The Dynamics and Morphology of Technology Upgrading: An Overview

In this section, we explore the differences among our sixteen countries on the three main indexes and six sub-indexes of technology upgrading, during the period 2002–16. We are interested in whether there are significant changes in technology upgrading speed across different groups of countries or individual countries. Figure 3.6 depicts countries' rates of change and shows that they are higher for index A (scale or intensity) compared to index B (scope or breadth). Technology upgrading scale and intensity have improved for all economies (except Hungary), although over a wide range from 0.04% (Spain) to 5.6% (China). Improvements to upgrading scope are narrower, ranging from no (Israel) or very little change (Belarus 0.05%) to 1.44% for China. In addition, seven of our sample economies show a deterioration in upgrading scope compared to only one economy showing a decline in upgrading

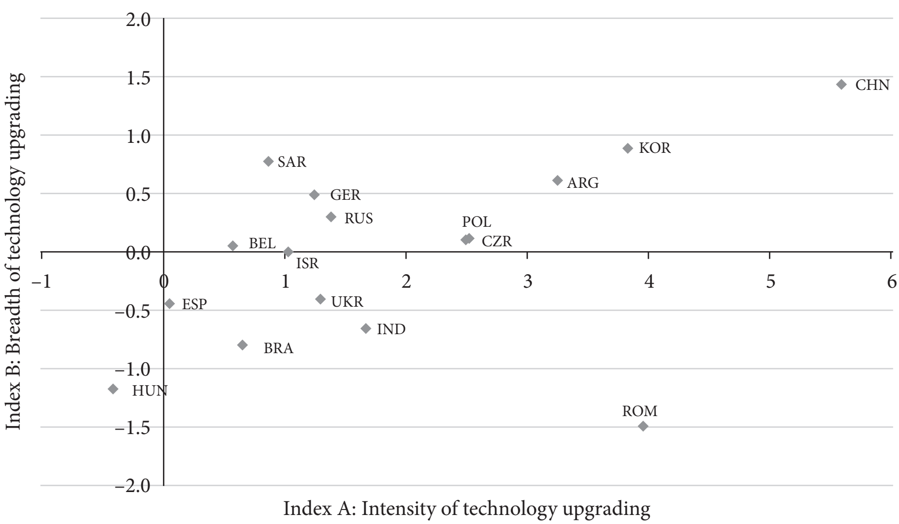

Figure 3.6 Relationship between average rates of growth of index A (intensity) and Index B (breadth) of technology upgrading 2002–16

scale and intensity. China is the fastest improving economy on both technology upgrading dimensions, followed at some distance by Korea, Argentina, Poland, and the Czechia. Five economies—Brazil, Romania, Spain, Ukraine, and India—show a decline in their scope of technology upgrading, although Romania is a special case. Its intensity of technology upgrading has improved significantly, but it has shown a steep decline in its scope of technology upgrading. Hungary is the only economy which shows a decline on both indexes.

The relationship between changes in the aggregate technology upgrading (A + B) index and the technology and knowledge exchange index (C) shows that there is not a simple association between openness to knowledge exchange and technology upgrading (Figure 3.7). China, Korea, and, to an extent, Argentina, have made more improvement to the aggregate index of technology upgrading than to the level of their technology and knowledge exchange. The remaining thirteen economies score higher for technology and knowledge exchange (Index C) than for technology upgrading (A + B). Six economies (Brazil, Hungary, Romania, Spain, Ukraine, and India) have increased their technology and knowledge openness, but show a reduced rate of technology upgrading. Brazil has fallen behind on both indexes (aggregate A + B and C) while Hungary improved its technology and knowledge exchange by 7.3% annually, but its technology upgrading declined by an average of 1% a year. These results demonstrate that, if not complemented by accumulation of domestic technology capabilities, openness and inflows of foreign capital and technology are not sufficient to increase the rate of technology upgrading.

Figure 3.8 and Table 3.2 show that only China has experienced strong growth in all three sub-indexes, and showed the highest growth in two sub-indexes.

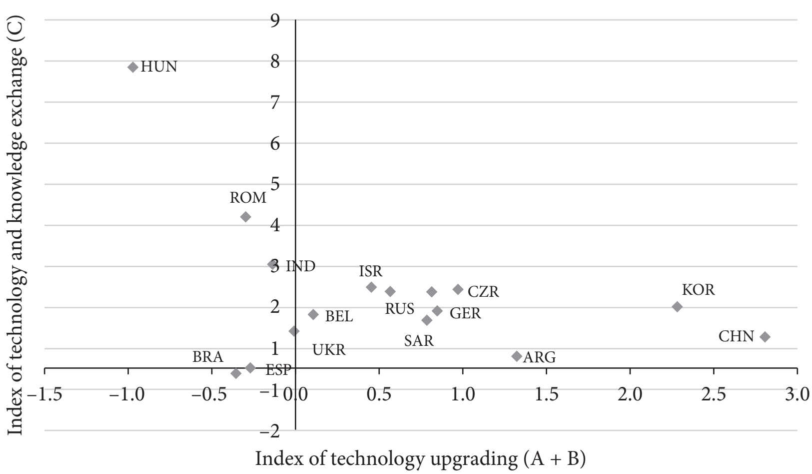

Figure 3.7 Relationship between average rates of growth of Index of "Technology Upgrading" (A = B) and "Knowledge Exchange," 2002–16

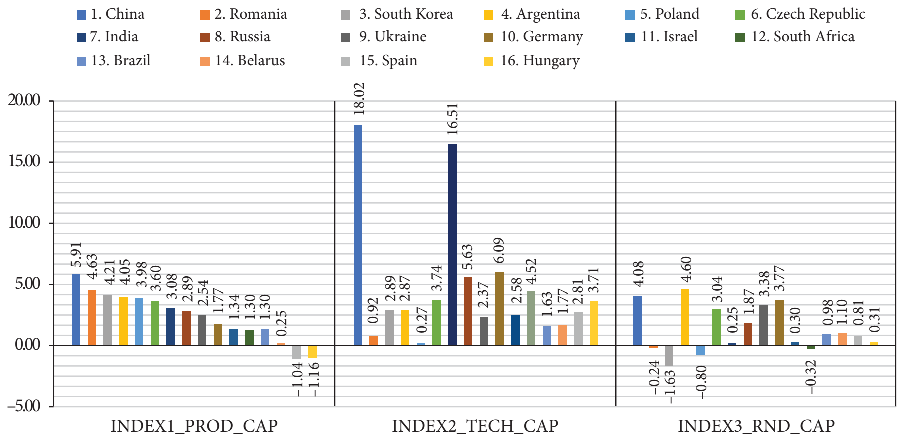

Figure 3.8 Rates of growth of sub-indexes of index A (intensity): Production (1), Technology (2) and R&D upgrading (3), average 2002–16

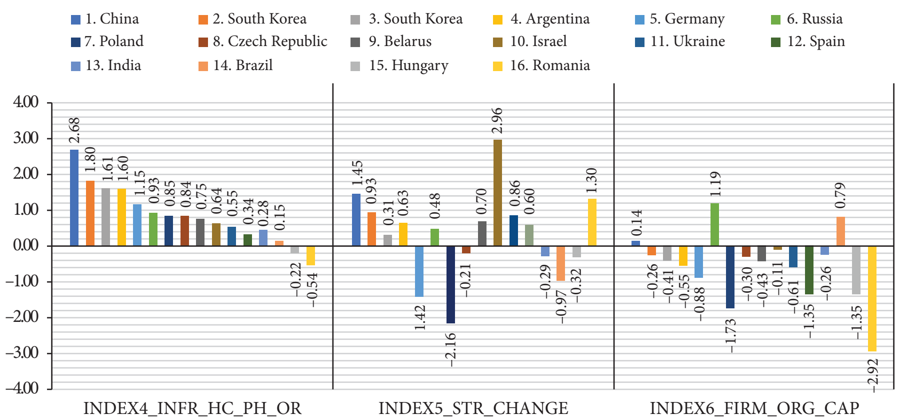

Figure 3.9 Rates of growth of index B (breadth): Infrastructure (4), Structural change (5) and Organizational capabilities (6), average 2002–16

The countries showing the biggest improvement to their production capability index are China, Russia, Ukraine, and Romania, while China and India achieved the highest technology capabilities improvements, with a significant margin by Korea, Poland, and Israel. In terms of R&D capability, the biggest improvers are China and Romania while four economies (Russia, Ukraine, Belarus, and Israel) have lost ranking. Differences in the rates of growth of different countries reflect differences in their positions in 2002 and their business and public policy strategies. Higher than average rates of improvements in production capability, demonstrated by Romania, Russia, and Ukraine, reflect their very low initial levels and, thus, represent a form of latecomer advantage. The very high technology capability rates registered by India

Table 3.2 Average rates of growth (%) of sub-indexes of A (intensity): production (1), technology (2) and R&D (3) upgrading (2002–16)

Country	Index1 prod cap	Index2 tech cap	Index3 R&D cap
China	**5.91**	**18.02**	**4.08**
Romania	**4.05**	2.87	**4.6**
Korea R	1.77	**6.09**	3.77
Argentina	3.6	3.74	3.04
Poland	2.89	**5.63**	1.87
Czech Republic	2.54	2.37	3.38
India	3.08	**16.51**	0.25
Russia	**4.63**	0.92	***−0.24***
Ukraine	**4.21**	2.89	***−1.63***
Germany	1.3	1.63	0.98
Israel	1.3	**4.52**	***−0.32***
South Africa	1.34	2.58	0.3
Brazil	0.25	1.77	1.1
Belarus	3.98	0.27	***−0.8***
Spain	***−1.04***	2.81	0.81
Hungary	***−1.16***	3.71	0.31

and China also reflect latecomer advantages while the Korean rate is based on its sustained growth in patenting activity, which started in the mid-1980s. The deceleration in the rates of growth of R&D capabilities in Russia, Ukraine, and Belarus are evidence of the truncated nature of their technology upgrading, while Israel's technology upgrading profile is reflective of a skewed technology upgrading focused on the high-tech sector.

Only Korea and China have extended the scope and breadth of their technology upgrading activities across all three dimensions (infrastructure, structural change, and organisational capabilities) (Table 3.3 and Figure 3.9). The majority of the remaining economies have improved on only one (Poland, Ukraine, Hungary, Romania, and India) or two dimensions, while Brazil has experienced decelerated rates of lower rates of changes to all three sub-indexes. This suggests that increasing the breadth of technology upgrading is a structural transformation process that involves extensive coordination and capability failures. It would seem that, since only two economies (Hungary and Brazil) have experienced decelerated rates of infrastructure upgrading, this is the most common form of technology upgrading breadth. Six economies have experienced lower rates of structural changes to technology upgrading and thirteen have experienced decelerated rates of improvement to their firms' organizational capabilities. This suggests that non-technological or organisational capabilities proxied, among other indicators, by growth of large domestic multinational firms, are more difficult compared to investment in firms' technological upgrading capabilities. It suggests, also, that a diversified knowledge base and higher demand for domestic technology are difficult to replicate or sustain at higher levels of income.

It is clear that technology upgrading proceeds at a different pace along the six different dimensions and our results show that it is not a linear activity. The different rates of production, technology and R&D capabilities reflect already achieved levels

Table 3.3 Average rates of growth (%) of sub-indexes of B (breadth): infrastructure (4), structural change (5) and organizational capabilities (6) upgrading (average 2002–16)

Country	Index4 infr hc ph or	Index5 str change	Index6 firm org cap
China	**2.68**	1.45	0.14
Korea R	0.93	0.48	**1.19**
South Africa	0.64	**2.96**	***−0.11***
Argentina	1.8	0.93	***−0.26***
Germany	1.61	0.31	***−0.41***
Russia	0.75	0.7	***−0.43***
Poland	0.84	***−0.21***	***−0.3***
Czech Republic	0.15	***−0.97***	0.79
Belarus	1.6	0.63	***−0.55***
Israel	0.55	0.86	***−0.61***
Ukraine	0.28	***−0.29***	***−0.26***
Spain	0.34	0.6	***−1.35***
India	1.15	***−1.42***	***−0.88***
Brazil	***−0.22***	***−0.32***	***−1.35***
Hungary	***−0.54***	1.3	***−2.92***
Romania	0.85	***−2.16***	***−1.73***

and firm strategies and public policies. Increasing the breadth of technology upgrading seems a more challenging and coordination failure-prone process than the intensification of existing technological activities which appears more sustainable.

3.5 Testing the Relevance of Technology Upgrading: A Dual Approach

The analysis described in the previous two sections demonstrates the value of a multifaceted approach to technology upgrading. A technology upgrading framework provides richer and more policy-relevant insights compared to conventional approaches which use TFP and labor productivity to proxy for technology upgrading. However, since some might consider technology upgrading framework as too "technology-specific" and exclude it from macroeconomic analyses of technology upgrading, we are keen to explore the relationship between the conventional macro-indicators of technology upgrading and how they relate to its different components. We test—both graphically and econometrically—the relationship between the different indexes and sub-indexes of technology upgrading in relation to TFP and labor productivity rates.

3.5.1 Descriptive Analysis

TFP and labor productivity are indicators of productive efficiency. Although they have the advantage that they are simple proxies, they do not allow us to observe the sources or components of this (in-)efficiency. The ITU measures the potential or capacity for technology capability-based growth, that is, it is a multidimensional proxy for the components that drive technology upgrading.

As a first approximation, we graphically explore the relationship between changes in the aggregate index of technology upgrading (A + B) and TFP/labor productivity. Figures 3.10 and 3.11 show that there is no relationship between changes in the index of technology upgrading and changes in either TFP or labor productivity.[4]

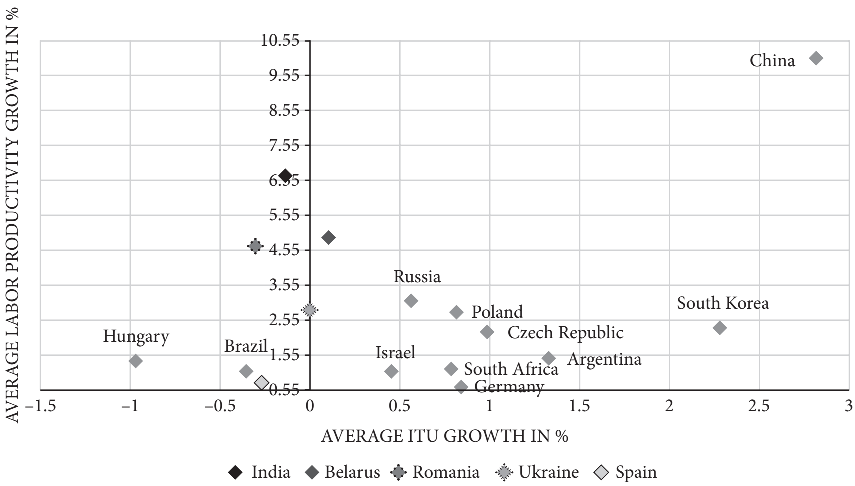

Figure 3.10 Relationship between rates of Index of technology upgrading and total factor productivity (TFP), 2002–16

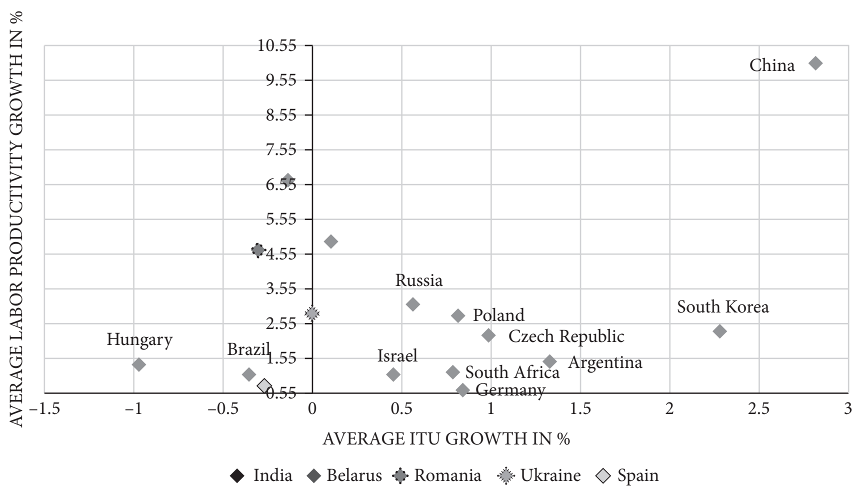

Figure 3.11 Relationship between growth of Index of technology upgrading and of labor productivity

4 In both cases, if China is excluded, the relationship turns negative, but remains insignificant.

Before calculating the growth rate, both variables are standardized using the min-max method. TFP is calculated as a residual of GDP growth minus the contribution of inputs and Labour productivity as value added per person employed in 2017 US$ (converted to 2017 prices based on updated 2011 PPPs). The average growth rate is calculated as the mean of the variables' yearly growth between 2002 and 2016.

We conclude that TFP and labor productivity growth is not associated with changes in technology upgrading. This suggests that changes in the capacity for technology upgrading are not necessarily converted into efficiencies, measured by TFP and labor productivity. On the other hand, this suggests, also, that productivity can increase with no increase in the potential for technology upgrading. Increased productivity can be based on higher capital intensity or low remuneration of labor. Further, removing institutional inefficiencies may improve labor productivity but not necessarily technological capabilities. At the same time, improvements to technology capabilities may not necessarily be reflected in aggregate productivity and it is possible that periods of higher productivity may come at the cost of structural deterioration.

Capability changes embodied in both labor and capital may not be captured by TFP or labor productivity. We can expect different TFP and labor productivity dynamics compared to the components of technology upgrading.

Table 3.4 shows that improving and laggard countries exhibit different trends: China and Korea are the leaders, while the laggards include a group of six emerging countries led by Hungary. This is as expected, since the ITU reflects investment and

Table 3.4 Average annual changes to technology upgrading, TFP and labor productivity 2002–16

Country	Growth of ITU	TFP growth %	Lab. prod growth %
China	**2.81**	**0.74**	**10.07**
Korea R	**2.28**	0.64	2.32
Argentina	**1.32**	0.64	1.45
Czech Republic	**0.98**	**0.65**	2.21
Germany	**0.84**	0.62	0.62
Poland	**0.81**	0.64	2.77
South Africa	**0.78**	0.63	1.14
Russia	**0.56**	**0.69**	**3.09**
Israel	0.45	0.63	1.07
Belarus	0.1	**0.75**	**4.91**
Ukraine	***−0.01***	**0.69**	2.82
India	***−0.14***	**0.67**	**6.68**
Spain	***−0.27***	0.6	0.75
Romania	***−0.3***	**0.67**	**4.66**
Brazil	***−0.36***	0.59	1.09
Hungary	***−0.98***	0.62	1.39

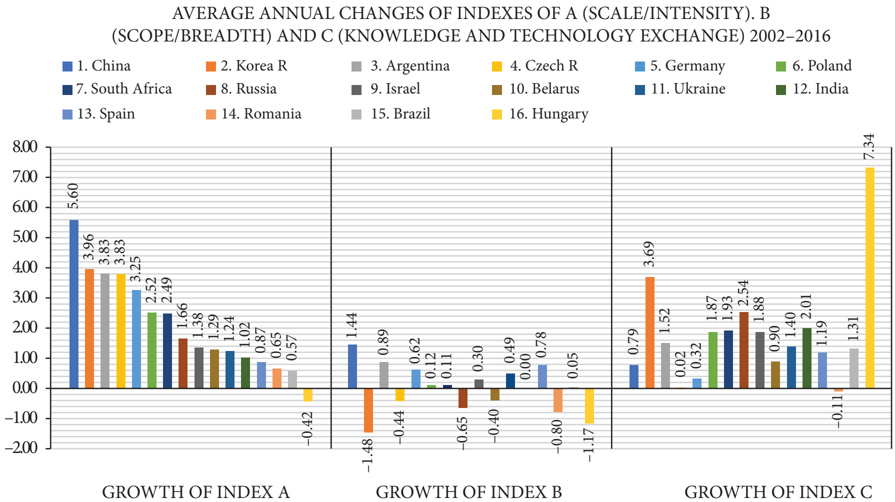

Figure 3.12 Fine-grained decomposition of the index A (intensity) index B (breadth) and index C (exchange) 2002–16

capability building activities, and processes not necessarily related directly to current growth. The ITU reflects the difficulty and effort involved in building capabilities, which often is not part of the business cycle, but rather is a reaction to strategic rather than only cost-cutting activities.

Figure 3.12 shows that the aggregate ITU is related more to changes to the intensity compared to the breadth of technology upgrading. Variations among countries in breadth of technology upgrading are high, which results in a small average change due to the canceling out of positive and negative trends. Figure 3.12 also shows the different patterns for breadth of technology upgrading, and the higher incidence (except Hungary) of improvements to technology upgrading intensity and scale. Index C shows high positive, but also variable rates of change.

3.5.2 Regression Analysis

We can derive two econometric models from a simplified, theory-based equation for the determinants of TFP (Section 3.5.2.1) and labor productivity (Section 3.5.2.2).

3.5.2.1 Total Factor Productivity: A Decomposition Exercise

We consider a standard Cobb-Douglas production function starting from the following neo-classical functional form:

$$VA = AK^{\alpha}L^{1-\alpha}$$

We consider the ***A*** component, or TFP, as denoting, in turn, a function of the three components of technology upgrading: Index A (intensity/scale), Index B (scope/breadth), and Index C (knowledge and technology interaction with the global economy or technology exchange). Therefore, we can write:

$$A = f\left(I_a, I_b, I_c\right)$$

After substitution, this can be rewritten as:

$$VA = \overline{A}\, I_a^{\alpha}\, I_b^{\beta}\, I_c^{\gamma}\, K^{\delta}\, L^{(1-\alpha-\beta-\gamma-\delta)}$$

where $\boldsymbol{A^{bar}}$ is the *unexplained residual efficiency* after accounting for I_A I_B I_C. Log-linearised and re-arranged equation entails:

$$logVA = log\overline{A} + \alpha log\left(I_a\right) + \beta log\left(I_b\right) + \gamma log\left(I_c\right) + \delta log\left(K\right) + \left(1-\alpha-\beta-\gamma-\delta\right) log\left(L\right)$$

$$logVA - \delta log\left(K\right) - \left(1-\alpha-\beta-\gamma-\delta\right) log\left(L\right) = log\overline{A} + \alpha log\left(I_a\right) + \beta log\left(I_b\right) + \gamma log\left(I_c\right)$$

$$logA = logTFP = logVA - \delta log\left(K\right) - \left(1-\alpha-\beta-\gamma-\delta\right) log\left(L\right)$$

$$logTFP = log\overline{A} + \alpha log\left(I_a\right) + \beta log\left(I_b\right) + \gamma log\left(I_c\right)$$

Finally, we derive the empirical equation:

$$logTFP = log\overline{A} + \alpha log\left(I_a\right) + \beta log\left(I_b\right) + \gamma log\left(I_c\right) + \varepsilon$$

Applying deltas and including country and time-fixed effects (to handle unobserved heterogeneity and common macro-shocks), we can estimate the following equation with standard errors clustered at country level:

$$\Delta logTFP_{it} = \alpha \Delta log\left(I_a\right)_{it} + \beta \Delta log\left(I_b\right)_{it} + \gamma \Delta log\left(I_c\right)_{it} + D_i + D_t + \Delta\varepsilon$$

Table 3.5 shows whether the components of technology upgrading can, individually or as a group, be considered significant determinants of TFP for our sixteen economies during the 2002–16 period. The results show that indexes A (scale) and B (scope) are statistically significant for explaining the variation in TFP, but Index C (technology exchange) is not. Also, in the so-called "horse race", that is, with all components included, the results are insignificant. The negative and significant time dummies post-2008 show that the relationship between TFP and our three indexes has been affected by the global financial crisis, suggesting changes to the technology upgrading regime, *ceteris paribus*.

Table 3.5 Individual components of technology upgrading as determinants of TFP (dependent variable growth rate of TFP, independent variables Deltas of I_A I_B I_C)

Variables	Index A	Index B	Index C	Horse Race
Dln_indexA_int_ tech_up_scale	4.205* (2.315)			3.089 (2.626)
Dln_indexB_breadth_ tech_up_scope		5.174* (2.792)		4.13 (3.169)
Dln_indexC_tech_ kn_ex			−0.703 (1.169)	0.329 (1.389)
2004.year	0.305 (0.455)	0.341 (0.398)	0.554 (0.441)	0.202 (0.421)
2005.year	−0.891 (0.656)	−0.881 (0.699)	−0.731 (0.666)	−0.968 (0.685)
2006.year	−0.13 (0.613)	−0.257 (0.675)	0.211 (0.533)	−0.412 (0.729)
2007.year	−0.259 (0.707)	−0.562 (0.803)	−0.034 (0.682)	−0.62 (0.833)
2008.year	−2.426*** (0.756)	−2.621*** (0.843)	−2.220*** (0.736)	−2.691*** (0.857)
2009.year	−6.653*** (1.599)	−6.652*** (1.609)	−6.578*** (1.62)	−6.693*** (1.624)
2010.year	−0.504 (0.981)	−0.512 (1.03)	−0.467 (0.982)	−0.53 (1.023)
2011.year	−1.393* (0.706)	−1.718* (0.83)	−1.542* (0.762)	−1.574* (0.799)
2012.year	−3.018*** (0.732)	−3.064*** (0.819)	−2.974*** (0.775)	−3.078*** (0.786)
2013.year	−2.682*** (0.831)	−2.832*** (0.946)	−2.602*** (0.823)	−2.844*** (0.941)
2014.year	−2.475** (0.909)	−2.672** (1.046)	−2.520** (0.926)	−2.608** (1.033)
2015.year	−2.650* (1.245)	−3.026** (1.347)	−2.647** (1.206)	−2.952* (1.385)
2016.year	−2.575*** (0.847)	−2.821** (0.981)	−2.540** (0.864)	−2.789*** (0.913)
Constant	2.895*** (0.642)	3.169*** (0.752)	2.917*** (0.654)	3.102*** (0.752)
Observations	224	224	224	224
Number of id	16	16	16	16
Adjusted R-squared	0.386	0.388	0.374	0.388

Robust standard errors in parentheses, all regressions include countries Fixed Effects.
*** p<0.01, ** p<0.05, * p<0.1

Table 3.6 Index of technology upgrading (A+B) and index of "technology exchange" (C) as determinants of TFP: Dependent variable Growth Rate of TFP, independent variables deltas of ITU (average A and B) and Technology Exchange (I_C)

Variables	ITU	Know Exchange	Horse Race
Dln_ITU	6.500*		6.570*
	(3.225)		(3.311)
Dln_indexC_tech_kn_ex		−0.703	0.314
		(1.169)	(1.359)
Year Dummies	Y***	Y***	Y***
Constant	3.166***	2.917***	3.166***
	(0.75)	(0.654)	(0.749)
Observations	224	224	224
Number of id	16	16	16
Adjusted R-squared	0.391	0.374	0.388

Robust standard errors in parentheses, all regressions include countries Fixed Effects.
*** p<0.01, ** p<0.05, * p<0.1

Next, we aggregate I_A and I_B to obtain a unified ITU to estimate:

$$\Delta logTFP_{it} = \lambda \Delta log\left[\frac{I_a + I_b}{2}\right]_{it} + \gamma \Delta log\left(I_c\right)_{it} + D_i + D_t + \Delta\varepsilon$$

Table 3.6 shows that, in the period 2002–16, the ITU (A + B) operates as a significant stand-alone determinant of TFP changes. Similar to the results in Table 3.5, the index of technology exchange (C) is not a significant determinant of TFP, but the "horse" race confirms that the ITU result is indeed robust.

Finally, we decompose ITU into six subcomponents I_1 production capability, I_2 technology capability, I_3 R&D and knowledge, I_4 infrastructure, I_5 structural change, and I_6 firm-level capabilities:

$$\Delta logTFP_{it} = \alpha_1 \Delta log\left(I_1\right)_{it} + \alpha_2 \Delta log\left(I_2\right)_{it} + \alpha_3 \Delta log\left(I_3\right)_{it} + \alpha_4 \Delta log\left(I_4\right)_{it} + \alpha_5 \Delta log\left(I_5\right)_{it} + \alpha_6 \Delta log\left(I_6\right)_{it} + D_i + D_t + \Delta\varepsilon$$

Table 3.7 shows that production capability is the only significant individual subcomponent of the determinants of TFP and it is robust to the inclusion in the regression of all the sub-components (the horse race).

3.5.2.2 Labour Productivity

We next consider the same standard Cobb-Douglas production function, but in an alternative transformation:

$$VA = AK^{\alpha}L^{1-\alpha}$$

Table 3.7 Individual sub-components of the index of technology upgrading as determinants of TFP (Dependent variable Growth Rate of TFP, independent variables growth rates of I_1 I_2 I_3 I_4 I_5 I_6)

Variables	Index 1	Index 2	Index 3	Index 4	Index 5	Index 6	Horse Race
Dln_index1_prod_cap	2.610**						2.566**
	(1.096)						(1.007)
Dln_index2_tech_cap		1.03					0.703
		(1.076)					(1.348)
Dln_index3_RnD_cap			2.619				3.042
			(3.479)				(3.506)
Dln_index4_infr_hc_ph_or				2.42			−1.876
				(3.255)			(3.865)
Dln_index5_str_change					1.952		2.009
					(1.374)		(1.251)
Dln_index6_firm_org_cap						0.647	0.535
						(0.885)	(1.226)
Year Dummies	Y***	Y***	Y***	Y***	Y***	Y***	Y***
Constant	2.975***	2.800***	2.886***	2.955***	3.039***	2.943***	2.990***
	(0.687)	(0.624)	(0.641)	(0.675)	(0.698)	(0.652)	(0.702)
Observations	224	224	224	224	224	224	224
Number of id	16	16	16	16	16	16	16
Adjusted R-squared	0.396	0.377	0.377	0.376	0.383	0.375	0.395

Robust standard errors in parentheses, all regressions include countries Fixed Effects.

*** p<0.01, ** p<0.05, * p<0.1

$$\frac{VA}{L} = \frac{AK^{\alpha}L^{1-\alpha}}{L} = \frac{AK^{\alpha}}{L^{\alpha}} = A\left(\frac{K}{L}\right)^{\alpha}$$

Labor productivity can be written as a function of A and the capital/labor ratio:

$$Labour_{Productivity} = A\left(Capital\ Labor\ Ratio\right)^{\alpha}$$

$$log\left(\frac{VA}{L}\right) = logA + \alpha log\left(\frac{K}{L}\right)$$

As in the previous decomposition, assuming A is a function of I_A I_B $I_{C,}$ we can write:

$$log\left(\frac{VA}{L}\right) = log\left(I_A I_B I_C\right) + \alpha log\left(\frac{K}{L}\right) = logI_A + logI_B + logI_C + \alpha log\left(\frac{K}{L}\right)$$

Employing deltas and including country and time-fixed effects, we can estimate the following equation with standard errors clustered at country level[5]:

$$\Delta log\left(\frac{VA}{L}\right)_{it} = \Delta logI_{Ait} + \Delta logI_{Bit} + \Delta logI_{Cit} + \alpha\Delta log\left(\frac{K}{L}\right)_{it} + D_i + D_t + \Delta\varepsilon_{it}$$

Table 3.8 shows that only scope or breadth of technology upgrading is a significant explanatory variable for labor productivity and it is robust to inclusion in the regression of all three components (horse race). Index C is negative, but not significant.

Next, we aggregate Indexes A and B to obtain the ITU:

$$\Delta log\left(\frac{VA}{L}\right)_{it} = \Delta log\left[\frac{I_A + I_B}{2}\right]_{it} + D_i + D_t + \Delta\varepsilon_{it}$$

Table 3.9 shows that the aggregate ITU (A + B) is a significant explanatory variable for labor productivity.

Finally, we decompose ITU into six sub-indicators:

$$\Delta log\left(\frac{VA}{L}\right)_{it} = \alpha_1\Delta log\left(I_1\right)_{it} + \alpha_2\Delta log\left(I_2\right)_{it} + \alpha_3\Delta log\left(I_3\right)_{it} + \alpha_4\Delta log\left(I_4\right)_{it} + \alpha_5\Delta log\left(I_5\right)_{it} + \alpha_6\Delta log\left(I_6\right)_{it} + D_i + D_t + \Delta\varepsilon$$

Table 3.10 shows that sub-indexes 5 (structural change) and 6 (organisational capabilities) contribute significantly to the variations in labor productivity. This result is robust within the "horse race" specification. Also, production capability contributes significantly to variations in labor productivity.

[5] We run regressions without the K/L ratio due to the high collinearity with country dummies. The version including the K/L ratio is available upon request.

Table 3.8 Individual components of technology upgrading as determinants of labor productivity: dependent variable growth rate of labor productivity, independent variables growth rates of I_A I_B I_C

Variables	Index A	Index B	Index C	Horse Race
Dln_indexA_int_ tech_up_scale	3.155 (2.726)			1.062 (2.975)
Dln_indexB_breadth_ tech_up_scope		7.984** (3.209)		7.565** (3.176)
Dln_indexC_tech_ kn_ex			−1.722 (1.54)	−0.168 (1.757)
Year Dummies	Y***	Y***	Y***	Y***
Constant	4.208*** (0.63)	4.616*** (0.754)	4.233*** (0.634)	4.592*** (0.758)
Observations	224	224	224	224
Number of id	16	16	16	16
Adjusted R-squared	0.368	0.392	0.363	0.386

Robust standard errors in parentheses, all regression include countries Fixed Effects.
*** p<0.01, ** p<0.05, * p<0.1

Table 3.9 Index of technology upgrading (A+B) and index of "technology exchange" (C) as determinants of labor productivity: dependent variable growth rate of labor productivity, independent variables growth of ITU (average A and B) and Knowledge Exchange (I_C)

Variables	ITU	Know Exchange	Horse race
Dln_ITU	8.524* (4.096)		8.432* (4.186)
Dln_indexC_tech_kn_ex		−1.722 (1.54)	−0.416 (1.762)
Time dummies	Y***	Y***	Y***
Constant	4.553*** (0.756)	4.233*** (0.634)	4.552*** (0.759)
Observations	224	224	224
Number of id	16	16	16
Adjusted R-squared	0.388	0.363	0.385

Robust standard errors in parentheses, all regressions include countries Fixed Effects.
*** p<0.01, ** p<0.05, * p<0.1

Table 3.10 Individual sub-components of the index of technology upgrading as determinants of labor productivity: dependent variable growth rate of labor productivity, independent variables growth rate of I_1 I_2 I_3 I_4 I_5 I_6

Variables	Index 1	Index 2	Index 3	Index 4	Index 5	Index 6	Horse Race
Dln_index1_prod_cap	1.914						2.159**
	(1.151)						(0.837)
Dln_index2_tech_cap		0.383					0.431
		(1.261)					(1.319)
Dln_index3_RnD_cap			3.136				4.155
			(3.264)				(3.738)
Dln_index4_infr_hc_ph_or				0.454			-4.845
				(3.5)			(3.847)
Dln_index5_str_change					3.075***		3.215***
					(1.008)		(1.031)
Dln_index6_firm_org_cap						1.916*	2.034*
						(0.972)	(1.137)
Constant	4.267***	4.179***	4.190***	4.229***	4.420***	4.312***	4.403***
	(0.673)	(0.597)	(0.626)	(0.626)	(0.665)	(0.63)	(0.669)
Observations	224	224	224	224	224	224	224
Number of id	16	16	16	16	16	16	16
Adjusted R-squared	0.372	0.362	0.366	0.362	0.383	0.371	0.398

Robust standard errors in parentheses, all regressions include countries Fixed Effects.

*** p<0.01, ** p<0.05, * p<0.1

3.5.2.3 Summary of the Regression Results

We used regression analysis to explore whether different components of technology upgrading are significant for explaining variations in TFP and labor productivity, used to measure macro-efficiency. The results show some clear patterns.

We found a positive and statistically significant relationship (robust to autocorrelation and heteroscedasticity of the errors). This allows us to hypothesize about TFP vis-à-vis labor productivity, as follows:

1. The ITU correlates with *both* TFP and labor productivity growth;
2. Technology and knowledge exchange (Index C) is *never* a critical explanatory factor in either TFP or labor productivity growth. Index C measures the scale and intensity of knowledge and technology exchange, but not the absorption of imported knowledge and technology. If imported knowledge is not absorbed or not complemented by domestic technology efforts, there will be no improvements to overall economic efficiency;
3. TFP/labor productivity growth and technology upgrading differ in their subcomponents:

   TFP growth is explained mainly by (scale/intensity/depth) of technology upgrading and, in particular, by production capability (Index 1). Intuitively, this seems plausible since production capability refers to the ability to work efficiently on a given technology, based on improved non-physical and non-technological investments such as better management practices, quality improvements, and better organisation; labor productivity appears to be driven by (breadth/scope) of technology upgrading. In particular, broadly defined structural change (index 5) and firms' organisational capabilities (index 6) play a major role in explaining improved productivity. This suggests that the labor productivity is driven by diversification to more productive technology-intensive activities, improved demand for and supply of technology, and domestic firms' internationalisation and improved organisational capabilities.

3.6 Conclusions and Policy Implications

Based on a sample of sixteen, mostly emerging, economies in the period 2002–16, we tested a new conceptual approach to measuring technology upgrading (Radosevic and Yoruk 2016, 2018). Our ITU is based on three complementary, but autonomous components, which proxy for three different dimensions of the technology upgrading process: scale or intensity of technology activities; breadth or scope of technology upgrading activities; and technology and knowledge exchange with the global economy.

The components of the ITU (scale and scope) are correlated to countries' income levels, but not their technology exchange index. We found that differences in the intensity of technology upgrading are driven by technological capabilities and R&D, with production capabilities secondary. This ordering reflects the hierarchical nature of technology upgrading and the cumulative nature of technological capabilities.

We found that differences among countries with respect to breadth of technology upgrading were driven by differences in organisational capabilities and infrastructure upgrading, and less by the scale of structural differences. Unless linked to organisational capabilities, technological capabilities do not contribute to growth. Our findings support the importance of organisational capabilities for economic catch-up (Chandler 1990).

Most countries show improvements to the intensity or scale of their technology upgrading activities, although with significant differences in rates of changes. Changes to the breadth of technology upgrading are less intensive and we observed some improvements, but also evidence of some countries falling behind in structural terms. Hungary is the only country that, despite relatively good average *levels* of technology upgrading, has experienced a decrease in both intensity and breadth of technology upgrading. Paradoxically, Hungary is ranked highest for technology exchanges, which is evidence that interactions with the global economy, on their own, do not guarantee technology upgrading. Brazil is the only economy registering negative growth for all three dimensions of technology upgrading. As expected, China is the only economy showing significant improvement in all three components of technology upgrading.

Different countries have taken different paths to technology upgrading based on their technology upgrading sub-components. Some show improved production capabilities, but diminished R&D capabilities (Russia, Ukraine, Belarus, and Israel), while India and China are the only countries to show evidence of increased technology generation capabilities.

Korea and China are the only economies showing improvements to all three sub-components of technology upgrading breadth, while Brazil is the only economy to show a decrease in all three "breadth" sub-components. The remaining countries show improvements in only one or two components. The most frequent improvements refer to infrastructure upgrading and the least frequent to organisational capabilities upgrading. The results for breadth of technology upgrading are more diverse, reflecting the higher risks of coordination failures or successes among different activities and players.

Our results show that the proposed technology upgrading framework uncovers new aspects of the technology upgrading process and the relative positions of countries, which conventional mainstream approaches and composite indicators do not reveal. To test the relevance of our technology upgrading framework compared to conventional macroeconomic approaches, we explored the relationship between the ITU and its individual components and subcomponents, and changes to TFP and labor productivity. We discussed the trade-offs of these approaches and explored whether changes to TFP and labor productivity could be explained by changes to the ITU and its subcomponents.

Our econometric exercise suggests that the proposed ITU could be used to explain changes to both TFP and labor productivity. Changes to TFP can be explained by the individual A and B indexes and their aggregate A + B index. Technology exchange (index C) has no explanatory power, which suggests that openness to technology exchange, unless complemented by own technology accumulation activities, does not contribute to increased TFP and labor productivity.

Among the individual components of the ITU, only production capability contributes significantly to variations in TFP. This would seem plausible since this is the component that requires the least investment in capital and labor and, thus, is not captured by other indicators. It also confirms the importance of production capabilities for the productivity of emerging economies, as exemplified by the case of ex-transition economies (see Kravtsova and Radosevic 2011). The components which potentially might explain labor productivity include the aggregate component (A + B) and the three autonomous components (A, B, C), although only breadth of technology upgrading is significant. Furthermore, the index of technology exchange does not contribute significantly to explaining changes in labor productivity.

The only subcomponents that are significant for explaining changes to labor productivity are structural change (Index 4) and organisational capabilities (index 5). The index of structural change is closely related to supply and demand side transformations toward more productive sectors and related knowledge bases. The index of organisational capabilities suggests that increased labor productivity is associated with increased firm organisation capabilities, reflected by an increase in the number of domestic multinational firms.

The research presented in this chapter has some policy implications. The significant links between the ITU, its components/sub-components and productivity, show that factors which contribute significantly to increased productivity go beyond conventional views, recipes for structural reforms and Schumpeterian inspired recommendations about more investment in R&D. First, our analysis demonstrates the need to broaden the scope of innovation policy to include production (manufacturing) capabilities in policy thinking and a policy framework (Kim 1997). A simultaneous increase in all three components of technology upgrading intensity (production, R&D, and technology generation) points to the need, also, for better coordination among these policies.

Second, broadening the scope of technology upgrading means it is linked inextricably to structural transformation. Coordination failures in this area are far more pervasive and coordination successes are more difficult to achieve than in the case of investments in R&D, production and technology generation capabilities. Our results show that countries are more successful at infrastructure upgrading than enhancing organisational capabilities' building in domestic firms and facilitating their internationalisation. Our analysis suggests that a stronger focus is needed on industrial and innovation policy. Also, the diversification of technological knowledge and coordinated improvements to the demand and supply of technology, requires improvements to innovative enterprises' social conditions (Lazonick 2002a,b). This suggests some coordination between conventional innovation and broader development policy.

Third, we provide evidence that technology exchange is not enough to ensure technology upgrading unless it is complemented by accumulation of technology capabilities. China's success in all three technology upgrading, and Brazil's failure on all these dimensions alongside the mixed results for the other countries, seem telling. Technology upgrading requires coordination across multiple institutional and policy spaces and, in a global value chains context, globalization is not straightforward (Kergroach 2019). The policy implication is that coordination among the three components of technology upgrading is crucial and requires systemic policies that cut across conventional policy areas. In this context, our analysis supports the view of innovation and industrial policy as a "discovery process" (Hausmann and Rodrik 2003; Radosevic et al. 2017).

Finally, we would highlight some limitations of our analysis. First, choosing appropriate indicators is inevitably difficult; we hope that future work might improve on our choice. Our analysis also would benefit from longer time series and a larger sample of countries.

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Appendix

The Index of Technology Upgrading (ITU) is composed of: Index A, intensity/type of technology upgrading; and Index B, breadth of technology upgrading:

$$\text{ITU} = \text{Index A} + \text{Index B}$$

Index A includes production capability, technology capability and R&D, and knowledge intensity, based on fifteen indicators. Index B includes human capital and physical infrastructure, and structural change, based on sixteen indicators. Appendix Table 3A.1 presents the weights and components of each category and the quantitative indicators for each sub-index. All indexes and sub-indexes are estimated based on standardised quantitative indicators and aggregation of components with equal weights:

$$I_c = \sum_{j=1}^{J} \sum_{m=1}^{M} w_{jm} \left\{ (X_{jmc} - X_{jm}^{min}) \mid \left(X_{jm}^{max} - X_{jm}^{min} \right) \right\}$$

where c indicates country, w is the weight, j and m are indicator and component subscripts and min and max denote the minimum and maximum values of each indicator across countries.

Table 3A.1 Indicators of technology upgrading

Category (Index)	Component (Sub-index)	Quantitative indicators	Component Weight	Category Weight	Cronbach's alpha
Index A: Intensity and Types of technology upgrading	**1. Production Capability**	1. ISO9001 Certificates pmi (Source: ISO website) 2. Trademark Application, residents pmi (Source: WIPO Database) 3. On the job training Q.5.C (Source: WEF Global Competitiveness Report Database) [6]	1/6	1/2	0.8615
	2. Technology capability	4. Patents resident applications to national office pmi (Source: WIPO Database) 5. Patent applications to USPTO pmi (Source: WIPO Database) 6. Patent applications to EPO pmi (Source: WIPO Database) 7. Resident's industrial design count pmi (Source: WIPO Database)	1/6		
	3. R&D Capability	8. Business enterprise sector R&D expenditure (as % of GDP) (Source: UNESCO UIS.Stat) 9. R&D expenditure (% of GDP) (Source: World Bank) 10 Researchers in R&D pmi (Source: World Bank)[7] 11 Technicians in R&D pmi (Source: World Bank)[8] 12. Scientific and technical journal articles pmi (Source: World Bank) 13. Science citations pmi (Source: Scimago Journal & Country Rank) 14. Quality of scientific research institutions Q.12.02 (Source: WEF Global Competitiveness Report Database) 15. University–industry collaboration in R&D Q.12.04 (Source: WEF Global Competitiveness Report Database)	1/6		

Continued

[6] All WEF variables for Belarus defined between 2002 and 2012 were constructed as the average of annual Russian and Ukraine observations.

[7] Data for Belarus are from the national Statistical Committee of the Republic of Belarus. Variable used number of researchers in R&D divided by total population. For Israel observations were extrapolated backwards from year 2010 based on the rate of growth which was calculated from GERD in `000 PPP$ (in constant 2005 prices).

[8] Data for Belarus are from the national Statistical Committee of the Republic of Belarus. Constructed as Payroll numbers of R&D workers minus total number of researchers in R&D divided by population. For Israel observations were extrapolated backwards from year 2010 based on the rate of growth which was calculated from GERD in `000 PPP$ (in constant 2005 prices). China data are from the OECD database and include R&D personnel by sector of employment and occupation. We use non-research staff to proxy for the number of technicians working in R&D between 2010 and 2016 and projected backwards (for 2009–2002) based on the trend in the share of non-researchers in total R&D personnel.

Table 3A.1 Continued

Category (Index)	Component (Sub-index)	Quantitative indicators	Component Weight	Category Weight	Cronbach's alpha
Index B: Breadth of technology upgrading: Structural Features	**4. Infrastructure: human capital and physical**	16. Average years of schooling 25+ (Barro R. & J.W. Lee v2.2 June 2018) 17. Quality of math and science education Q.5.04 (Source: WEF Global Competitiveness Report Database) 18. Availability of research and training services Q.5.07 (Source: WEF Global Competitiveness Report Database) 19. Availability of scientists and engineers Q.12.06 (Source: WEF Global Competitiveness Report Database) 20. Fixed broadband internet subscribers (per 100 people) (Source: World Bank) 21. Gross Fixed Investment as % of GDP (Source: World Bank)	1/6	1/2	0.7051
	5. Structural Change	22. Herfindahl-Hirschman Index for total national patent applications (Source: WIPO Database) 23. Herfindahl-Hirschman Index for patent applications to EPO (Source: WIPO Database) 24. Herfindahl-Hirschman Index for patent applications to USPTO (Source: WIPO Database) 25. Buyer sophistication Q.6.16 (Source: WEF Global Competitiveness Report Database) 26. Change in buyer sophistication (% change in Q. 6.16) (Source: WEF Global Competitiveness Report Database) 27. Availability of state-of-the-art technologies Q.9.01 (Source: WEF Global Competitiveness Report Database) 28. Change in availability of latest technologies (% change in 9.01) (Source: WEF Global Competitiveness Report Database)	1/6		
	6. Firm organizational capabilities	29. Number of firms in Forbes 2000 pmi (Source: Forbes Global 2000 companies reports)[9] 30. Firm level technology absorption Q.9.02 (Source: WEF Global Competitiveness Report Database) 31. Reliance on professional management Q7.07(Source: WEF Global Competitiveness Report Database)	1/6		

[9] Observations for all countries were extrapolated using the last available year (2006).

Index C: Interactions with the Global Economy	**Technology and knowledge exchange**	32. Technology balance of payments (receipts) as % of GDP (Source: World Bank) 33. Technology balance of payments (payments) as % of GDP (Source: World Bank) 34. Share of exports in complex industries in total exports (SITCRev3 5 71-79 87 88) (2002-16 avg) (Source: UN Comtrade database) 35. Foreign direct investment, net outflows (% of GDP) (Source: World Bank) 36. Foreign direct investment, net inflows (% of GDP) (Source: World Bank)	1/5	0.7721

4
Middle Innovation Trap

Capability Transition Failure and Stalled Economic Growth

Jeong-Dong Lee, Chulwoo Baek, and Jung-In Yeon

4.1 Introduction

In the context of emerging economies, long-run economic growth and development through technological progress encompass mechanisms from catching up with the leading countries to moving forward by one's own upgrading. Some successful cases in newly industrializing economies have been highlighted in this respect, exemplifying how to grow quickly through technological catch-up and upgrade (Kim and Nelson 2000). However, in the recent decade, we have witnessed the diminishing trend of these countries' economic growth rates, and even China's growth rate has slowed to single digits. According to the World Bank (2012), among the 101 countries that have passed the lower threshold of the middle-income level in the 1960s, all but thirteen failed to surpass the upper threshold of the middle-income level. It has become a stylized fact that economic growth slows down in the middle-income range for most countries (Eichengreen et al. 2013), and "the middle-income trap" was coined to describe this phenomenon (Gill and Kharas 2007). As for the source of the middle-income trap, scholars have mainly pointed to the erosion of latecomers' advantages (e.g., the diminishing returns of resource reallocation, technological imitation, and cost competitiveness) (Agénor 2017; Fagerberg and Verspagen 2007; Vivarelli 2016), as well as the changed conditions for catch-up in the recent global economic systems (e.g., positioning in global value chains (GVCs)) (Lee et al. 2018; Ravenhill 2014).

A classic explanation for economic growth and catch-up, particularly in developing countries, has been based on a Lewis-type development model (Lewis 1954). At the first stage of economic development, underutilized, low-cost labor that is locked in the less productive agricultural sector moves toward the more productive manufacturing sector. Simultaneously, simple adoption of foreign technology, facilities, and efficient operation based on imported and codified knowledge (e.g., manuals) has increased cost competitiveness of products in the export market (Radosevic 1999), referring to the so-called economically backward country's advantage

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(Gerschenkron 1962). However, as the economy reaches the middle-income range, the latecomer's advantage weakens since competitors equipped with lower labor costs and up-to-date technology and facilities diminish the rents, slowing growth and thereby likely locking the country in the middle-income trap.

Although such arguments logically explain the steps leading to the middle-income trap, they do not address how to escape from the risk. Therefore, in this study, we revisit such stalled economic growth from the perspective of capability transition failure, based on our analytical framework explaining long-run economic growth through the development dynamics of two types of technological capabilities, namely, *implementation capability* and *design capability* (Lee et al. 2019). Doing so enables us to identify the bottleneck in endogenous mechanisms of technological development and suggest a way to overcome the difficulties in sustaining long-run economic growth.

The remainder of this chapter is organized as follows. In Section 4.2, we review the literature on long-run economic growth and technological capability development and introduce a conceptual framework for this study. In Section 4.3, we demonstrate the development pattern of the two technological capabilities for a range of countries, discussing how the typical pattern of technological capability development emerges and corresponds with the long-term process of economic growth. Section 4.4 describes the middle-income trap as a *"capability transition failure"* from an implementation-based to a design-based approach and discusses its difficulties from the innovation systemic perspective of institutional rigidity. In the last section, we conclude this study with the policy implication for constructing *"innovation commons"* as a coherent transition platform for the development of design capability.

4.2 Two Types of Technological Capabilities and Their Distinct Characteristics: An Analytic Framework

4.2.1 The Need for Two Different Capabilities in Long-Run Economic Growth

The importance of technological progress in economic growth and development has long been acknowledged by Schumpeter (1934), but it was Solow (1956, 1957) that triggered the academic race on quantifying the contribution of technological progress in sustaining economic growth. In particular, since the late 1980s, the relation between endogenous technological change and economic growth has been formulated by the mechanisms of human capital accumulation (Lucas 1988; Romer 1986), of product variety (or idea) creation (Romer 1990), and of product quality upgrading (Aghion and Howitt 1992; Grossman and Helpman 1991). These endogenous models clearly highlighted deliberate innovation efforts, and thereby the role of policies on technological progress, in contrast to the basic Solow model where the supply of physical capital is of utmost importance.

Further, such growth models predicted that the levels and rates of economic growth across countries are hardly converged if the outcome from the endogenous technological progress results in a technology gap. This is unlike the classical literature on economic catch-up or convergence hypotheses stating that an initially poor country with low capital accumulation will grow faster than an initially rich one (Barro 1991; Baumol 1986). Thereafter, empirical studies on the pattern of economic catch-up and convergence have been actively conducted to find real-world evidence. These studies have found a compromise (recognizing the undeniable differences in economic performances across countries) such that a set of educational, political, and other regional variables needs to be considered as a pivotal explanatory vector in growth regression, the so-called "conditional β-convergence" (Islam 1995; Mankiw et al. 1992; Sala-i-Martin 1996). In short, this implied that economic catch-up is the process of endogenous technological progress through human capital accumulation and technological knowledge production, thereby reducing differences in the level of technology across countries.

Meanwhile, some studies emphasized that such a technology gap is not easily reduced because technologies are not freely spilled over or simply acquired by probing into the ability to embrace the flow of technologies (Abramovitz 1986; Castellacci 2004; Fagerberg 1994; Verspagen 1992). Their arguments, developed from the Gerschenkron (1962)'s backwardness hypothesis concerning technological advances in industrial development, were strongly inspired by the evolutionary theory of technological innovation and intrinsic capability within an organizational structure (Nelson and Winter 1982). In particular, they stressed that the heterogeneity of the endogenous mechanism for technological development itself resulted from the level of "social capability" in each country, based on the Abramovitz (1986)'s quotation. In this respect, the literature emphasizing a coherent system for achieving national-level capability differs sharply from the neoclassical tradition of endogenous growth models highlighting a single key factor for technological progress. However, this social capability literature only explained the catch-up mechanism using a single type of capabilities, although it contributes to our understanding of intrinsic capability as a key player of technological progress and economic growth. Further, it is limited to a quite passive role of intrinsic capability under the circumstances of importing and adopting foreign technologies, for example explaining its complementarity from the perspective of "absorptive capacity" (Cohen and Levinthal 1990).

However, in the context of emerging economies, long-run economic growth and development encompass mechanisms from technologically catching up with the leading countries to moving forward by technologically upgrading themselves. Therefore, it is necessary to consider a comprehensive ability to absorb, adapt, create, upgrade, and commercialize existing and new technologies as an endogenous driver for sustained growth and technological development. In general, this is called "technological capability," and technological learning refers to the dynamic process of securing technological capabilities (Kim and Nelson 2000). Accordingly, some scholars have proposed the presence and need for different types of technological capabilities depending on the economic development stage (Bell and Pavitt 1992; Kim 1997; Lall 2000; Lee et al. 2019), revising the existing hypothesis focused on a single type of intrinsic capability and an unconditional expansion of overall technological capability at the national level.

Kim (1997) listed three elements of technological capability: *production capability, investment capability, and innovation capability*. To climb up the economic development ladder, he argued that technological capability should be upgraded through dynamic learning processes, ultimately securing innovation capability to develop frontier technologies. Bell and Pavitt (1992) distinguished between "production capacity", manufacturing products with a given efficiency, and "technological capability", generating and managing further technological advances. In addition, they stressed that technological capability does not automatically follow from the establishment of production capacity but is only strengthened by deliberate efforts toward cumulative learning. According to Lall (2000), there is a distinction between "know-how" acquiring disembodied knowledge in production facilities and "know-why" comprehending the principles of technologies. Therefore, as the national technology level reaches maturity, the development of autonomous innovation capability becomes more important than the development of operational capability so that the focus of national learning should be shifted from know-how to know-why.

According to Lee et al. (2019), to elucidate the cause of the middle-income trap and the strategies to overcome it, the national technological capability needs to draw a distinction between the two types of capabilities. "Concept design capability" (hereafter design capability) refers to the ability to create new blueprints, business models, or standard levels of new products and services, while "implementation capability" refers to the ability to actualize a given design and improve efficiencies through manufacturing experiences. This is quite similar to the separation in the above literature, specifically, the distinction between "technological capability" and "production capacity" (Bell and Pavitt 1992), between "innovation capability" and "production capability" (Kim 1997), and between capabilities in terms of "know-why" and "know-how" (Lall 2000). However, compared to other studies, the theoretical framing of (Lee et al. 2019) specified the two technological capabilities by focusing more on the different types of technological knowledge, the different modes of technological learning, and the different objectives of technological activities. The distinct characteristics of the two capabilities and relevant literature are discussed in greater depth in Section 4.2.2.

Inspired by the above theoretical frameworks, some scholars have attempted to demonstrate the correlation between different types of technological capabilities and their contributions to economic growth (Fagerberg and Srholec 2008; Lee and Kim 2009; Radosevic and Yoruk 2018). However, most of the empirical studies in the field of measuring technological capabilities or innovation performances have rarely applied these theoretical frameworks in quantifying national technological capability in a dynamic sense (Archibugi and Coco 2005; Desai et al. 2002; Dutta et al. 2016). For example, in the Global Innovation Index (GII), knowledge creation and diffusion are aggregated into the sub-indicator of "knowledge and technology output" despite their significant dynamic differences. As Radosevic and Yoruk (2016) pointed out, such approaches have been more effective in ranking countries' overall performances and making cross-sectional comparisons rather than understanding the dynamic relationship between technological capability development and long-run growth. In other words, a conceptual framework on different features and roles of the two technological capabilities is necessary to be applied and validated in the empirical analysis.

4.2.2 The Characteristics of Implementation Capability and Design Capability

As its definition indicates, the demonstration of technological capabilities covers various activities from the assimilation of existing technologies to the creation of new technologies. Additionally, based on Lee et al. (2019)'s definition of implementation and design capabilities, any proposal for products and services requires technological capabilities to actualize them at each step: (i) design capability to define the specifications and functions of the product or service, and (ii) implementation capability to physically engineer the design to deliver such specifications and functions. Therefore, "national technological capability" as an aggregated concept naturally incorporates multifaceted aspects with respect to the role, relevant activities or tasks, and learning processes. In this section, we introduce our conceptual framework in detail to describe the differences between the two technological capabilities by synthesizing the knowledge management literature and the organizational learning literature.

According to the knowledge management literature, there are two different dimensions of technological knowledge in the production field: tacit and explicit knowledge (Polanyi 1958). The essence of successful innovation and knowledge creation in the organizational context is to understand how tacit knowledge is converted into explicit knowledge that again stimulates the creation of new tacit knowledge (Nonaka and Takeuchi 1995). Further, Nonaka and Takeuchi (1995) introduced an analytic framework describing how organizational knowledge is created through four modes of knowledge conversion from one dimension to another, namely, socialization, externalization, combination, and internalization (i.e., the "SECI" model). Based on this evolutionary mechanism of the organizational knowledge creation process, we can derive the following implication for technological capability development at the national level: the process of knowledge conversion embraces two different types of technological learning and capabilities. To be specific, the clockwise process from socialization to combination matches with the technological learning and ability to share individuals' tacit knowledge and then create new technology, while the process from combination to internalization aptly describes the technological learning and ability to actualize explicit knowledge and implement available technology.

In the literature of organizational learning and search behaviors, the trade-off (or complementarity) between exploration and exploitation is one of the most widely discussed topics, and its main focus is how to regulate new opportunities and old certainties through technological search activities under limited resources (Katila and Ahuja 2002; March 1991). According to March (1991), exploration indicates activities on variation, experimentation, discovery, and innovation; whereas exploitation refers to activities related to efficiency, production, refinement, and implementation. Further, he illustrated that the relation of two search activities and their outcomes may vary in their combinations: a firm that prioritizes exploration with no consideration for exploitation is likely to suffer from unsuccessful experimentation on new ideas and technologies due to the lack of relevant competencies, while a firm that only pursues exploitation to the exclusion of exploration is likely to end up with a "trapped status in suboptimal stable equilibria." Katila and Ahuja (2002) reinterpreted the distinction between exploitation and exploration into the two concepts, *search depth* and *search scope,* with the degree of using or reusing existing and new knowledge. Accordingly, they suggested that a firm's ability to create new products depends on the degree of interaction between these two search efforts. Based on this literature, we can also draw out a stylized fact on learning and technological capabilities as follows: there are two distinct learning and search activities upon the development and use of knowledge, and successful innovation is determined by how the exploration of new possibilities and the exploitation of old certainties are combined and organized.

By integrating the theories on different knowledge and learning types into the technological capability literature, we can describe the key characteristics of implementation and design capabilities in detail. As we defined in Section 4.2.1, implementation capability refers to the abilities to actualize a given concept design. Knowledge used by implementation capability is mostly expressed in explicit forms such as manuals (Bell and Pavitt 1993) and therefore, is relatively easier to transfer (Cowan et al. 2000). Efficiency in terms of speed and cost is then the performance measure to pursue, so countries need repetitive execution of available technologies, as well as exploitation activities, to nurture implementation capability through production, refinement, and implementation for inducing the learning-by-doing effect (Zollo and Winter 2002).

Design capability to make a new concept design is often expressed in tacit knowledge such as accumulated experiences of individuals or embedded technologies in an organizational setting. The performance criterion of design capability is in line with the target of exploration activities such as uniqueness and differentiation of the products and services. In this respect, creative and novel concept design can only be obtained by accumulating the experience of trial and error (Zollo and Winter 2002),

Table 4.1 Key characteristics of implementation and design capabilities

Key aspects	Implementation capability	Design capability
Mode of expression	Explicit	Tacit
Performance criteria	Efficiency	Differentiation
Strategy to nurture	Learning-by-doing with the accumulation of repetitive execution	Learning-by-building with the accumulation of trial and error
Time and cost for learning	Low to medium	Medium to high

through the learning-by-building experiences such as experimentation, variation, and discovery. Moreover, due to its tacitness and accumulation effect, design capability is relatively difficult and costly to acquire. In Table 4.1, we summarize that the two capabilities are different mainly in four aspects: mode of expression, strategy to nurture, performance criteria, and learning time and cost.

Meanwhile, some scholars have explored the development mechanisms of technological capabilities through global connections among countries. They highlighted the important trend in the recent global economic systems where increased vertical specialization has led to a division of labor between technologically leading and lagging countries determined by the two technological capabilities (Dedrick et al. 2010; Ernst and Kim 2002; Lee et al. 2018; Morrison et al. 2008; Pietrobelli and Rabellotti 2011). According to Pietrobelli and Rabellotti (2011), the learning mechanism of local enterprises on the global market varies according to factors such as the governance type of GVCs, and that competitiveness in national technological capabilities can be specialized in their main tasks accordingly. This argument also enlightens the dynamic relationships between different types of technological capabilities and economic development stages.

To return to our framework of two capabilities with distinct characteristics, we can predict the typical process of long-run economic growth driven by technological capability development in the globalized market as follows. First, a developing country starts its economic development with implementation capability to manufacture products based on the concept designs imported or ordered from advanced countries. When the country succeeds at this stage and task, it is expected to reach the lower threshold of the middle-income level. As the country enhances its implementation capability and starts to assimilate and further refine the given concept design, it will reach the upper threshold of the middle-income level. Simultaneously, the country needs to start the development of design capability via the learning-by-building strategy, and then it becomes a high-income country as the country continues to accumulate sufficient design capability. This conceptual description of the typical development pattern is empirically investigated in the following section.

4.3 Development Pattern of the Two Technological Capabilities: An Empirical Evidence

In this section, we quantify national technological capability with two components, namely, implementation capability and design capability. We then demonstrate the dynamic process of national technological capability development, not only identifying quantitative growth but also presenting the sequential pattern of compositional changes from the implementation-based capability to the design-based capability. In addition, we discuss the relationship between capability transition and sustained economic growth by examining the national technological capability dynamics according to per capita income levels. The empirical demonstration in this section is mainly based on our recent empirical study (Yeon et al. 2020).

4.3.1 Measuring Two Technological Capabilities

To quantify national technological capability, we applied a composite index methodology in which a theoretical concept with multifaceted aspects can be represented into a standardized figure. In particular, we ensured that each component of the index has a clear economic interpretation as well as measurable content, given the various choices of national-level indicators consisting of different information. Therefore, the key features of implementation and design capabilities (mainly concerning performance criteria and learning mechanism) were reflected in the composite index structure as shown in Figure 4.1. As summarized in Table 4.1, it is distinctive that implementation capability is geared towards improving efficiencies in actualizing a given design, while design capability functions in differentiating new concept designs from existing technologies or products. Moreover, implementation capability is developed from repeated practice to adapt and assimilate technological knowledge at production sites (i.e., learning-by-doing). In comparison, design capability is learned through trial and error to combine and build new technological knowledge in pursuit of new designs (i.e., learning-by-building).

To capture the performance criterion of implementation capability, we first selected the data for ISO9001 certificates and trademark applications by residents of the countries under study (Radosevic and Yoruk 2018), indicating the level of production efficiency to manage and operate production facilities efficiently and the ability to establish recognizable brands with a certain quality of products and services. The three indicators related to manufacturing activities (i.e., domestic manufacturing value added per capita, total manufacturing employees, and gross fixed capital formation in the total manufacturing sector) are included as a set of proxies for repetitive execution at production sites, accounting for strong local manufacturing bases for the development of "know-how" (Cantore et al. 2017; Lall 2000; Lee and Baek 2012; Lundvall and Johnson 1994).

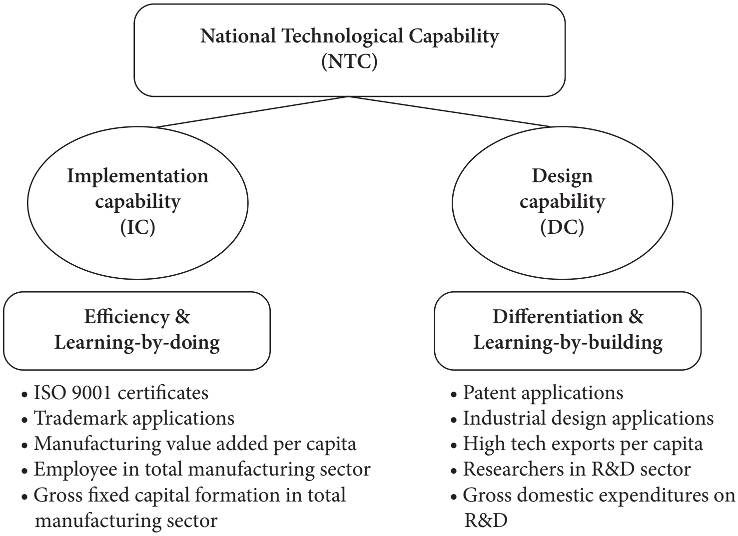

Figure 4.1 The analytical framework for measuring national technological capability (NTC) with two components, implementation capability (IC) and design capability (DC)

Symmetrically, for the design capability index, we used data for total patent applications by residents (direct and via the Patent Cooperation Treaty (PCT) national phase entries) and total industrial design applications by residents (direct and via the Hague system). These indicators are well-known proxies for the ability to propose differentiated technological knowledge for a new setup (Furman et al. 2002; Kang et al. 2015; Radosevic and Yoruk 2018). The learning mechanism dimension was captured by the indicators of gross domestic research and development (R&D) expenditure and R&D personnel in terms of resource bases that encourage technological trial and error (Dutta et al. 2016; Filippetti and Peyrache 2011) and learning "know-why" (Lall 2000; Lundvall and Johnson 1994). Additionally, the data for high-tech exports per capita was used as a proxy for commercial experiments to introduce and scale up a newly designed technology into the global market (Eichengreen et al. 2013; UNIDO 2017).

We used relevant data (from internationally reliable sources) on ninety-seven countries from 1996 to 2016. Before calculating a set of technological capability indices, we first imputed missing values in the data using a conventional methodology. Then each indicator was rescaled to a value between 0 and 1 over the analysis period using the min-max method (Archibugi and Coco 2004; Desai et al. 2002; Filippetti and Peyrache 2011; Freudenberg 2003; Nasir et al. 2011; Radosevic and Yoruk 2018; UNIDO 2017). After that, the two indices of implementation capability (IC) and design capability (DC) were calculated as an equal-weighted sum of five normalized variables. By definition, IC and DC are in the range of 0 to 5. Finally, we calculated the overall index of national technological capability (NTC) as the sum of

IC and DC, and NTC is in the range of 0 to 10. Further details in evaluating a set of indices are not discussed here and instead referred to in the original paper (Yeon et al. 2020).

4.3.2 Dynamics of the Two Technological Capabilities along with a Long-Run Economic Growth

Figure 4.2 illustrates the development process of national technological capability by means of changes in overall technological capability composition. In this figure, we trace the national trajectory of technological capability development by connecting the points for each panel in chronological order. We also presented the trend lines for IC and DC, applying the local regression method (LOESS, a non-parametric approach by fitting multiple least square regressions in a local neighborhood). The left panel shows the development trajectory of each country based on the index score per se, with the representative trend line of its typical pattern. The right panel represents the same data but is based on the composition ratio of the total index score. This figure demonstrates a typical pattern of technological capability dynamics, from the implementation-based to the design-based capability in terms of compositional changes.

To be concrete, in the left panel of Figure 4.2, countries with low levels of NTC first develop their overall technological capabilities by aggressively securing IC, but they maintain relatively low levels of DC. Thereafter, as NTC approaches the median level, countries start a full-scale development of DC while controlling for the degree of IC development. Further, based on the right panel, we can interpret the sequential pattern of national technological capability development as a transition dynamics of technological capability composition, dividing the capability development process into stages. At an early developmental stage where NTC is almost zero, countries build up national technological capabilities that are implementation based, defined

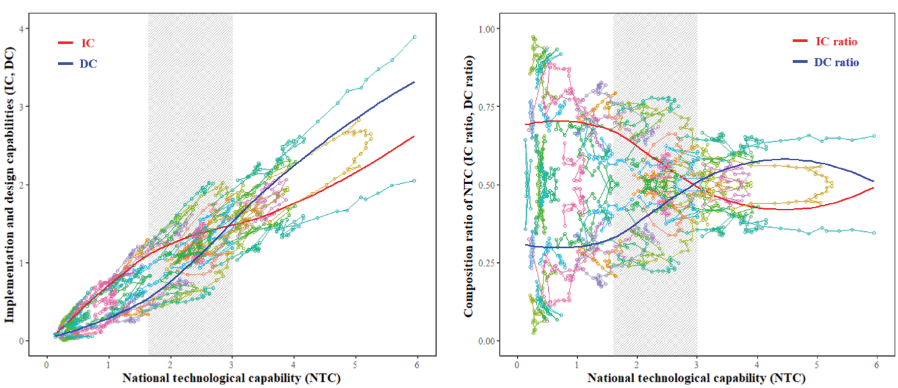

Figure 4.2 The development pattern of implementation capability and design capability

by an IC ratio over 0.5. Then, as NTC continues to be developed, the DC ratio increases and symmetrically, the IC ratio gradually decreases. After that, the complete transition from implementation-based to design-based capabilities (i.e., the intersection of the two trend lines) is finally observed when the index score of NTC reaches around 3. This suggests that, as indicated by the shaded area on the figure, there is a *"transition stage"* in the development of national technological capability, where the composition ratio of NTC vigorously changes before the complete transition. In short, this result verifies that the development of implementation capability precedes that of design capability so that a country needs to undergo the national technological capability transition from the implementation- to the design-based capability, rather than an unconditional increase in the overall level.

To examine the typical process of economic growth driven by technological capability development, we linked the above capability dynamics to the per capita income dynamics[1] as shown in Figure 4.3. Although there is heterogeneity in national trajectories, the general trend of overall national technological capability is to increase with per capita income levels, as shown in the literature (Dutta et al. 2016). Interestingly, we also found the non-linear relation between the index score of NTC and the income level in this figure, and this nonlinearity appears to be linked with a *"transition stage"* of national technological capability development. In consideration

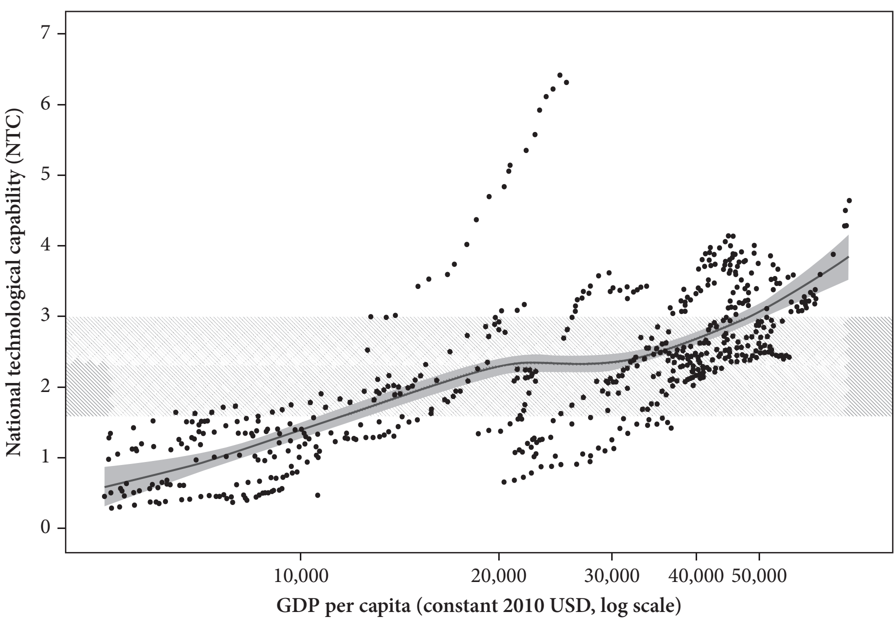

Figure 4.3 The overall index of national technological capability as per capita income increases

[1] In this study, the per capita income level refers to the log of gross domestic product (GDP) per capita in constant 2010 US$, with data collected from the World Bank.

of the World Bank's standard of classifying countries with respect to GDP per capita, the corresponding income range to this nonlinearity starts from the upper boundary of the middle-income countries to the threshold of the "lower" high-income level of over USD 30,000 of GDP per capita (Radosevic and Yoruk 2018). This implies that the transition dynamics of national technological capability is correlated with the cause of the middle-income trap or post-middle-income trap. In this respect, Lee et al. (2019) considered the development pattern from implementation capability to design capability in order to explain the fundamental source of the middle-income trap, referring to the middle-income trap as "the middle-innovation trap" or "capability-transition trap." This capability transition failure is discussed in detail in the next section.

4.4 Middle Innovation Trap and Transition Failure

4.4.1 Middle Innovation Trap and Growth Stall

Among middle-income countries, some have succeeded in narrowing the economic gap and getting incorporated into high-income countries, while others have failed to reduce the gap, thus remaining stagnant. Figure 4.4 compares the per capita income of countries against the United States in 1963 and 2008 to confirm this. Thirteen countries in Group A at the top of the middle were middle-income countries in 1963 but grew into high-income countries in 2008, while countries belonging to Group B underwent a growth stall they could not escape for more than forty-five years, thus remaining middle-income countries.

Figures 4.2 and 4.3 in Section 4.3 imply that there is a positive correlation between per capita income and national technological capability (NTC), and that countries with higher NTCs tend to have relatively higher concept design capability than implementation capability. Figure 4.5 shows the percentage of concept design capability versus national technology capability (DC ratio) to distinguish how these stylized facts differ from countries in Group A from those in Group B. South Korea is designated as a representative country belonging to Group A, and Thailand and Mexico as countries belonging to Group B. The thick blue solid line in Figure 4.3 represents the mean of DC ratio at each NTC level. The NTC of Korea increased drastically from about 2.3 (in 1996) to 5.6 (in 2016), and the DC ratio remained above 0.6 over that period, which was higher than countries with similar NTC. In comparison, Mexico, and Thailand show a low NTC growth pattern depending on the implementation capability because the NTC was kept at 0.3 ~ 1.2, with the DC ratio only at 0.1~0.35 during the same period.

The cases of Thailand and Mexico suggest that countries undergoing growth stalls experience a transition failure from implementation capability to concept design capability. Figure 4.6 depicts how concept design capability and implementation capability in Korea, Thailand and Mexico have changed over the period from 1996 to

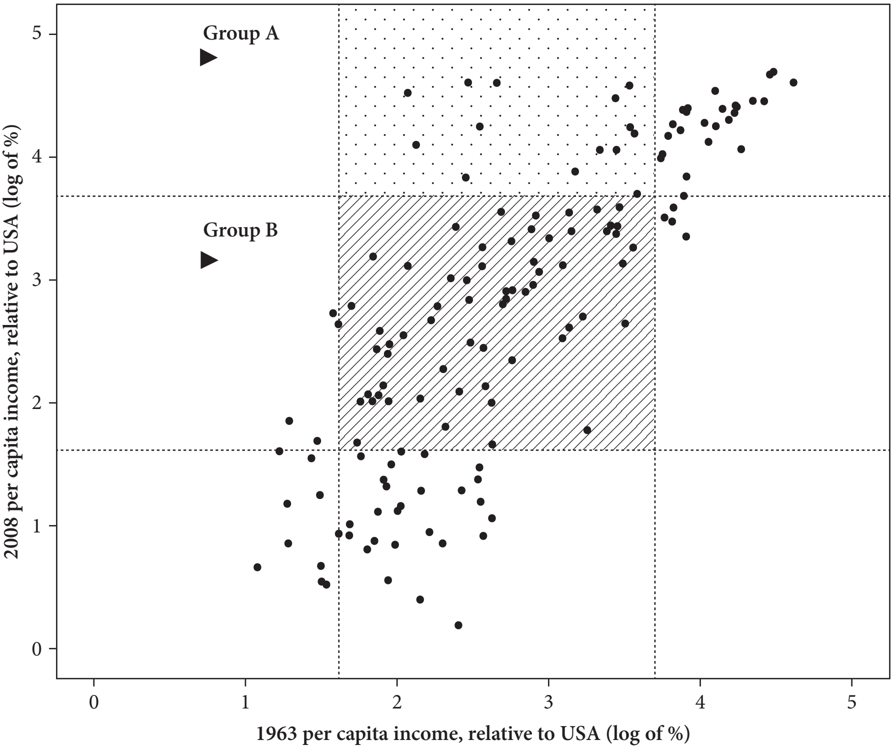

Figure 4.4 The distribution of countries by 1963 per capita income and 2008 per capita income

2016. While Korea has been rapidly growing its NTC with concept design capability, Thailand and Mexico have gradually increased their implementation capability, but their concept design capability has been stagnating for twenty years. Thailand and Mexico have fallen into the middle innovation trap, signifying the failure in switching from implementation capability driven growth to concept design capability driven growth.

4.4.2 The Reasons for Transition Failure

Once institutional arrangements are set based on implementation capability, the incentive system resultantly favors activities that reinforce implementation capability. Thus, entrepreneurial challenges that necessarily entail trial and error would not be favored. This pushes human resources into sectors that focus on efficient implementation over concept design. Competent talent is not motivated to develop concept design, and companies are also less interested in this field; consequently, companies become more strongly locked in implementation capability routines. This is a typical transition failure wherein firms concentrate mostly on what they

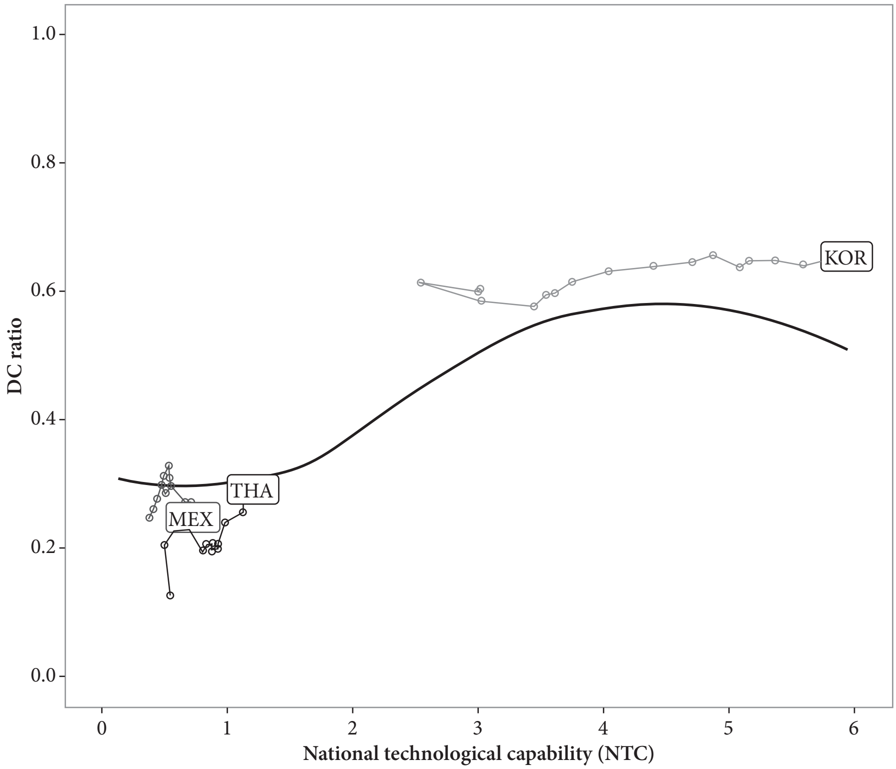

Figure 4.5 The ratio of concept design capability to national technological capability

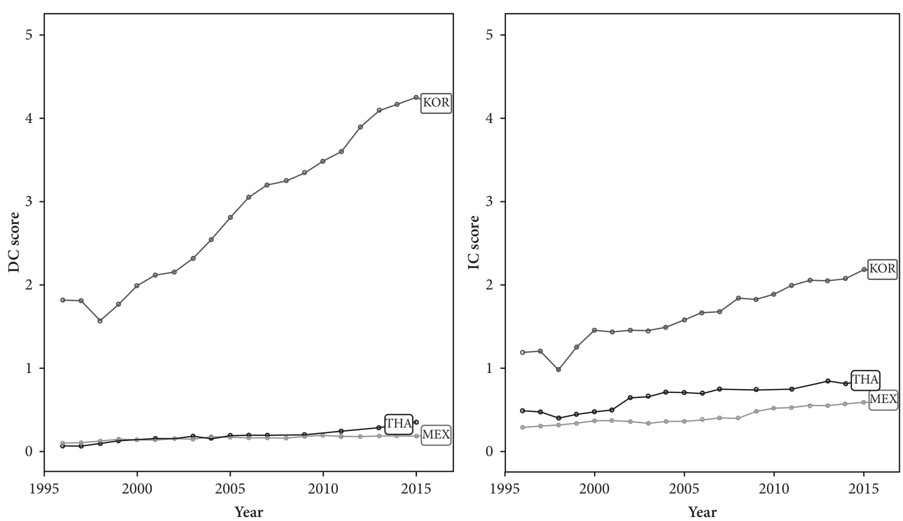

Figure 4.6 Development pattern of concept design capability (left) and implementation capability (right)

know best and focus on products and technologies where they have experience and skills (Smith 2000).

There are two reasons for transition failure. First, institutional rigidity prohibits a country in the middle innovation trap from adapting its national innovation system toward developing concept design. Transitioning from implementation to concept design capabilities in an innovation system is difficult because all the components in the innovation system surrounding implementation capability should change simultaneously. Moreover, the components of innovation should change according to the development stages and changes in external business environments (Matthews 2002). In short, coevolution of a coherent system is required for the transformation of an innovation system (Geels 2005) or institutional adaptation (Choung et al. 2016). However, once a specific type of coherent innovation system is organized, vested interests emerge that block changes.

Second, path dependency can mislead towards investing more on implementation capability than concept design capability. A coevolutionary process may systematically address some types of activities or ideas while constraining others. Moreover, this process emphasizes variety creation, adaptation, selection, and retention, all of which are time- and path-dependent (Arthur 1994; Narula 2002; Fagerberg et al. 2008). Economics literature has noted that path dependency enables economies of scale through, for example, the adoption of standards. Moreover, political literature has verified that it is difficult to establish a system or the "rules of the game;" but once set, this would cause a scale advantage (Pierson 2000; Whitley 2002; North 1990). The stronger the path dependency is, the higher the probability of transition failure to occur. According to the resource-based theory, the possession of a specific resource determines the competitiveness of the enterprise or country such that success in a field without the necessary resources is unlikely. Therefore, there is a huge risk that a company or country with a high level of implementation capability will not be able to switch to a concept design capability if it has insufficient experience or resource. Ultimately, if the state or society does not share the risk of transition, then individual firms will lose their competitiveness and die slowly while sticking to implementation capability.

4.5 Innovation Commons to Facilitate the Transition from Implementation to Concept Design Capability

Many countries experiencing stalled growth have failed in transitioning from implementation capability based growth to concept design capability based growth. In addition, we confirmed through previous research that this transition failure is due to institutional rigidity or path dependency of innovation policies. The process of securing design capability requires simultaneous changes of all institutional arrangements of the national innovation system ranging from education, finance, industry structure, and trade regime to industry/innovation policies that are the coevolution of a coherent system. To facilitate concomitant actions of individual actors, we need the concept of an innovation commons as a platform with tangible and intangible parts to mobilize the actions. Specifically, we have to define an innovation commons for design capability that contributes to nurturing the key components of the evolutionary process of design: challenging vision-setting, networking, and accumulating trial and error. Based on the innovation system theory and stylized evolutionary process of innovation, the following four factors should be included: (1) a strong, advanced manufacturing base, (2) learning capability to nurture professionalism, (3) socio-cultural institutions to favor the accumulation of trial and error, and (4) consistent innovation policies to lead the change.

4.5.1 A Strong Advanced Manufacturing Capability as a Platform for Trial and Error

An advanced manufacturing plant can provide the physical platform to test prototype designs. It is a proven stylized fact that the speed and quality of building a new concept design improve greatly when innovation and production sites are located near each other (Nahm and Steinfeld, 2014). Knowledge-based, high-value-added services have limited ability to generate jobs, and low-cost services such as personal services have limited scalability to the domestic industry. In particular, the service industry is a cause of Baumol's disease (Baumol and Bowen 1965), which means that the relatively low level of productivity causes a chronic productivity deterioration of the overall economy. By contrast, manufacturing can be a source of high-quality jobs and a basis of experience accumulation. In other words, manufacturing can act as a physical innovation commons to support challenging trial and error. Because the digital business, in the context of the digital transformation, must also be linked to physical economic activities, it is impossible to establish an endogenous industrial structure without a manufacturing industry.

Some developed countries have attempted offshoring to relocate manufacturing plants overseas due to high labor costs. However, this leads to a weakening of the manufacturing base and deprives entrepreneurs who have long accumulated the experience to start a business the opportunity to prototype innovative ideas. Based on this awareness, the United States reaffirmed the role of the manufacturing industry in the report "Making in America." The United States recognizes that offshoring has made the link between the manufacturing site and R&D more vulnerable than simply shifting the production base overseas, and emphasizes reshaping and reshoring manufacturing to solve this problem (The White House 2014). Therefore, the establishment of a manufacturing environment in which trial and error can accumulate in the long run through the process of scaling-up, growth, and survival should be set as an important direction of industrial/innovation policies. Additionally, relevant policies in the areas of human resource training, finance, and R&D must be consistently and efficiently utilized.

In the above discussion, however, manufacturing is not limited to traditional manufacturing. Due to rapid technological advances, manufacturing is expanding into new areas, not only by producing products but also by combining with knowledge intensive business services (KIBS). Smart factories that combine big data-based management solutions with traditional manufacturing can be a good example. In other words, what is emphasized in this section is the necessity of manufacturing as a stage to experiment and scale up the conceptual design capability, not the manufacturing as one of industry classifications.

4.5.2 Learning Capability to Nurture Professionals

Differences in per capita income between developing and developed countries are mostly due to differences in knowledge. Efforts to reduce the knowledge gap by converting developing countries into learning societies can improve per capita income (Stiglitz 1987). However, as knowledge itself is endogenous, learning ability is also endogenous. Therefore, learning how to learn is required (Stiglitz and Greewald 2014).

Concept design capability ultimately resides in the memory of professionals and develops as an organizational routine. A professional who can challenge concept design in his field is important in leading change through challenging trial and error. This professional can change a job, and the flexibility of the labor market can be of benefit both at the individual and social levels. Therefore learning capability is one of the most important innovation commons from which every actor can benefit.

However, in the era of rapid technological change, the effects of formal schooling are diminishing; thus, in order to nurture professionals it is necessary to have a system of lifelong learning that will replace schooling. Basically, the regular education in schools should focus on strengthening the curriculum related to STEM (science, technology, engineering, and mathematics), software competency, and entrepreneurship, so as to develop basic competence to understand and participate in future innovation direction. However, as much of the learning associated with economic activity occurs through jobs rather than schools, schooling should be designed to complement vocational education (Stiglitz and Greewald 2014). Certainly, both are possible within the university because universities are the platform of lifelong learning and serve as a hub of social accumulation. It is also possible to use universities as a base for outcubation in order to support prepared entrepreneurship that is centered on incumbents and experienced workers.

4.5.3 Socio-Cultural Institutions to Favor the Accumulation of Trial and Error

Innovation is expressed in a place filled with a cultural and practical mind open to trial and error. Therefore, it is important to have an open atmosphere where professionals that accumulate trial and error in their fields are respected, and unique ideas are allowed. To do this, it is important for leaders who have a strong will to innovate to recognize and trust trial and error in the long run. An accumulation-oriented culture and leadership must be embedded in tangible systems that can lead to continuous change.

In order to actualize this socio-cultural commons, first, it is important that leaders continuously present messages on the importance of innovation, the value of trial-and-error accumulation, and the need for pragmatic attitudes. When trust is built on the authenticity of the leader, the members can safely accumulate trial and error. Second, innovative attempts should be allowed in principle, with the regulations updated to reflect trial and error. New attempts should be based on the principle of negative regulation that allows for trial and error. Moreover, policies and political procedures that immediately analyze the causes of regulation failure and update the regulations whenever problems are discovered should be developed. With regard to unexpected problems and conflicts caused by regulatory changes, it is necessary to allow the immunity of regulatory practitioners. Third, in assessing policy performance, it is necessary to focus on how to improve execution procedures and achieve long-term performance rather than to achieve short-term quantitative goals, and to establish a culture that accepts socially honest failure in trial and error.

4.5.4 Consistent and Coherent Innovation Policy to Lead Change

The benefit of investing in the innovation commons should go beyond the boundary of individual actors; as such, consistent and coherent innovation policy is strongly required. Coherence mainly implies that individual policy attributes from various ministries complement each other by being aligned with a single objective. A coherent policy framework enables the market to receive consistent signal for its decision-making (Lee and Baek 2012) and to reduce social inefficiency (Amable 2000). Mazzucato (2011) and Stiglitz et al. (2013) elucidated the various active roles of industrial and innovation policy, but this study suggests the three most relevant policy agendas considering the key components of evolutionary process for concept design.

First, it is necessary to build an enduring financial system that understands the innovation process. As the economy grows, finance tends to pursue profits more strongly. This tendency has weakened the intrinsic role of finance to hedge the risk of trial and error associated with innovative challenges. Finance must be capable of understanding the industry to support trial and error in the industry. To this end, institutional incentives should be strengthened so that internal reserve funds can be turned into investments in new industries rather than being used for treasury stocks or dividends. In addition, by encouraging investments through public offerings, it is possible to make unencumbered funds available to support industrial trial and error.

Second, public procurement can play an important role as a test bed for innovative concept design. The trend of innovation is shifting from technology push to demand pull, and the public procurement of government is large and highly demanding, which can trigger entrepreneurial awareness. Innovative public procurement can contribute to the creation of early market for small and medium enterprises that cannot secure track record by themselves, thereby contributing to the enhancement of concept design capability in industrial sectors that are easily marginalized in the competition for innovation. For this purpose, it is necessary to improve the procurement system so that innovation-oriented public procurement is separated from other types of public procurement to achieve the social purpose and its performance evaluation standard is different to socially accept the honest failure. Furthermore, allocating part of each department's budget to innovation-oriented public procurement may also be considered.

Third, the R&D system should be constructed to enable the concept design to be developed through a scale-up process that verifies an invention for mass production. Because the process of creating a concept design is highly uncertain, it is more effective to proceed step by step, rather than all at once, through perfect planning in the beginning. This is different from a simple repeat of trial and error. Instead, it refers to a process of learning through trial and error, revising the goal based on this, increasing the possibility of success in the next stage, and sharing and internalizing the experience of failure through a public evaluation system so that trial and error can be linked to learning. In this process, open innovation to compress the accumulation of trial and error should also be actively utilized. Collaboration with an organization with complementary competence can reduce time and resources related to trial and error. In order to do this, it is inevitable for universities, companies, and public research institutes to change their research planning, experimental methods, performance evaluation, and cooperation methods.

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5

Economics of Technological Leapfrogging

Keun Lee

5.1 Introduction

One of the key issues in economic development by latecomers is whether they are to follow the same path of the forerunners or to create a new or different path of development (Lee and Lim 2001).[1] Early literature (Lall 2000; Kim 1980; Westphal, Kim, and Dahlman 1985; Hobday 1995) has observed that the latecomer tends to achieve economic development by assimilating and adapting the forerunner's obsolete technology. This is consistent with product life cycle theory (Vernon 1966). However, an emerging view (Lee and Lim 2001; Lee 2013) points out that the latecomer does not simply follow the advanced countries' path of technological development but sometimes skips certain stages or even creates their own path that is different from those of the forerunners. This observation is consistent with the idea of leapfrogging (Perez and Soete 1988) as it states that some latecomers may be able to leapfrog older vintages of technology, bypass heavy investments in previous technological systems or stages, and make preemptive investments in emerging technologies to catch up with advanced countries in new markets. Simply, leapfrogging can be defined as latecomers trying something different ahead of the forerunners, thereby leaping over them.

Several studies have confirmed leapfrogging or path-creating through case studies of catch-up in East Asia (Lee and Lim 2001; Lee et al. 2005; Mu and Lee 2005). Here, catch-up refers to a substantial closing of the market share gap between firms in a leading country and those in a latecomer or follower country. A recent article (Lee and Malerba 2017) and the companion articles published as a special issue in *Research Policy* also examined the cases of catch-up by the latecomers to see if they involved leapfrogging by the latecomers or not.[2] Having observed that many industries have witnessed numerous changes in industrial leadership and in the successive

[1] This is a short and revised version of the background paper prepared for the UNIDO IDR 2020 Report.

[2] The special issue on catch-up cycles includes cases of various sectors, such as that of cell phones, the memory-chip segment of semiconductors, cameras, steel, mid-sized jets, and wine.

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catch-up by late entrants, they called this phenomenon the catch-up cycles, in contrast to the product life cycle (Vernon 1966) which involved only the changes in factory location but not the leadership.

A common finding from this literature is that successful cases of catching-up tend to involve variants of leapfrogging although they may start from imitating and learning from the incumbent at their early stage of catch-up. Similarly, Joo et al. (2016) analyze the data of patent citations of Huawei and Ericsson to see whether a latecomer (Huawei) catches up with the incumbent (Ericsson) by developing different (or similar) technologies compared with those of the forerunner (Ericsson).[3] The result is that Huawei's patents tended to cite those by Ericsson initially but eventually reduced such reliance and created a new path different from the incumbent. So, the catch-up paradox (Lee 2019) is that one cannot catch up (meaning overtake) if s/he continues to work on catching up (meaning imitation). In other words, eventual catch-up and overtaking require latecomer economies to pursue a path that differs from that taken by its forerunners.

In his most recent book, Lee (2019) proposed a comprehensive theory of economic catch-up, consisting of "late entry→ three detours→ leapfrogging," and positioned leapfrogging as the final stage of catching-up after the detour stage of building technological capabilities. The three detours, in terms of innovation, include the following: the first detour is to promote minor innovations via petit patents rather than the high level of innovation via regular patents, the second detour is to increase the share of domestic value-added in exports rather than keep relying on GVCs, and the third or final detour is to specialize in short-cycle technologies rather than long-cycle technologies. Taking detours are necessary because of the two failures (capability and size failures) in latecomer economies and one barrier of IPR protection in the north and small space for intervening policy under the WTO regime. In this theory, leapfrogging is necessary because the detours are not enough to raise the latecomers to the level of high income beyond the middle-income trap situation.

In other words, leapfrogging becomes necessary as a means of bypassing the IPR that forerunners hold by jumping ahead into new generations of technologies. Thus, leapfrogging is highly likely to succeed when executed during a shift in paradigm or generation or during exogenous moments of disruption, which early Schumpeterians, such as Perez and Soete (1988), coined as "windows of opportunity." Finding ways to overcome entry barriers is one of the key motivations for utilizing leapfrogging. A window of opportunity is a moment in time in which the entry barriers for latecomers recede. Meanwhile, Hidalgo et al.'s (2007) concept of product spaces and economic complexity does not consider entry barriers and related competition with the incumbent.

[3] Similar technologies imply that the latecomer simply attempts to imitate the incumbents, whereas different technologies refer to the latecomer seeking to create new technologies and take a different technological path or trajectory from those of the incumbents.

Latecomers tend to experience difficulties because of entry barriers existing in many product areas, and because they have to compete with the incumbents to be able to enter and occupy spaces. Thus, in our dynamics of economic catch-up, the role of leapfrogging is similar to "flying on a balloon when the conventional ladder used to catch up is kicked away" (Lee 2019). As we can only fly balloons under favorable weather conditions, economic leapfrogging becomes successful only when exogenous windows of opportunity are available. Certain preconditions for flying also exist, such as having built-up capabilities meaning driving skills. Otherwise, we may fall to the ground instead of flying into sky.

This chapter provides an updated review of the literature on leapfrogging. Specific topics to be covered include the following. Section 5.2 discusses the origins and variations of the concept of leapfrogging. Section 5.3 discusses why the latecomer economies and firms need to try leapfrogging in terms of its benefits as a strategy for technological development. Section 5.4 discusses the pre-conditions to try leapfrogging and the associated risks of leapfrogging and how to manage the risks. Section 5.5 identifies the three windows of opportunity to try leapfrogging, such as emerging new techno-economic paradigms, changes in demand conditions, and the institutional windows including asymmetric regulation and industrial policies.

Section 5.6 discusses how leapfrogging can be an effective response by the latecomers in preparing for the fourth industrial revolution (4IR hereafter) and to achieve the goals of sustainable development, and illustrates diverse cases of leapfrogging in latecomer economies. Finally, the last section, Section 5.7, discusses the issues of implementing the leapfrogging strategies under the heading of enabling conditions and policies for leapfrogging, and also discusses prospects of leapfrogging-based development. In the last two sections, discussion of policy issues related to leapfrogging will be based on the Schumpeterian conceptual framework, called the NIS (national innovation systems), which is about the relationship among the actors involved in creating, diffusing, and utilizing knowledge and innovations, such as firms, public labs, government ministries, financial actors, IPRs systems, and educational systems (Lundvall 1992). The effectiveness of each nation's NIS would determine the innovative and economic performance of countries, and the wrong response to new innovations is considered as a symptom of system failure which leads to malfunction of the systems.

5.2 What is Leapfrogging: Origins and Variations

The origins of the leapfrogging thesis may be regarded as going back to the idea of the so-called latecomers' advantage by Gerschenkron (1962; 1963) that these countries may adopt and use the technology only after it becomes matured enough to have the standardized capital goods suitable for mass production. However, this discussion was confined to the catching-up in the mature technology. It is Freeman and Soete (1997) and Perez and Soete (1988) that apply the idea with focus on the role of the new technological paradigm which brings forth a cluster of new industries. Their insight is that emerging technological paradigms serve as a window of opportunity for the latecomers not to be locked into the old technological system and thus to be able to grab new opportunities in the emerging industries.

Perez and Soete (1988) discussed the latecomers' advantages for leapfrogging in terms of the following three aspects: entry barrier, accessibility of knowledge, and the possibility of lock-in by the incumbents. First, since the equipment to produce new industry goods is not developed yet, general-purpose machines should be utilized and production volume is small. Therefore, the entry barrier associated with economy scale does not exist. Second, in the initial stage of new technological paradigm, the performance of technology is not stable and not parochial to a firm. Therefore, if there are only the human resources who could access the sources of knowledge and create new additional knowledge, entry into emerging technology can be easier than during the later stage of technological evolution. Third, catching-up countries can be said to be in a rather advantageous position as they are not locked into old technologies whereas the advanced country tends to be locked into old technologies due to the sunk costs of their investment.

It was in Lee and Lim (2001) that the idea of leapfrogging was provided more flesh from the examples from the Korean industries and the concept was further clarified by the concepts of path-following, stage-skipping, and path-creation by the latecomers in their technological development, in which *path* means the trajectory of technologies and *stage* means the stages in the trajectories. Lee and Lim observed that the strategies of path-creation and stage-skipping can be regarded as two variants of leapfrogging.

Following Lee and Ki (2017), these three strategies can be explained in Figure 5.1, which shows the different trends of the productivities (shown at the vertical axis) of technologies of different generations (with the horizontal axis representing time). Let us suppose that the current time is period 91 in Figure 5.1 and that the incumbent firms have adopted the currently most up-to-date, second-generation technology, and are thus enjoying the highest productivity. Therefore, three choices or strategies are available for a latecomer firm that intends to make a late entry.

The first choice is to adopt the first-generation or oldest technology with the lowest price, that is, a path-following strategy, which indicates that latecomers move along the old technical trajectories of incumbents. An advantage of this strategy is that established firms care less about the transfer or leakage of proprietary technologies. Old technologies tend to be readily available at low prices, particularly during business downturns. However, given their low level of productivity, late-entrant firms cannot compete with the incumbent in the same market. Thus, these firms must try to enter a different segment (low-end segments).

The second choice is the stage-skipping strategy, which refers to the case in which latecomer firms follow the same path as that of incumbents but skip older-generation technology (Generation 1 in Figure 5.1) to adopt the most up-to-date technology (Generation 2 in Figure 5.1); this technology is of the same generation as the

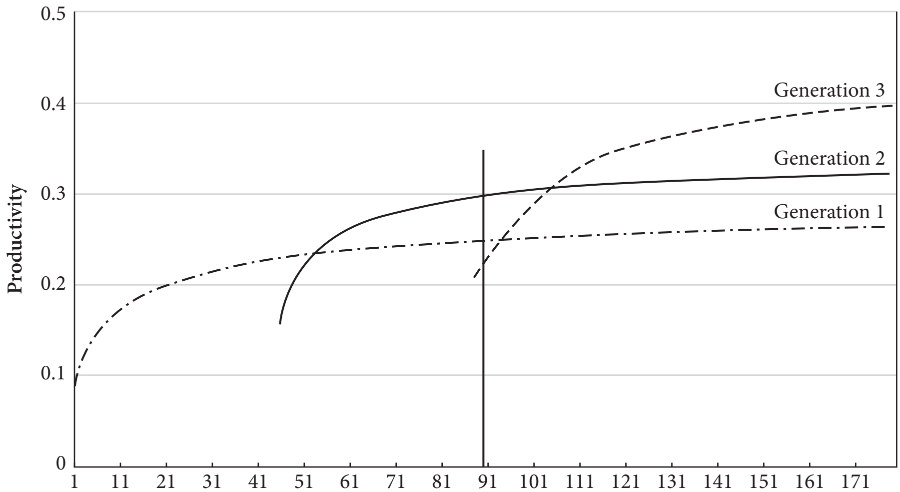

Figure 5.1 Leapfrogging and Path-following Strategies of Latecomer Firms

Notes: Path-following strategy = To adopt the oldest (generation 1) technology.

Source: Lee (2019: Figure 5-1) which is from Lee and Ki (2017), adapted from Lee et al. (2016).

technology of incumbents. Thus, fierce competition may occur between incumbents and late entrants as the latter is to adopt up-to-date technology. Aside from the matter of available financial resources to purchase up-to-date technology, another issue is the market availability of such up-to-date technology or the willingness of an established firm to transfer such technology to latecomer firms (Lee and Ki 2017). In this context, IPR (intellectual property rights)-based protection of technologies may be a barrier for catch-up. Once this matter of technology transfer or acquisition is solved to the benefit of a late entrant, this firm may emerge as a powerful rival because the late-entrant firm not only enjoys the same productivity levels as the incumbent but also utilizes the probably low costs of labor.

The third choice is the path-creating strategy. This refers to the case of a latecomer exploring its own path of technological development by utilizing a new generation of technology. Figure 5.1 shows that, in this strategy, the late entrant chooses the emerging or third-generation technology ahead of the incumbent. This strategy is consistent with the idea of leapfrogging discussed by Perez and Soete (1988). An apparent advantage of this path-creating or leapfrogging is that this strategy is focused on technologies with high long-term potential or productivity as shown in Figure 5.1. However, a risk is that the emerging or new technology is neither stable nor reliable, and it has low productivity or high costs at its early stage as shown in Figure 5.1. Despite the high potential of this emerging technology, a firm that adopts the technology has to endure high costs. Thus, losses during the initial stage in the market might be incurred.

As explained in Lee and Ki (2017), the preceding idea is consistent with theory of S-curves (Foster 1986), which states that the inferiority of a new technology at its first appearance discourages incumbents from introducing the new generation of technology. In this sense, a new technology can be a source of the incumbent trap and a window of opportunity for latecomers that are free from the "replacement effect of new technology" (Arrow 1962). In other words, incumbent firms tend to ignore, by rational calculation or mistake, emerging technologies with potential, and these firms remain complacent with high productivity from current technologies. Although this choice may be rational in the short run, incumbent firms may lose out to other firms that take the risk of adopting emerging technologies and eventually attain higher productivity, thereby winning the market from incumbents.

Interestingly, not every firm, but probably late entrants or inferior firms with productivity levels that are lower than those of the leading firm, have many reasons to shift rapidly to new technologies. In this sense, latecomers have a greater incentive than incumbents to take the risk of adopting new technologies. However, even such risk-taking by latecomers usually requires initial support from the government. Without subsidies or incentives, few latecomer firms would take the risk of adopting emerging technologies because they tend to face small or weak demand during the initial entry stage and thus would have a hard time achieving the initial production volume that would enable some degree of scale economy.

Thus far, technologies are treated as exogenous, and firms, especially latecomer firms, are treated as if they are facing the binary choice of adopting new technologies or not. However, latecomers usually not only assimilate the adopted technologies but also improve them substantially, an approach that is often called *follow-on innovation*, *incremental innovations*, or *reinvention* (Lee and Ki 2017). Rogers (2003) observed that reinvention occurs at the implementation stage for numerous innovations and for many adopters, and reinvention leads to an increased rate of adoption of an innovation. Following this line of thought, we can conceive of two types of path creation depending on whether a new path is created by in-house, endogenous innovation activities by the latecomers, or by adopting the exogenous or supplier-driven innovation earlier than the incumbents do and then further improving the adopted technologies. The former type may be common in product innovation or IT sectors, such as semiconductors, whereas the latter type may be relevant in process-innovation-prone sectors, such as the steel industry, and can be termed the *adoption and follow-on innovation mode*.[4]

Another dimension of leapfrogging can be conceived in terms of inter-sectoral and intra-sectoral leapfrogging depending upon whether it is happening with the same sector or across different sectors. The inter-sectoral leapfrogging is, to a certain extent, similar to "long jump" in Hidalgo et al. (2007) which argues that latecomer economies must shift to core product spaces that are located far away from their current or periphery position. By contrast, intra-sectoral leapfrogging involves jumping across generations of technologies within the same sector. Intra-sectoral leapfrogging is easier or less risky than the inter-sectoral long jump, as long as

[4] This observation was suggested by Martin Bell as a comment to the paper of Lee and Ki (2017).

Table 5.1 Variations of technological leapfrogging

1) Compared with the Path of the Incumbent (Lee and Lim 2001)
a) Stage-skipping
b) Path-creating
cf) Path-following catch-up
2) Two variations of Path-Creating Leapfrogging (Lee and Ki 2017)
a) Follow-on Innovation-Based Leapfrogging
b) Radical Innovation-Based Leapfrogging
3) Inter- vs. Intra- Sectoral Leapfrogging (Lee 2019)
a) Intra-sector Leapfrogging
b) Inter-sector Leapfrogging

Source: the author.

latecomers have already built certain absorptive capabilities, such as manufacturing experiences, in the given sectors.

Table 5.1 below summarizes the above discussion on the several variations of the concept of leapfrogging.

5.3 Why the Latecomers Need it: Two Reasons

The two reasons for latecomers to try leapfrogging can be discussed in what follows. First of all, one theoretical point is the possible diminishing of the so-called catch-up effect as the latecomers get close to the frontier. At the earlier stage of development, many immediate benefits can be obtained by learning from and copying the practices of forerunning economies as suggested by Lin's theory of latent comparative advantages (Lin 2012). However, these low-hanging fruits may be depleted, and some economies may need to reach high-hanging fruits with much effort or fewer marginal benefits. Eventually, an economy may need to grow its own fruits, and growing fruits that taste differently from those grown by others may be even better because in such a way, an economy does not have to compete directly with others.

The above point is related to the concept of the "catch-up paradox" introduced in a book by Lee (2019). This paradox states that "you cannot catch up if you just keep catching up," where the former "catch up" means closing the gap between you and your targets, while the latter "catch up" means imitating your targets. This idea makes sense because if the latecomer keeps following the same path taken by his/her forerunners, then the latecomer cannot easily catch up or overtake them. In other words, the inferior cannot beat the superior if the former fights using the same weapon or strategies. In the old fable, David was able to beat Goliath by using a different weapon instead of engaging in physical contact. Another analogy can be made by referring to Xenon's paradox, which is also introduced in Lee (2019). This paradox explains how Achilles cannot overtake a turtle in a marathon by referring to the gradual exhaustion of the catch-up effect, which is observed as the latecomer gets closer to the target. Therefore, the latecomer must find an alternative path to free itself from the exhaustion of the catch-up effect.

The latecomer may also try taking a shortcut. However, this shortcut may become crowded when it becomes known to everybody, thereby jamming the latecomer in the road and preventing him/her from reaching the goal. This phenomenon is similar to the so-called adding up problem (Spence 2012; Lee and Ramanayake 2018), in which latecomer economies all try to export the same or similar products, thereby flooding the market and ending up with record-low prices. As an alternative, these economies may take detours that may be longer yet less crowded than the main path, thereby allowing them to move fast if they have innovation capabilities.

The second reasons for latecomers to try leapfrogging has to do with the barrier of IPR protection by the incumbents against the possible imitation and imitative creation efforts by the latecomers (Lee 2019; ch. 2). Under the auspices of the World Trade Organization (WTO), free trade has been promoted as a vehicle for world economic development. The WTO also regulates and provides guidelines for IPRs through the Trade-Related Aspects of Intellectual Property Rights (TRIPS) agreement, which represents the most extensive multilateral agreement toward the global harmonization of IPRs by setting out minimum standards for protection across member countries. One impact of TRIPS is that developing countries have increased their level of IPR protection to reduce the gap in the IPR protection level of developed and developing countries by 2005. The impacts of the expansion and enforcement of global IPRs contribution to export growth might be different because developed and developing countries correspond to different stages and mechanisms of economic development. Specifically, many exporting firms in the developing world tend to incur high costs when adapting to TRIPS obligations, and the strict enforcement of IPR laws in developed countries may curb the imports from developing countries because the latter's exports is negatively affected when they are too imitative in nature or are invented around existing products.

According to Shin et al. (2016), the US International Trade Commission (US ITC) has witnessed a fourfold increase in IPR-related disputes against foreign imports over the past two decades, and, interestingly, more US firms have complained against IPR violations than against unfair dumping, thereby highlighting the increasing importance of IPRs as a measure of trade protection. In fact, the entry of Korean firms into the US market has been marred by the patent disputes between US and Korean firms since the mid-1980s. One of the most noteworthy cases is the ban on Samsung's computer chip exports imposed by the US ITC for violating the patent rights of Texas Instruments.[5] A leading high-tech firm from China, Huawei, also had a serious patent dispute with Cisco in 2011, thereby explaining the weak performance of Huawei's main product (telecommunication switches) in the US market.

[5] For details, see Lee and Kim (2010).

Although Samsung and Huawei are big businesses with many resources to handle such disputes, solving these disputes can be a matter of life of death for SMEs as shown by the examples from Korea.[6] If SMEs are entangled in IPR lawsuits, then the litigation usually hurts these firms in many ways and not only in terms of sales. Prohibitive patent license fees and marketing channels can be lost during the extended lawsuit period. Given these difficulties, most SMEs are highly concerned with patent lawsuits especially during the stage when they are starting to develop a new technology. In one survey, the Korean SMEs in the semiconductor equipment sector answered that while the localization of intermediate materials and goods is not difficult (which feasibility they estimated as "very high" (40.9 percent) and "high" (59.1 percent)), they regarded "IPR-related legal disputes" (64.3 percent) as the biggest obstacle to localization.[7]

The implication of these incidents is that the possibly negative impact of the levels of IPR protection in the North may be greater for rapidly catching up developing countries than for low-income countries with very low technological capabilities, weak export performance, or exports that are arranged by inter-firm trade in the form of contract manufacturing and FDIs. Such reasoning has been verified by the extensive econometric analysis in Shin et al. (2016), who found that as the IPR level of an importing country increases, the net marginal effect of technology on exports decreases, especially in the case of exports by those countries in which technological levels are currently catching up. This finding implies that the strong IPR protection is the North acts as an obstacle to exporting from the South, which countries are currently catching up in terms of their level of technology. In this sense, IPR protection is identified as a source of MIT.

Given the situation that the IPR protection by incumbent economies and firms has acted as a barrier against the technological catch-up by the latecomers, one fundamental way to overcome this barrier is not to follow the same technological trajectory of the incumbent to avoid IPR disputes but to create a new path, take a detour, or try leapfrogging. In general, this means that the latecomer must make eventually a transition from imitation to innovation. In this regard, an interesting case can be that of Huawei, a leading IT company in China.

One study used patent citation data to investigate the catch-up of Huawei in China with Ericsson in Sweden, and found that Huawei relied on Ericsson as a knowledge source in its early days but subsequently reduced such reliance and increased its self-citation ratio to become more independent.[8] The investigation of mutual citations (direct dependence), common citations (indirect reliance), and self-citations strongly indicate that Huawei has caught up with or overtaken Ericsson by taking a different path. Moreover, unlike Ericsson, Huawei developed its

[6] These SME cases are taken from Kim and Lee (2009).

[7] A survey conducted by the Center for Corporate Competitiveness of Seoul National University in 2004 (Kim and Lee 2009).

[8] The study of this leading IT company from China is done in Joo et al. (2016).

technologies by relying on recent technologies, which resulted in a patent folio with short citation lags (which means that its technologies have a short cycle). Huawei also relied heavily on scientific knowledge (so-called non-patent literature), which is a public good that is free from IPR disputes with the incumbents. The citations to non-patent literature and the patent folio with short citation lags all imply that Huawei has extensively explored basic research and maintained up-to-date technologies to accomplish a technological catch-up, thereby avoiding another patent dispute with incumbent firms.

Overall, the examination of successful catch-ups (or overtaking cases) in East Asia suggests that exploring a technological path that differs from that taken by forerunners presents a possible and viable catch-up strategy for latecomers, and, in this sense, a "necessary" condition for overtaking. However, this strategy is not a sufficient condition as it involves a higher amount of risk (than going along a straight yet probably jammed road) and may end up in failure or accidents along the road. We turn to this issue of risks involved in leapfrogging in the next section.

5.4 One Pre-Condition and the Two Risks of Leapfrogging

5.4.1 Pre-condition for Leapfrogging

As discussed in the Introduction, leapfrogging is like "flying on a balloon when the conventional ladder used to catch up is kicked away," and then a certain precondition for flying does exist, that is, having built-up technological capabilities. Without such capabilities, one may fall to the ground instead of flying into the sky. However, it is not easy to build such capabilities which are quite different from production capabilities. Thus, although consolidating technological capabilities has long been suggested by many as a vital component of economic catch-up, guiding details for this process are lacking. Lee (2019) has thus suggested the three detours in building capabilities.

Latecomer economies must take detours because of the presence of two failures and one barrier: firm capability and size failures and IPR (intellectual property rights) protection from the incumbent North, respectively. Firm capability failure refers to the intrinsic difficulty of building innovation capabilities in developing countries. This type of failure radically differs from conventional market failure which states that R&D subsidies help achieve optimal (or increased) R&D amount. This view is valid only under the hidden assumption that firms are already capable of conducting R&D. Otherwise, or under the lack of such capability, nothing will happen even with increased incentives or subsidies. A similar criticism applies to the notion that strong IPR protection leads to further innovation, which is true only under the assumption that the firm is already equipped with innovation capabilities.

Size failure refers to the lack of world-class businesses in developing countries that are currently filled with SMEs, which are considered insufficient in leading a country toward a high-income status. The existence of these "two failures and one barrier" has necessitated latecomer economies to explore a new path or detour in building their innovation capabilities instead of replicating practices employed by advanced economies.

The first detour promotes imitative innovation under a loose IPR regime in the form of petit patents and trademarks instead of promoting and strengthening regular patent rights. The second detour focuses on global value chains (GVCs), specifically a non-linear sequence of the first increased, then reduced and increased GVC. In contrast to Baldwin (2016) who states that increased GVC participation is preferable, Lee (2019) and Lee, Szapiro, and Mao (2018) warns against such a linear view. Instead, they suggest a GVC-related detour, in which an economy should initially learn by participating at the GVC but should later reduce its reliance on these chains at a certain point by building increased domestic value chains in sequential entries into high-end segments. Otherwise, the latecomers would remain at low value-added segments, which is a middle-income trap (MIT) symptom. The third detour means specializing first in short-cycle technology-based sectors and products (i.e., ITs) and, only at a later stage, in long-cycle sectors and segments (i.e., pharmaceuticals). Long-cycle technologies means that previous knowledge remains useful and important for a long period of time. Such technologies act as entry barriers against latecomers although they denote high profitability and thus, desirable attributes. Therefore, latecomers are advised to target short-cycle technologies, where entry barriers are low but growth prospect is good because of high innovation frequency that often disrupts the dominance of the incumbent.

In other words, the pre-condition for leapfrogging is to correct capability failure by providing latecomers with learning opportunities in order for them to enhance their innovation capabilities. Then, a starting point for a latecomer firm to build innovation capabilities is to establish its own in-house R&D center. Independent R&D efforts are required because foreign firms become increasingly reluctant to grant technology licenses to the rising latecomer firms, especially when the latter attempts to enter the higher value-added or profitability markets that are dominated by advanced countries. By establishing in-house R&D laboratories, firms may explore diverse channels of learning and access foreign knowledge beyond simple licensing. Accessing foreign knowledge and trying new modes of learning are crucial because isolated in-house R&D efforts are often insufficient in building indigenous R&D capabilities. A diverse set of alternative modes of learning is available, including co-development contracts with foreign R&D specialist firms and/or with public R&D institutes, mastering the existing literature, establishing overseas R&D outposts, and initiating international mergers and acquisitions (M&As).[9] For example, since the early 1990s, a small number of Korean firms began to establish

[9] For details on these diverse learning modes, see Chapter 3, Section 2 of Lee (2019).

overseas R&D posts to obtain easy and fast access to foreign technologies that cannot be easily acquired through licensing.

Only after building certain level of technological capabilities along the detours, the latecomer firms are getting ready to take the risk of trying leapfrogging.

5.4.2 The Two Risks Involved in Leapfrogging

One early paper (Lee et al. 2015) identified the following two risks involved in leapfrogging. The first kind of risk is that of choosing right technologies out of several possible emerging standards, and the second risk is how to create the initial market after the choice of technology to produce new goods.

In the early stage of technological paradigm, there tend to be available alternative technologies, among which one dominant or successful technology shall emerge eventually in the later stages. Therefore, if the catching-up country invests in wrong technologies, the country will fail in gaining returns from investments. Next, even after the catching-up country becomes successful in choosing the right technology, it still needs to be successful in competition with other competitors from the advanced country. What follows discusses each of these two risks and how to manage the risk, using the example of the classical case of leapfrogging which happened in the TV industry of Korea (Lee et al. 2005) and also in cell phones (Lee and Lim 2001).

5.4.2.1 The Risk of Choice over Alternative Technologies

When the Koreans decided to enter the high-definition (HD) TV technology, they faced tough choices regarding technology standards. Initially, they were heavily influenced by the Japanese leaders in analogue HD TV. The Japanese group arrived in Korea during the 1988 Seoul Olympic Games and staged a promotional tour of their achievement in the hope that the Koreans would follow them as in the past. Recognizing that HD TV would be a next-generation hot consumer item with immense technological and market potential, the Korean government established the Committee for Co-development of HD TV in 1989 with the participation of seventeen institutions comprising private firms, GRIs (government research institutes), and universities.

One year after Korea began the project, GI in the United States, a leading firm in digital TV technology, staged a historic demonstration of the possibility of digital TV in 1990. At the turn of this event, the Korean consortium decided to target digital HD TV instead of the Japanese developed analogue HD TV. However, the US standard was not yet determined at that time. In this regard, one interesting strategy by the Korean team was the decision to develop several alternative standards simultaneously, with different private companies in the team assigned to watch and follow different standards. This strategy can be called a "parallel mover" in comparison with the first-mover strategy. Immediately after the so-called "grand coalition" agreed to a common standard for digital TV, the Korean firms became a first mover in terms of launching their first digital TVs compatible with the common standard in the US markets.

In terms of access to foreign knowledge, Korean firms have been closely monitoring the technological activities of GI and other leading firms in the United States. As early as September 1989, Samsung first established an R&D team for digital TV and a US branch (AML: Advanced Media Lab) in Princeton, New Jersey. In the case of LG, as early as 1990, it acquired a minor share of 15 percent of Zenith, a US company with a core technology in digital TV as early as 1990. LG eventually acquired 100 per cent of equity of Zenith and was able to use the patented technology without fear of patent violation.

Another case of leapfrogging by the Korean consortium was cell phones, one of the most successful cases of a path-creating or leapfrogging event led by the private–public collaboration. When the Korean firms and the government authorities considered entry into this sector, the leader was the US firm Motorola, and the analogue system was dominant in the United States, whereas the TDMA-based GSM system was the dominant system in Europe. However, the Korean authorities (i.e., the Ministry of Information and Telecommunication) considered an emerging alternative of CDMA technology with higher efficiency in frequency utilization and higher quality and security in voice transmission. Thus, despite great uncertainty in the development of the world's first CDMA system as well as the strong reservations expressed by the telephone service provider and private manufacturers (e.g., Samsung and LG), the Ministry and the Electronics and Telecommunication Research Institute (ETRI) decided to support the CDMA. One of the main reasons for the decision is the consideration that if Korea merely followed the already established standards, the gap between Korea and its forerunners would never be reduced and thus catching up would take even longer. Thus, Korea chose a shorter but riskier path.

The Korean government first designated the CDMA system development as a national R&D project as early as 1989. In 1991, the contract to introduce the core technology from and to develop the system together with the US-based Qualcomm was forged. In 1993, the Ministry declared CDMA to be the national standard in telecommunication. Given the high frequency of innovation and the high fluidity of trajectory, the telecommunication industry does not provide the latecomers any incentives for R&D effort. Expected profits and other related gains from first-mover advantages served as a strong attraction, and the high risks were shared by the government-led R&D consortium and knowledge alliance with Qualcomm. The ETRI also contributed to reducing technological uncertainty by providing accurate and up-to-date information on technology trends and by identifying the correct R&D targets that were more promising than alternatives.

5.4.2.2 The Risk of Finding the Initial Market

In mitigating the second risk of the existence of initial markets or not, we may first emphasize the importance of standard which is a critical factor in the market success of the new innovations, in particular digital technology. When the involved products are in the area of information or other emerging technology, an isolated development that does not pay attention to the issue of standards might lead to a failure of the whole project. In standard setting, collaboration and getting partnership with rivals or suppliers of complementary products are important. Also important is who creates and gets to the market first, as the size of the market determines the success or failure of one standard against other. Again, in this competition for standard setting and market creation, the role of the government can be noted as it can play the role of facilitating the adoption of specific standards and thereby influencing the formation of markets at the right times.

5.4.2.3 Implications: Public-Private R&D Consortium and the Incumbent Trap

The above cases of digital TV and mobile phones in Korea demonstrate how the emerging new technological paradigm can serve as a window of opportunity for the catching-up firms.[10] Actually, a long list of success with the public–private R&D consortium, from digital telephone switches to memory chips (D-RAM), wireless phones (CDMA), and finally digital TV in Korea, confirms the positive role of the government and the GRIs in technological catch-up by the latecomer firms. The private firms that participated in the public–private consortium all acknowledged the important function of the government in providing legitimacy to the large projects that are often difficult for private firms to support. The consortium also served as a field to pool together the domestic resources from various sources, especially resources in the universities. The contribution of public research laboratories is also critical in conducting the role of "technology watch" to interpret and monitor the state-of-the art trend of R&D activities in foreign countries.

In the meantime, the reasons why the Japanese digital TV producers became laggard toward Korean digital TV producers can be discussed in terms of the concept of the incumbent's trap. Japan was locked into "analogue" HD TV since the 1980s as it created the first HD TV system in the 1980s. Although the Japanese government attempted to shift to digital TV in 1994, the effort was stifled by the firms that invested greatly in analogue HD TV. This early start and lock-in by the Japanese firms signify the disadvantages and risk of being the technological pioneer, which is close to the so-called innovator's dilemma proposed by Christensen (1997). Japan was the forerunner in taking initiatives toward HD TV, but it was along the trajectory of analogue technology. However, Japan's merits turned into debt as the United States and other countries accepted the digital TV as the standard, and the latecomers decided to follow this trajectory. In this sense, this case eloquently demonstrates that shift of technological paradigm can penalize the leader while serving as a window of opportunity for latecomers who command complementary assets for using a new technological opportunity.

[10] These implications are also explained in Lee et al. (2005).

5.5 Three Windows of Opportunity for Leapfrogging

The preceding sections observed that leapfrogging involves latecomers accomplishing something ahead of the forerunners, thereby leaping over them. Thus, leapfrogging is highly likely to succeed when executed during a shift in paradigm or generation or during exogenous moments of disruption, which early Schumpeterians, such as Perez and Soete (1988), coined as "windows of opportunity." A window of opportunity is a moment in time in which the entry barriers for latecomers recede. Latecomers tend to experience difficulties because of entry barriers existing in many product areas, and because they have to compete with the incumbents to be able to enter and occupy spaces. Thus, in our dynamics of economic catch-up, the role of leapfrogging is similar to "flying on a balloon when the conventional ladder used to catch up is kicked away." As we can only fly balloons under favorable weather conditions, economic leapfrogging becomes successful only when exogenous windows of opportunity are available.

The concept of leapfrogging has been also utilized in the theoretical framework called "catch-up cycles" developed by Lee and Malerba (2017), which pertain to successive changes in industrial leadership. Many industries have witnessed numerous changes in industrial leadership and in the successive catch-up by late entrants. The incumbent often fails to maintain its superiority in production or market shares, and a latecomer catches up with the incumbent. The latecomer who gains leadership then loses to another latecomer. In addition to the lead article by Lee and Malerba (2017), attempts to explain these phenomena are sectoral studies collected in a special issue on catch-up cycles published in *Research Policy*, which includes cases of various sectors, such as that of cell phones, the memory-chip segment of semiconductors, cameras, steel, mid-sized jets, and wine.

The framework of catch-up cycles originated from the belief that product life cycle theory of Vernon (1966) cannot explain the phenomenon because the theory merely focuses on the location change of factories from advanced to developing countries, and leadership is assumed to remain with firms from advanced countries. The catch-up cycle concept is based on Schumpeterian notions of innovation systems applied at the sector level and on the evolution of these systems over time.[11] Several discontinuities may occur during such an evolution of systems. These discontinuities are called windows of opportunity, which refer to the role of the rise of new techno-economic paradigms in generating leapfrogging. These windows of opportunity can be extended to additional dimensions corresponding to the building blocks of a sectoral system, such as changes in demand conditions or in regulation and policies by the government.

Three window types can be opened for late entrants. One is the rise of a new techno-economic paradigm that tends to threaten the advantage of existing first

[11] For the concept of the national systems of innovation, see Freeman (1987), Lundvall (1992), Nelson (1993), and for the SSI, see Malerba (2002, 2004) and Malerba (2005).

movers or incumbents involved in investment in the existing capital vantage. When a new paradigm arrives, latecomers and incumbents stand by the same starting line with the new technology. However, incumbent may fall behind by grasping onto old technology, with which they hold a dominant position. The propensity for incumbents to remain with the old paradigm for a prolonged time can be considered rational as they considerably invested in it. Thus, incumbents want to fully recover their investment costs. Depending upon the situation, instead of the full=scale techno-economic paradigm shift, a mini-paradigm, a new generation of technologies, or a new trajectory, can be a such window.

The second window of opportunity type is derived from the secondary components of SSI (i.e., demand conditions or market regimes), that is, a business cycle and/or abrupt change in market demand, including the rise of new consumers. Mathews (2005) indicated that business cycles create opportunities for challengers to rouse the industry as downturns play a cleansing role. Thus, weak players are forced into bankruptcy, and resources are released at low prices to be acquired by challenger firms aiming to enter the industry. These demand changes can be exogenous or intrinsic to the sector but exogenous to firms (e.g., the short-term cyclical behavior of prices of IT-sector memory chips and panels).

The third window of opportunity can be opened by the government. This opportunity usually generates an asymmetric environment for incumbents and entrants through a range of regulations and supportive actions for entrants. Latecomers can utilize such asymmetries to offset initial cost differences associated with late entry.

Although the three types of windows of opportunity are assumed to be events that are often exogenous to latecomer firms, the firms should recognize and take advantage of these open windows to realize their potential. In other words, together with the notion of windows of opportunity, the catch-up cycle framework also uses the concept of "responses" by firms and systems at sectoral or national levels. A few firms from emerging countries and the sectoral system supporting them may respond to the opening of windows and then successfully catch up or rise in local or global markets. Current leaders from a certain country may fall behind due to a lack of effectiveness in firm and sectoral system response, such as in "incumbent trap" behavior, leading to misalignments with the new window. The gist of our theory is that diverse combinations of windows of opportunity and the responses of firms and sectoral systems of latecomers and incumbents determine the pattern of successive catch-ups that most likely emerge in a sector.

5.5.1 Two Industry Cases

It is also interesting to see that one or more windows come into play in a single sector over evolution of sectors. Here some example stories of some sectors are in order, starting from a case of steel industry. The steel industry has experienced two leadership changes (Lee and Ki 2017). The first change was from the US to Japan in the late

1970s and early 1980s, and the second was from Nippon Steel in Japan to POSCO in South Korea during the late 1990s.

In this steel sector, the leadership shift from the US to Japan involved the technological and institutional windows but not the demand window. Japanese firms immediately adopted the Austrian innovation of the basic oxygen furnace method (BOF) that they further improved through follow-on innovation (Yonekura 1994). The Japanese government was also involved because it arranged the collective licensing of BOF for significantly reduced royalty fees (Nakamura and Ohashi 2012). In contrast, the US firms fell into an incumbent trap of remaining with existing methods (OHF).

Then, in the rise of the Korean steel company, called POSCO, the downturns in the global steel industry provided windows of opportunity for this latecomer. POSCO first initiated gradual catch-up from the low-end segment, adopting a path-following strategy of importing mature technologies from Japan, and then switched to the stage-skipping strategy for forging ahead by adopting up-to-date technology and capitalizing on downturns. The demand window in this case was significant because POSCO purchased state-of-the-art technologies at considerably low costs as a result of the global recession in the 1980s (D'Costa 1999). The institutional window was also present for POSCO because the government participated in indicative planning for the growth of steel-consuming sectors, such as shipbuilding and automobile sectors. Eventually, POSCO, outperformed its "teacher" firm, Nippon Steel, in Japan in the late 1990s.

The POSCO case indicates that not upturn but downturn in business cycle can be a window of opportunity that allows latecomers to purchase and install state-of-the-art technologies at lower costs because of the downturn. The role of downturns was also noted in semi-conductors in the study of Shin (2017), which indicated that the Japanese firms (in the 1980s as late entrants to the US firms) and then the Korean firms (in the 1990s as late entrants to the Japanese firms) conducted aggressive investment during the downturns, while the incumbent firms were more cautious in their investment.

It is also worthwhile to look at the case of the cell phone sector. Giachetti and Marchi (2017) found that leadership change in the cell phone sector occurred twice, with an interval of fourteen years. The first change was in 1998 when Nokia and its digital cell phones dethroned Motorola, which invented analog cell phones. The second leadership change occurred in 2012, during the transition from regular cell phones to smartphones, when Samsung, together with Apple, dethroned Nokia in market shares.

In the cell phone sector, technological change was the most significant window of opportunity in both leadership change incidents. The emergence of digital technology was the window of opportunity in the transition from Motorola to Nokia, and the change from regular phones to smartphones was the significant window of opportunity in the transition from Nokia to Samsung. Unlike previous mobile operating systems, such as the Symbian of Nokia, the Android OS of Google was custom-built to support the touch interface that gained popularity among consumers. The first mobile phone vendor that incorporated the Android OS was Samsung. The demand window was significant in the first leadership change as individual phone users increased instead of business users, and the institutional window associated with the exclusive support of EU for digital GSM standards compared with the support of the US for multiple standards. In the transition from Nokia to Samsung, the role of the demand or institutional window was unclear during the forging-ahead stage in 2000, whereas the entry and gradual catch-up of Samsung in the 2G era in the 1990s were facilitated by regulatory intervention by the Korean government that established the code division multiple access (CDMA) as exclusive standard in Korean market.[12]

In general, the stories of catch-up in several sectors (Lee 2019, Ch. 5) suggest that although the path-following strategy based on initial factor–cost advantages may permit the gradual catch-up of the late entrants' market shares, a sharp rise of the latecomers' market shares is more likely to occur with a shift in technologies or demand conditions (particularly downturns). These shifts are facilitated by variants of leapfrogging, either by path creation or stage skipping by latecomers. Decisive investment on the opening of new windows irreversibly changes the leadership of the industry, namely a forging ahead, which pushes the old incumbent towards the cliff of falling behind. Windows are always likely to open because generations of technologies and business cycles change frequently. Therefore, leadership change and catch-up by latecomers can be predicted to occur repeatedly. The decline of leadership can be predicted not only from the rise of latecomers but also from the "falling into trap" behavior of the incumbent. That is, leaders tend to be complacent with the current success and pay less attention to the emerging technological or market paradigm, including new types of consumers.

5.6 Leapfrogging for the Fourth Industrial Revolution and Sustainable Development

5.6.1 Leapfrogging for the Fourth Industrial Revolution

With the arrival of the fourth industrial revolution (4IR) noted by Schwab (2016) at the 2016 World Economic Forum, the question and challenge today is whether the next generation of latecomer economies can also use manufacturing as a path to prosperity. The 4IR refers to the new waves of innovations consisting of several technologies comprising 3D-printing, IoT (Internet of things), AI (artificial intelligence), Smart car, big data, and on-demand economy (sharing economy), but could include smart health, renewable energies, and VR (virtual reality) technologies which are not much mentioned in Schwab's book.

[12] See Lee and Lim (2001).

Thus, it can be said that the existing mode of economic catch-up faces many challenges with the arrival of the 4IR in several aspects (Lee et al. 2019). First, the fourth industrial revolution is re-writing the rules of manufacturing. As the cost of automation plummets, low-cost labor is a less effective strategy to attract manufacturing investment. Second, with the 4IR, we see possibly the beginning of a trend towards re-shoring of manufacturing back to the rich world (e.g., Apple in the US and Adidas making shoes in Germany). Third, some expect global supply chains would become flatter, and more regional and even national in order to reduce delivery times and to make manufacturing more responsive to local tastes and local demand conditions. This potentially reduces the level of economies of scale required for the producing for the whole world.

The ride and response of latecomer economies to these challenges would determine their eventual economic fortune. Those capable in performing new innovations would take advantage of the 4IR as a new window of opportunity (Perez and Soete 1988), while those who are unable would see it as window of falling behind (destruction) and be stuck in the low-income or middle-income trap (Lee 2013). In Schumpeterian economics, this 4IR can also be considered as an arrival of the new techno-economic paradigm, and thus could also be a window of opportunity for latecomers to leapfrog. At the moment, most 4IR technologies tend to be initiated not by latecomers but by the advanced economies, and also the response by the latecomer economies have been perceived as slow or in smaller scale (ILO 2016a). To the extent that this is true, the 4IR seems to be a counter-attack by the incumbent countries against the recent catch-by the latecomers, in particular against those in East Asia. In other words, the incumbent and latecomers do not stand at the same start line, but the former has already departed from the line, leaving the latter behind again.

Despite the above conjecture, it still seems necessary to explore the possibility of the 4IR becoming a window for the latecomer economies and how they should prepare for the 4IR revolution so as not to be stuck in the development trap. In general, we do not think it is already too late but there is still time left to respond and take strategic actions. Ideally, while the 3IR was a window of opportunity for the first tier Asian economies, there is a possibility that 4IR can be so for the next tier latecomer economies.

Another dimension of the window of opportunity implied by the 4IR can be discussed in terms of startups and young SMEs versus incumbent firms in emerging economies. In other words, the 4IR can be a new window of opportunity more for startups and young SMES than incumbent firms in emerging economies in the sense that the latter firms are more like to be locked in, or be complacent with, existing technologies or business models, or to respond with inertia and a lukewarm attitude toward new technologies. In contrast, new firms have no or less sunk investment in old or exiting modes of technologies and business models and thus are more inclined to try, or switch to, new technologies and business models.

Now, given that the scope of the 4IR is very broad and many of the related technological revolutions are not happening very much in developing countries, one may define the 4IR flexibly. In this context, the concept of industry 3.0 (automation) and industry 4.0 (smart factory) would be more relevant for countries with some manufacturing basis. As a matter of fact, typical factories in developing countries are at the stage of industry 2.0 or mass-production stage, and thus even the automation (industry 3.0) has not progressed much, not alone transformed into a Smart Factory or industry 4.0 (ILO, 2016a: 4 and ILO, 2016b: 3). In general, the 4IR is expected to expedite the transition from mass-production (industry 2.0) to automation or leapfrogging into the Smart Factory system (industry 4.0).

Even if one takes the option of leapfrogging, it should be carefully managed because it comes together with both potentials and risks (Lee et al. 2005). As discussed in the preceding section, the primary risk has to do with the choice of right technologies or standards. For instance, regarding 5G, we are seeing the emergence of multiple standards. While Korean and US companies are about to launch the world-first 5G services and the associated cell phones, there exist differences in specifications of the standards. While Korean firms, like Samsung and LG, are preparing to produce the full scale 5G-compatible phones, the Verizon and Motorola team may launch LTE phones that may insert 5G module chips. In contrast, Chinese firms, like Huawei, are reported to opt for a different standard, called 5G Advanced, which is supposed to be a further improved version of the 5G products first released in 2019. The possibility of diverse 5G standards might affect the choices of firms which plan to launch new products or services associated with 5G, such as health-related wearables, autonomous driving solutions and products, drones and other IoT-based products and services in Smart Factory systems.

In the meantime, an ILO study also illustrates both the opportunity and threat side of robotic automation. An ILO study of the sector finds that robot-based automation is basically "human centric," occurring in the form of collaborative robots, or "cobots," able to perform repetitive, high precision and difficult tasks, and thus this automation aids workers rather than replaces them (ILO 2016a: 32 and xx). Thus, the report by ILO determined that people still exceed the capabilities of robots in overall assembly, perception, flexibility, dexterity, and adaptation to new duties, which means human workers are (for now) more cost effective. However, the threat side is also there because compounded with predicted uptakes in 3D printing, displacement of lower-skilled packaging and assembling jobs is possible.

5.6.2 Leapfrogging for Sustainable Development

Another impetus for leapfrogging can be discussed in terms of the global consensus toward sustainable development for which leapfrogging can serve as an effective way to switch to an environment-friendly, sustainable, mode of development (Lee 2019, Ch. 7). Figure 5.2 below shows the so-called Environmental Kuznets Curve, where

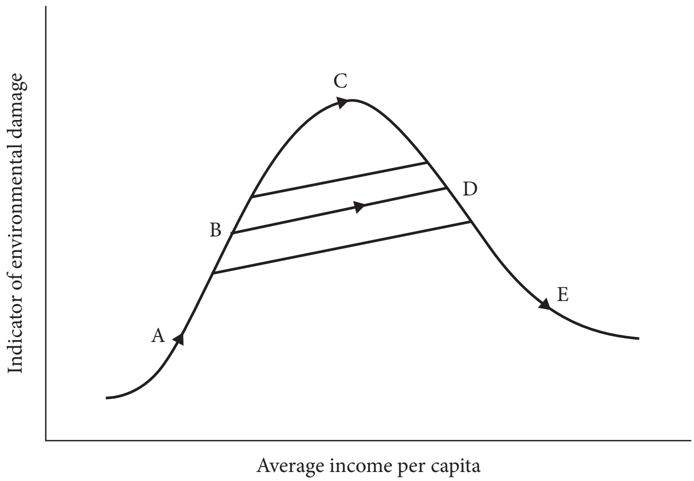

Figure 5.2 Leapfrogging and the Environmental Kuznets Curve
(Redrawn by the author following the graph in Jackson and Roberts, 2000: copied from Figure 7–1 of Lee 2019).

the degree of environmental damage is measured along the vertical axis and with per capita income on the horizontal axis. The idea of this curve is that increasing environmental damage is expected with the initial rise of per capita income. Environmental damage may be mitigated after a certain point of growth of the income levels. Given this path of the forerunning economies, if all current latecomer economies continue to follow the path of the existing economic model of growth, the global goal to reduce carbon emission would be impossible and with substantial damage to the global environment. A better alternative is to skip a middle point, such as Point C, by jumping or leapfrogging to Point D from B. With proper composition of economic activities and the use of better technologies, such leapfrogging becomes a possibility.[13]

If the advanced countries see their path blocked by "carbon lock-in" (excessive dependence on fossil fuel systems), then latecomer countries can bypass such blockages by leapfrogging to cleaner and greener technologies. Mathews (2017, 2018) calls this alternative, "green development," based on the green industrial system free from fossil fuels and extensive resource throughput. Actually, a green window of opportunity has been opened up with the rise of various renewable energy technologies enabling the production of solar panels, wind turbines, new smart grid devices, electric vehicles, recharging stations, and others.

Thus, considering this green window of opportunity, late latecomers (those economies other than several East Asian economies who are already achieving significant catch-up) are in an appropriate position to attempt leapfrogging into

[13] This remark was also made in Lee and Mathews (2013, 2018).

an environment-friendly trajectory of development. Certainly, such leapfrogging requires the pre-existence or building up of a certain level of capabilities.

In what follows, we discuss several examples of leapfrogging in latecomer economies to explore the possibility of leapfrogging as the key latecomer development strategies for the twenty-first century.

5.6.3 Cases of Leapfrogging in Latecomer Economies

In a certain context and under certain conditions, such as the availability of foreign assistance, access to knowledge and/or funding, latecomers may attempt to leapfrog into newly emerging sectors, such as renewable energy or a broad spectrum of technologies associated with the 4IR. In what follows, we discuss diverse cases of leapfrogging in latecomer economies.

5.6.3.1 Two Cases from China

Solar thermal technology is one of several alternative sources of energy in the search for low-carbon energy solutions. However, its diffusion has been slow or not effective. In contrast, China is making a notable success, especially in rural areas rather than in urban areas (Zhou et al. 2012).[14] Solar thermal technology in China was developed early, in the 1980s, as a result of the R&D project executed by the Tsinghua University as a part of China's national R&D initiatives. Since the university disclosed the vacuum tube patent so that the technology could be easily transferred to the manufacturing sector, its production has increased to large scale. Now an interesting story in this market expansion is that it did not succeed in urban areas due to the mismatch with the existing urban architecture but succeeded in rural areas. In other words, compared to the gas and electric thermal systems which are already installed in cities, solar thermal systems which function for only six months cannot be attractive to urban dwellers. In contrast, solar thermal systems in the rural market can be successful because rural buildings tend to have a simpler structure which can be rebuilt by individual owners who care more about practical utility and less about appearance. Most importantly, compared to no hot water at all, six months of hot water supply is a big attraction for rural users.

This case of solar thermal energy in China indicates that rural areas bypassed the stage of gas- or electricity-based heating and leapfrogged into the stage of solar-thermal-based heating. It also indicates that not only supply-side (technology) but also a relative match or mismatch with the demand-side factor can be a source of a leapfrogging. Solar water heaters meant a huge disruption to the existing life and residence style of high-end or urban dwellers, whereas underdeveloped areas had no such high degree of lock-in, and this meant they had more receptive attitudes to alternative energy systems.

[14] This case is originally from Lee and Mathews (2013, 2018).

A case directly involving 4IR technologies can also be made, which may be considered a broadly-defined leapfrogging, such as Deep Glint which is one of the leading intelligent IoT technology companies located in Beijing, China. It was founded by Zhao Yong in April 2013. He used to be a senior researcher at Google's research institute and one of the core members in the R&D team for Google Glass.[15] It was started as a hi-tech camera and advanced security system company using computer vision to help monitor crowds. Currently, this company utilizes advanced AI (artificial intelligence) technology to create products and services at low cost which can be deployed in a large scale. In 2018, DeepGLint was in the top thirty Chinese artificial intelligence (quasi) unicorn list and the top 100 Most Emerging Growth Enterprises list. It is a very technology-intensive company, with an increasing number of patents; by the end of 2018, Deep Glint had obtained thirteen invention patents, five utility model patents, three design patents, and ten software copyrights.

Given its original strength in face-recognition technologies, its area for future growth seems to be autonomous driving which requires AI-based technology to monitor a large number of moving objects and that seems to be why this company received equity investment from Hyundai Motor Company from Korea. So far, it has gone through the first two stages (A and B) of venture-capital funding with each stage's amount of investment of more than 18 million Chinese Yuan.[16] Before it got investment from the market, this company was also supported by several Chinse government programs, such as the Torch Program and the Start Entrepreneur Program, which targeted, among others, the AI industry.

5.6.3.2 Using IoT technologies for Fish Farming in Indonesia

Founded in 2013, eFishery is one of the first "fishtech" startups in Indonesia. It provides an IoT solution for fish and shrimp farming businesses. According to eFishery, feeding cost accounts for around 80 percent of total fish farming expense but feeding is done inefficiently by unskilled labor with no control or supervision.[17] Thus, this company created a device that enables automated feeding of stock in fish farms, which results in lowering feeding expense, better feed performance, fish growth, better water quality, and eventually multiplies the profit of fish and shrimp farmers. On average, the company's smart feeding product helps reduce the amount of feed used by around 21 percent.[18]

eFishery's product comprises hardware and software, including several sensors to monitor fish's movements and ripples in water in a pond. In this sense, it is a manufacturing company. If the sensors detect certain motions, the feeders can determine that fish are hungry and agitated, then dispense food appropriately. Farmers can

[15] The basic information about this company is from the company website, http://www.deepglint.com/aboutus, accessed 15 January 2021.

[16] Source: https://www.crunchbase.com/organization/deep-glint#section-funding-rounds, accessed 15 January 2021, and https://pulsenews.co.kr/view.php?year=2019&no=151329, accessed 15 Januart 2021.

[17] eFishery's website at https://efishery.com/en/home/; also https://www.techinasia.com/this-startup-is-building-smartphone-powered-fishtech-for-indonesias-commercial-aqualife/, accessed 15 January 2021.

[18] https://www.techinasia.com/indonesia-startup-efishery-funding-news/, accessed 15 January 2021.

watch the whole process in real-time on their smartphone and even schedule the system when they want to do so. The device also collects information on fish behaviors and farm production patterns, which eFishery wants to utilize to improve their products and create more solutions for the aquaculture industry.

It took eFishery several months to see its business flourish. The company first won first place in two Indonesia startups competitions. With a price of US$975 per piece, eFishery sold 140 units in only seven months from February to September 2014 with the total revenue that year exceeding $100,000 dollar.[19] In 2015, the company disclosed it had more than 17,000 fish and shrimp farms in its sales pipeline.[20] It claimed to be profitable in 2018 with 261 times revenue growth in the 2016–18 period. These initial successes have helped the company to raise a total funding of $5.2 million dollars up to the present.[21]

eFishery could have a massive impact on Indonesian aquaculture. The company's products could help enhance the lives of more than 3.3 million Indonesian fish farmers (FAO 2018). With 3.3 million fishponds and 2.7 million fish farms, Indonesian aquaculture machinery is a million-dollar industry and thus the huge impact of eFishery has yet to come. The company's products are currently used in thousands of farms in sixteen provinces and sixty-seven cities/districts in Indonesia; from Maluku to North Sumatera. The company has also received orders from Singapore, India, Thailand, China, Brazil, and some countries in Africa, and is operating pilot projects in Bangladesh and Vietnam as well. The future of eFishery is to become a platform that connects the entire ecosystem in fish and shrimp farming, creating a more accountable and profitable industry across the region.

5.6.3.3 Biofuels in Brazil

Brazil[22] has been able to build an urban private transport system based largely on home-grown and processed ethanol and (now) biodiesel. Brazil developed its bioethanol program in the 1980s through utilizing its own domestic resources (sugar cane plantations fed by rainfall without the need for irrigation) and technology. Through the National Alcohol Program, dating back to the military dictatorship in the 1970s, a market for ethanol was mandated as a means of saving oil imports. Domestic producers were encouraged as well as local suppliers of equipment (such as Dedini), thus creating an entire value chain on the supply side. On the demand side there was initial resistance because cars had to be either ethanol-adapted or conventional, and consumers that switched to ethanol-only vehicles in the 1980s were then burned as the global price of oil fell and ethanol became non-competitive. But in the 2000s Brazil's ethanol program was revived with the strong support of

[19] https://www.techinasia.com/this-startup-is-building-smartphone-powered-fishtech-for-indonesias-commercial-aqualife/, accessed 15 January 2021.

[20] https://www.techinasia.com/indonesia-startup-efishery-funding-news/, accessed 15 January 2015.

[21] https://www.techinasia.com/indonesian-aquaculture-startup-efishery-nets-4m-funding/, accessed 15 January 2021.

[22] This case is originally from Lee and Mathews (2013, 2018).

the government, of the national oil company Petrobras, and with the demand-side innovation (developed in Brazil) of flex-fuel vehicles, which could run on ethanol, gasoline, or any combination of the two.

The success of the Brazilian bioethanol program (now being replicated in the case of biodiesel) is not a conventional story of import of product, followed by import of equipment and insertion in GVCs in order to access technology. Rather, Brazil was already a sugar producer at the world frontier in terms of technology and world leader in terms of costs—and was able to carry these initial advantages across to the production of ethanol. Technology for ethanol production was initially imported and rapidly domesticated (leading to the formation of domestic equipment suppliers such as Dedini) and then diffused rapidly through the R&D efforts of the national R&D institution, EMBRAPA. This was the body (equivalent to ITRI in Taiwan) that maintained a technological watch on global developments, and utilized advanced technological methods for researching Brazil's sources of comparative advantage, for example, soils suitable for sugar cane cultivation as revealed by satellite surveillance. But these advantages inherent in Brazil's situation would have been reduced to naught had it not been for strong government support in mandating a steadily increasing market share for domestically produced ethanol, and the role of the national oil company Petrobras in acting as primary distributor of ethanol through pipelines and terminals and fuel outlets across the country. Now Brazil is building an entire value chain for production of first-generation ethanol as well as creating companies to usher in the second generation (in competition as well as collaboration with US and European firms).

5.6.3.4 Cases from Africa

There do exist several cases of leapfrogging in Africa.[23] A notable example of leapfrogging in Africa is the M-Pesa in Kenya, which serves as efficient and convenient mobile banking and payment systems for African people without access to offline banking.[24] M-Pesa's founders were looking for a method to apply their mobile payment system to solve other problems. Thus, they started another company, called M-Kopa Solar, to provide solar energy to rural households in Africa. Their system uses three readily available technologies, namely, solar generation and low-energy LED lights, mobile payments similar to M-Pesa, and the SIM cards embedded in the M-Kopa control unit. M-Kopa's innovation is to package these technologies and combine them with a mobile payment system, thereby providing solar energy products at affordable prices. M-Kopa is an effective off-the-grid solar system for Africa, with poor land-based infrastructure and frequently erratic electricity supply. M-Kopa enabled children in rural areas to study after school and relieved their mothers from the burden of fetching firewood and burning kerosene late into the night. Thus, the process is a leapfrogging out of kerosene-based lighting, bypassing

[23] These cases are also presented in Chapter 7 of Lee (2019).
[24] This story of M-Pesa and M-Kopa relies on Shapshak (2016).

the grid-based electricity into off-grid renewable energies. This system is an innovation. not only in technological terms. but also in terms of business models suited to African conditions.

An example from Africa is the use of solar power in desert grasslands in rural areas in Jigawa, Nigeria (Lee and Mathews 2013). This semi-desert area has no water supply. The traditional option was to open wells with ropes and buckets, hand pumps, or government-supplied diesel-powered pumps that worked until they broke down or until villagers ran out of money to buy the expensive diesel. This problem was solved through solar-powered pumps designed to run maintenance-free for at least eight to ten years.

Another example is the O&L Group in Namibia (Lee et al. 2014). Established by Mr. Shilongo, this company started in retail and brewery and then diversified into dairy and solar energy. O&L survived and expanded quickly with government support (against a South African company's effort to sabotage this company by price dumping), with sales reaching approximately 4 percent of the GDP of Namibia. O&L plans to enter the energy business, including wind power, because Namibia imports electricity from South Africa and Angola. However, the company must first solve the hurdle of a government-imposed grid monopoly.

India: A Case of Country-Level Stage-Skipping Leapfrogging

In the economics literature,[25] a contrast has been made between China's manufacturing-led growth and service-led growth.[26] China's impressive catch-up since the 1980s is deemed classical, as its catch-up growth has been accompanied by typical structural changes, with the share of primary sector shrinking over time, whereas that of the secondary and tertiary sectors is increasing. India's case is unusual because the increase in the share of the service sector is matched closely by the decrease in agriculture, whereas the share of the secondary sector remains almost flat.[27] Actually, India's service sector has grown steadily since the 1980s, with its GDP share exceeding 50 percent. There is some view among economists that the growth of India's service sector might be another story of premature tertiarization typical in developing countries, in which generally low-paying service jobs are generated in the urban informal sector. Although this may be partly true in India, it is not representative of India's whole service sector. In particular, India's IT service industry has generated high-paying jobs and upgraded into higher value-added segments of the value chain.

Another impressive indicator of India's success is its rising share of service exports in relation to total exports. This share reached 35 percent in the mid-2000s in India

[25] This case of India is a summary based on Chapter 8 of Lee (2013).

[26] For instance, see Winters and Yusuf (2007).

[27] According to Figure 8.1 of Lee (2013), in China, the manufacturing sector's contribution to the total GDP has steadily increased, reaching 30 percent by the 2000s and accounting for the sharp decrease in agriculture's contribution to GDP. By contrast, the GDP of India's manufacturing sector has never exceeded 20 percent, with its size remaining constant at around 15 percent for over two decades.

and more than 50 percent in the 2010s, one of the highest in the world, surpassing even that in advanced economies. In contrast, the export share of service in China stayed at around 10 percent in the 2000s. Therefore, if India follows the proven success path of export-led growth, then it is likely to do so through service exports (tertiary) and not through manufacturing (secondary) or agriculture (primary) exports, as in other developing countries.

Growth in most industrialized countries in the world has been fueled by manufacturing, with the service sector increasing only after this stage of manufacturing-based growth ends. Such a pattern has been explained in terms of the income elasticity of service, or service as an intermediate input to manufacturing. However, in India, the service sector progressed even without going through the usual growth stage in the manufacturing sector (Ok et al. 2014). Thus, we consider the case of India as leapfrogging in terms of industrial structure because the service sector developed first, even before the manufacturing sector grew to take some share in the economy. Now under Modi's leadership, India is trying to promote manufacturing too. In this sense, it is a detour via leapfrogging; India bypassed the stage of manufacturing-led growth but leapfrogged into the service-led growth and then back to promote manufacturing.

It is to be noted that this service-led growth has been led by the three giants, namely, Infosys, Tata Consultancy Services (TCS), and Wipro, and that these Indian firms have undergone the three stages of upgrading: body shopping, off-shoring, and global delivery model (GDM), which are similar to the manufacturing stages of OEM, ODM, and OBM, respectively (Lee et al. 2014). Among these three, the case of Wipro is a perfect fit in this story of leapfrogging. This company was established as an agro-business company that produced and sold vegetable oil products (Hamm 2007). However, with its entry into the personal computer era, Wipro engaged in the business of assembling and selling personal computers as well. Shortly thereafter, the firm realized its weak competitiveness against foreign products and thus switched to PC maintenance and repair service. The Y2K panic near to year 2000 brought a decisive boost to Wipro's business, turning the firm into a global IT service company listed in the New York Stock Exchange. Wipro's historical evolution illustrates a company's leapfrogging into IT service, bypassing the stage of IT manufacturing.

5.7 Enabling Policies and Prospect for Leapfrogging

5.7.1 Enabling Conditions and Policies

The enabling conditions and policies for leapfrogging can be discussed in terms of the NIS (national innovation systems). Specifically, implementation of a leapfrogging strategy should first start from considering the one-pre-condition and two risks of leapfrogging discussed in Section 5.4. In other words, the first thing for a latecomer economy to do is to build up a certain level of capabilities in production technologies, if not innovation capabilities. As discussed in Section 5.4, the Korean case of leapfrogging into digital TV ahead of Japan was possible because Korean companies had the experience of making analog TV.

The need for building certain level of technological capabilities does not necessarily mean an isolated style of indigenous R&D effort. If it is going to lead to leapfrogging, local R&D effort should go together with getting access to the global knowledge base, without which leapfrogging catch-up is almost impossible as the latecomer firms cannot generate radically new technologies themselves. Although we are trying leapfrogging, the products from leapfrogging are often a combination of the latecomer production capability with the seed technology from the forerunning firms. Although what the latecomer firms developed is a new product, it was possible by applying the foreign-sourced sciences and the seed technology to the specific development target.

Thus, the possibility of leapfrogging also calls for a need to modify the theories of technological development (Lee et al. 2015). According to the stage theories of technological development, the latecomer country moves from the "internalization stage" to the "generation stage" to produce "new knowledge" to the world. Now, this sequential mode of learning has to be modified, specifically in terms of the change in the channels for knowledge access. While in the past or in the path-following catch-up, the main channels have been licensing or FDI, the current cases of a path-creating or leading catch-up during the paradigm shift period show the importance of new channels such as co-development with, and acquisition of, foreign firms or university startups as well as collaboration based on complementary assets owned by latecomer firms. Horizontal collaboration with universities, public research organizations, or forerunning firms is possible only when the latecomer firms have something to give in return. While absorption capacity was emphasized in the old story of technology transfer via license or FDI, now complementary assets, which have been created with speedy R&D activities and investment in production, seems to be important in these new ways of accessing knowledge.

The next important thing is to manage the risks involved in leapfrogging. The primary risk with leapfrogging has to do with how to make a right choice among the several alternative technologies. In this regard, cooperation with public R&D organs, universities, and other entities is critical as such R&D consortium can reduce the involved risk by pooling knowledge together. These collaborating entities may contribute critically by conducting "technology watch" to interpret and monitor the state-of-the art trend of R&D activities in foreign countries (Lee et al. 2015). For example, in the case of Korean leapfrogging into mobile phones or digital TV, it was the ETRI (a government research institute) which identified a small firm like Qualcomm as the R&D partner to develop digital cellular phone systems, and the KITECH and ETRI that carried out R&D activities and coordinated the consortium of research projects in digital TV.

Despite the possibility of mitigating the risk of making right or wrong choice among emerging technologies, the issue of whether sensible targeting is possible has always been a controversial issue. But, in such debate against targeting, design failure is often mixed up with targeting failure (Lee 2017). An example is the case in South Africa, where they developed their own electric cars called "Joule." Swart (2015) explained that the South African government provided the initial funding and established a state-owned startup called Optimal Energy in 2005. The company initially succeeded and had four roadworthy prototypes by December 2010. However, the company closed in June 2012 despite the technical success. The government, who was the major shareholder, decided to stop the funding required to start large-scale production of the electric cars because of uncertainties of marketing success. The failure of "Joule" cars was caused by the lack of involvement of private companies to take the role in volume production and sales. Thus, existing foreign multinational companies and local auto companies did not want this new "disruptive innovator," a state-owned company, to grow as another rival that sells cars. The government should have formed a public–private consortium with the plan that volume production would be carried out by private actors after the consortium developed the prototype (Lee 2017).

Thus, this South African case can be considered one of "design failure" rather than a "targeting failure" (Lee 2017). The reason that the process should involve private firms in terms of design is twofold: they know where market demand is, and they eventually run the show. Caution against government activism often does not distinguish whether the sources of failure are due to targeting or design. The sources are often mixed together. While one might expect more cases of targeting failure, this is not always the case. Uncertainty diminishes if targeting is seen in terms of identifying the potential or existing markets as long as the private sector with knowledge about the markets are involved. If not on the frontier, the targets may be obvious because there often exists a clear benchmark case, and then you may attempt to identify niches between existing firms and projects. Numerous public initiatives fail because of design or capability failure, where the latter means low execution capabilities.

While the above discussion is about avoiding design failure, targeting failure does exist. One way to minimize the possibility of target failure is to utilize the idea of entrepreneurial discovery (ED) suggested by the smart specialization framework (Foray 2015). The process would be as follows (Lee 2017). First, policymakers should organize a public–private joint taskforce, which includes representatives from the private sector, and administer a survey to existing private firms and entrepreneurs on the nature of business items or technological areas where they see near-future potential, opportunities, risks, and bottlenecks when entering or starting out in these future areas. The business areas to be identified by surveys are those areas where the private sector sees certain market potentials often associated with emerging technologies but with some technological, financial, and other related environmental (regulation) uncertainties. Private firms may know better where the next markets are, but cannot be sure whether they will be able to develop the necessary and right technologies and whether they will be able to raise the funds for such R&D

and initial marketing. In other words, new business/technology areas with more certain market potential but uncertain technological, financial, and regulatory uncertainty will be targetable areas. Policy intervention promotes these identified areas by mobilizing public and private resources and competencies that correct market and coordination failures.

5.7.2 Prospect of Leapfrogging-Based Development

The answer to the question of whether the 4IR can be either a new window of opportunity for leapfrogging or source for further risk for the latecomers is that it depends on each country's responses and readiness, including industrial policy, digital literacy, and skill and educational level compared to wage rates, and domestic market size and position in GVC (Lee et al. 2019). We can conceive of the following three groups of countries (Table 5.2).

The first group of countries may correspond to a most promising scenario consistent with a proper leapfrogging from industry 2.0 (mass production) to industry 4.0 (Smart Factory) bypassing the intermediate stage of industry 3.0 (automation). This seems to be possible or happening in an economy with a certain level of indigenous manufacturing basis, like China, South Korea, or Brazil, supported by the commitment from the government and consensus at the society level. Smart Factory paradigm has also risen also a solution to maintain competitiveness by overcoming the issue of the increasing wage rates or labor shortage in several economies, which

Table 5.2 Possible responses to the 4IR by country group

	Group A	Group B	Group C
Main feature	National manufacturing base	FDI-based manufacturing	Weak manufacturing base
Examples	China, Rep. of Korea, Brazil	Malaysia, Thailand Brazil, Mexico	Indonesia, India, Philippines Africa, Argentina
Promising responses	Leapfrogging into Smart Factory	Automation and upgrading	4IR-related service startups
Main initiator	Public–private partnership	MNC decision	Local entrepreneurs introducing business model innovations
Key enabling factors	Industrial policy providing funds and technologies	Local existence of skills and training institutions	Initial financing; venture capital
Risks	Waste of public funds	Relocation to cheaper wage sites	Entry by, & competition with large foreign businesses

Source: the author.

is basically similar to the underlying motivation for Germany to initiate Industry 4.0. A mode of implementing this initiative toward Smart Factory (or automation) can take the form of public–private partnership or collaboration, in conjunction with active industrial policy. Of course, the possible risk in this regard is the wastes of public resources or budget in case of failures with such initiatives.

The second group of economies are those with FDI-based manufacturing, like those in Southeast Asia or Latin America, where leapfrogging is up to the choice of parent MNCs. In these economies, MNCs face diverse alternatives, such as relocation to other economies looking for cheaper wages and reshoring back to home countries. In this regard, some promising stories from the FDI-based electronics sector in Penang, Malaysia, and auto sector in Thailand about some automation and upgrading into higher-end segments indicate that the key factor for success is the local institutions which have enabled training and upskilling of the local force, and thereby enabled MNCs to remain in the localities (Lee et al. 2020).

The last group may include other latecomer economies where more promising areas and stories related to the 4IR seem to be happening in service sectors or servicitized-manufacturing sectors. Possible example countries may include Indonesia, Philippines, Argentina, and many countries in Africa. For instance, there is recently a boom of startups in Southeast Asia, but the successful cases tend to be all in services, like mobility, ecommerce, games, mobile payments, travel, music, and entertainments, and other apps-based services.[28] Some of these, like Grabs are very successful and largescale and thus even competing with global giants like Uber, and are creating many jobs locally. Most importantly, they should have spillover effects on related manufacturing too; for instance, GO-JEK is Indonesia's first unicorn which started as a motorbike and taxi-hailing app and then expanded to food delivery, groceries, massages, and mobile payments.

It is quite plausible that success in services may have a boosting effect on local manufacturing, given the emerging trend of blurring the boundary between service and manufacturing. The cases of companies like eFishery and DeepGlint introduced in Section 5.6 can be considered as examples of companies sitting on the borderline between manufacturing and solution providers; eFishery provides an Internet of Things (IoT) solution for efficient feeding of fishes and produces hardware for fish- and shrimp-farming businesses. DeepGlint produces a security camera and provides a face-recognition system based on big data.

Of course, the possible risk facing these kinds of local startups would be the entry and competition from big businesses from abroad. Thus, these startups are advised to seek niches unless there is market protection by the government against foreign firms; it is well-known that many IT startups and later giants in China (e.g., Baidu, Alibaba, and Tencent) were able to grow owing to asymmetric regulations against foreign firms, like Google, Amazon, Uber, and Facebook.

[28] See the list of top fifteen startups in Southeast Asia at the https://www.techinasia.com/15-most-wellfunded-startups-southeast-asia.

The case of Indian leapfrogging into IT service followed by recent promotion of manufacturing discussed in the preceding section indicates the possibility of the idea of service-first leading to manufacturing later as a development strategy. The service sector in India has risen as a viable export sector accounting for more than half of total exports, the highest ratio in the world. The earnings in convertible currency generated by such exports has become a basis for Indian promotion of manufacturing which requires imports of capital goods by dollars. We do not have to discount this already-occurring phenomenon by labeling it as premature deindustrialization. Some latecomer economies might have to go along this road of economic growth, given the high entry barrier in manufacturing compared to services.

One insight from emerging promising cases in these latecomer economies would be that latecomers do not have to be the original inventors of new innovations but that it often suffices to be follow-on innovators or even fast-adopters with local twists, which have been classified as one variation of leapfrogging in Section 5.2. Leapfrogging is possible not only by hard technological innovations but also by business model innovations adopting technological innovation abroad. This has important implications for more laggard economies, like those in Africa. The cases of leapfrogging in Africa discussed in the preceding section tend to be more like adoption of new technologies than local innovations. However, adoption is a beginning or stepping stone for learning and eventual innovation. Learning is not possible without adoption. Manufacturing firms in East Asia, such as Samsung and Hyundai Motors in Korea, all started from the adoption of foreign technology for production, learning from using, enhancing productivity by mastering production technologies, and finally acquiring design technology (Lee 2005, 2013). Recent examples can be found in the renewable energy markets of China, Brazil, and India, which involve the transition toward low-carbon economies. Options for LDCs in low-carbon technologies include wind, solar, biogas, and geothermal energy sources. In this case, coordinated initiatives and incentives for early adopters are essential in reducing the risks associated with weak initial markets.

While the discussion above centered upon the different types of economies facing the different initial conditions, policy suggestions involving leapfrogging can also be made in terms of different types of firms with different level of initial capabilities. Here we may divide firms in an economy into incumbents and startups, and the former can further include three types like leader, followers, and laggards in terms of their level of capabilities. Then, we can discuss the issue of which types of leapfrogging or other alternative might be suitable for which types of firms.

Relatively speaking, one can argue that path-creating type leapfrogging would be more likely to happen to startups because they are the ones which have made the least amount of investment into the existing or old modes of technologies or business models. In other words, diverse technologies associated with the 4IR can be a source for product (or business model) innovations rather than for process innovation which is more relevant for incumbents. Of course, even the product innovation does not have to be really new or radical but follow-on innovation or adopt-then-improve type innovation.

Next, leader or follower type firms in emerging economies tend to have some experiences and absorptive capacity and thus are likely to be in a position to try stage-skipping leapfrogging. Given their accumulated know-how and production experience, they can be considered to satisfy the pre-conditions for such leapfrogging, but they should be aware of the two risks involved in leapfrogging discussed in the preceding section (5.4.2). Given that they are incumbents, their leapfrogging is likely to be not inter-sectoral but intra-sectoral, leapfrogging over different generations of technologies; for instance, from mass-production to Smart Factory, bypassing the stage of traditional automation; or from lean production to Smart Production, bypassing the stage of integration production. Also, the nature of innovation would be more process innovation than product innovation.

Last, laggard firms are advised not to try premature leapfrogging, but build first absorptive capacity and technological capabilities in their niche areas and thereby to try to upgrade by moving into higher-end segments of GVC. In other words, they need to go through the stage of "several detours" (Lee 2019) which is a pre-condition for trying leapfrogging. Some of the detours include the detour from imitation to innovation by providing somewhat weak IPR protection to promote imitative R&D and diffusion of innovations, as well as from building certain degree of domestic value chains while participating at the GVC (Lee 2019).

Supportive policies can also be different across firm types. For instance, for start-ups, venture capital (VC) funding including public–private joint VC, may be more relevant, whereas for incumbents, more relevant modes of financing would be conventional loans from commercial banks or subsidized loans from the public sector, as well as conventional financing from equity markets.

In general, new innovations in the 4IR and sustainable development seems to require new forms of public policy and public–private partnerships. Its comprehensiveness and across-board nature require policy response not by one specific government ministry but consultation and responses by multi-ministries with the coordination by the prime minister's office. Also, the responses should be timely because some negative impacts of 4IR could happen earlier than expected, such as losses of some assembly jobs and BPO jobs. Also, the 4IR would also disrupt and reshape the current GVC, and then new forms of insertion into the new GVC could be not necessarily at the level of firms but at the level of individuals. In this light, education and training would take a decisive role, and it would be desirable to integrate the labor market at the regional level, and to promote startup by young entrepreneurs by spreading successful role models and cases.

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6
Innovation Surveys as Evidence for Technological Upgrading and Catch-Up Studies

Vitaliy Roud

6.1 Introduction

Studies of catch-up development and technological upgrading need quality measures of innovation capabilities. General statistics (national accounts, the balance of trade) provides core metrics for catch-up success, and countries' roles in the global economy. However, to understand the mechanics of upgrading processes, to construct and implement the development strategy, it is necessary to obtain detailed knowledge of the country's technological capacities, and localization of the abilities to perform adoption, imitation, and dissemination of frontier technologies, and to innovate. Conventional statistical indicators can capture only a fraction of this information. The search for better metrics of innovation is ongoing.

Recent research on catch-up and technological upgrading comprehends the recipe for successful development as a unique combination of capabilities and opportunities (allowing to talk about the "art of upgrading" (Lee 2019)). Compared to earlier logic of continuous modernization of industries in a specific sequence (e.g., Rostow 1960; Von Tunzelmann 1995), new evidence emphasizes that the successful trajectories significantly vary given the intramural and extramural starting conditions. Drivers of success are different for the emerging and middle-income economies facing the need to cope with the growth slow-down often referred to as the "middle-income trap" (Lee et al. 2019; Lee 2013; Radosevic and Yoruk 2018; Vivarelli 2016). A country's distance from the global technological frontier (Aghion et al. 2014; Freeman and Louçã 2001; Perez 2010) may influence the efficiency of particular activities (e.g., fostering frontier R&D; technological modernization, and dissemination of advanced technologies) and affect the choice of priorities and transformative efforts. One landmark characteristic of a successful upgrading trajectory is the increasing ability to innovate. The framing idea of gradual transition through the stages of innovation capability development (such as "adoption, assimilation, innovation" by Kim (1980)) provides a comprehensive system of coordinates

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for research and governance of development processes. It creates a demand for better metrics of innovation capabilities useful for the catch-up and upgrading studies (Radosevic and Yoruk 2016).

This chapter discusses the essential methodological insight and empirical contribution to innovation capability measurement from the so-called "innovation surveys"—a family of internationally harmonized statistical surveys of business innovation. Section 6.2 provides an overview of the main methodological features of the surveys and the strengths and weaknesses against other available innovation capability proxies. Section 6.3 emphasizes the potential of the firm-level data on innovation to capture the heterogeneity of innovation capabilities and to construct composite indicators useful for the research on catch-up development. Section 6.4 introduces an approach to measure innovation capabilities with composite indicators of output-based innovation modes. It uses data from the Russian innovation survey to discuss the dynamics of innovation capability accumulation in Russia. The last section summarizes the main implications and points for further discussion.

6.2 Search for Internationally Comparable and Comprehensive Measures of Innovation Capabilities

6.2.1 Indicators of Innovation Capabilities Used in Catch-Up Development and Technological Upgrading Studies

The indicator of innovation capabilities most widely used in the context of development studies is the expenditure on research and development (R&D). Such statistics have been available since the mid-1950s and follow international standards (first and foremost, the Frascati Manual[1]). It is relatively unambiguous and provides a sound basis for cross-country comparative research on the intensity of involvement in technological development. Longer time series encourages the researchers to use the data on R&D in a broad range of studies related to growth and development, economic forecasting, international benchmarking, and comparisons. However, using this indicator as an ultimate proxy for technological progress and innovation capabilities leads to a range of systemic biases and estimation errors.

First and foremost, excessive focus on investment in R&D makes it impossible to analyze the effectiveness of these efforts. By definition, R&D expenditure is an input-side indicator, thus non-informative about the efficiency of the innovation process. At the same time, there is ample evidence in the academic literature that R&D represents only one type of activity related to the creation and introduction of product innovations, improvement of production processes, and other forms of efficiency improvement. The importance of expenses not connected with research and

[1] *Frascati Manual: Guidelines for collecting and reporting data on research and experimental development* (OECD 2015).

development is discussed in detail, for example, by (Kline and Rosenberg 1986). A study (Brouwer and Kleinknecht 1997) showed that R&D might account for less than a quarter of all costs of developing new products.

Moreover, the very class of companies involved in the processes of creation, distribution, and use of new knowledge (products, technologies, principles of production organization, etc.) turns out to be much more extensive than the number of companies formally engaged in research and development. For example, cross-country analysis (Gault 2010) shows that the share of companies that introduced new products or production processes without any accountable investments in R&D may exceed 50 percent of all such enterprises. There are also difficulties in taking into account informal and irregular practices that are typical of small firms' innovation activities.

Patent statistics is commonly used to construct the most reliable proxy for the country's technological effort and ambition. The strongest side of this data is the factual character of patent applications, as opposed to a survey-based collection. This approach is even more attractive due to the long historical series (at the aggregate level) and the indirect possibility of determining the economic value of scientific and technological results based on the frequency and nature of citations of patents. At the same time, scholars (see (Archibugi and Planta 1996; Griliches 1998; Pavitt 1985)) emphasize the well-known weaknesses of this approach. In particular, the focus on patenting misses a significant number of unpatentable inventions and innovations (know-how, production secrets). A significant proportion of patents are never transformed into commercial products or manufacturing processes but are used as part of a business strategy aimed, among other things, at deterring competitors. The country's specificity turns out to be essential. The use of patent protection mechanisms for inventions is mainly conditioned by the quality of relevant institutions and other national features. For example, the intensity of patenting is significantly different even among the "technological leaders" (USA, Western Europe, Japan), not to mention the "follower" countries.

A range of indirect measures is often related to innovation capabilities. Structural characteristics of GDP and trade balance, such as the share of high-tech industries, are considered as a vital indicator of a country's technological progress and are often mentioned in official policy documents and scientific papers. As a result, innovation efforts in specific industries (including those in traditionally recognized "low-tech" sectors such as light and food processing) are considerably underestimated. It leads to a significant misperception of the roles of different economic activities in the processes of economic growth. For example, the "high-tech myopia" of the policy frameworks implies an excessive focus on the support for high-tech industries (e.g., aerospace, electronics) without attention to the innovation dynamics in other industries.

Contemporary studies of country-specific strategies within the so-called "smart specialization" paradigm (Balland et al. 2019) successfully operate a range of economic complexity indicators associated with the sophistication of production capabilities. These indicators capture the composition of outputs (e.g., country's or region's product sales, or exports, or patents in case of technological specialization) and lay the basis for planning tailored development trajectories based on the existing competitive advantages. This approach inherits the strong power of evidence from the baseline data. However, much of the capability building remains a "black box." A high level of aggregation makes it challenging to analyze dynamics within individual industries and the specific strategies behind the development of the economic outputs.

When used in the studies of technology upgrading and catch-up development, the above-mentioned conventional proxies for innovation capabilities suffer from a range of systematic errors, including the fact that it is practically impossible to analyze modern forms of creation and distribution of innovations implying complex chains of knowledge and value creation, and intensive technological exchange in various forms (including trade in licenses for new technologies and purchase/sale of finished equipment). Focus on formal R&D-driven processes, and mature innovation management may discriminate against the effort of smaller yet capable actors. Such systematic errors may lead to laggard, biased, or even inconsistent perspective on the country's previous development path and the potential trajectories of upgrading.

An understanding of the problems of existing indicators has led to the formation of specialized statistical monitoring of innovation activities in the business sector through a system of so-called "innovation surveys." To date, this branch of statistics has been successfully implemented on either a regular or an experimental basis in more than eighty countries. It represents a promising yet underused source of data for technology improvement and catch-up studies.

6.2.2 Innovation Surveys: An Internationally Harmonized and Systemic Data Source on Business Innovation

Innovation surveys introduce a powerful and flexible approach to measure innovation capabilities in the business sector. The main provisions of the methodology for innovation surveys adopted in international statistical practice are contained in the so-called *Oslo Manual*,[2] prepared through joint iteration initiatives between OECD and the Statistical Service of the European Union (Eurostat). It provides basic terms and definitions that reflect current thinking on the structure of innovation processes, institutional classifications, and approaches to measuring innovation, as well as links to other international standards. Since initial dissemination in 1990, there have been four revisions of the *Oslo Manual*. According to many researchers (e.g. (Gault 2013; Godin 2002)), it was the introduction and dissemination of the *Oslo Manual* that

[2] *Oslo Manual: Guidelines for collecting, reporting and using data on innovation* (OECD and Eurostat, 2018).

contributed to the flourishing of analytical research on innovation and the inclusion of innovation in policy agendas around the world. To date, adherence to the *Oslo Manual* basic principles and definitions has been a prerequisite for integration into the international academic and expert discourse. As a rule, deviation from the categories described in the OECD and Eurostat recommendations can lead to the loss of consistency of analysis, misinterpretation of facts, and the accumulated inconsistency of conclusions.

An essential methodological breakthrough of the approach is the simultaneous measurement of inputs (resources spent on the development and implementation of innovations), multiple outputs of innovation activities, and quantitative and qualitative characteristics of the innovation strategy of the enterprise. This division ensures the optimal flexibility of the approach, allowing for nearly thirty years to adequately describe all kinds of (including previously not revealed) forms of organization of innovative activity of enterprises in the conditions of continuously developing theoretical ideas, requests from interested communities, global trends in science, technology and innovation, and the evolution of business models, as well as changing economic and institutional situations. Surveys cover both innovative and non-innovative enterprises, which allows for a comparative analysis of all types of economic actors.

Innovation surveys implement the subject approach to innovation measurement. An innovative enterprise is an enterprise that engages one or multiple types of innovation at the same time. The enterprise determines the direction, timing, and type of innovation activities and establishes cooperative relationships for the development of innovations, participation in joint research projects, and acquisition of new technologies. The identification of an enterprise as innovation is made by the enterprise itself based on certain characteristics. Enterprises are to reflect on their business activities and provide their performance across a range of self-assessed dimensions.

A central concept, innovation is considered to be the final result of innovative activity, embodied in a new or significantly improved product (product, work, service) or business process. The *Oslo Manual* distinguishes several levels of the novelty of the products and processes and sets the minimal level of novelty to consider as significant changes new to the firm. Innovation includes both products and business processes that an enterprise develops for the first time and those that it adopts from other enterprises. Thus, several categories of novelties fall into the field of innovation surveys: fundamentally new to the world market; new to the market but existing on international/national markets; and already existing on the market but new to the organization. It helps to address the dissemination of innovations, which makes this data source particularly valuable for catch-up studies.

Innovation inputs mainly refer to the enterprise expenditure on innovation activities. The latter includes all activities associated with the transformation of ideas (usually the results of research and development or other scientific and technological achievements) into new or improved products, services, or business processes. The *Oslo Manual* introduces a closed set of these activities, namely, research and experimental development (R&D); engineering, design, and other creative work; marketing and brand equity activities; IP-related activities; employee training; software development and database activities; activities related to the acquisition or lease of tangible assets; and innovation management. All these activities can be performed in-house or extramurally (outsourced to organizations).

Innovation outputs include quantitative and qualitative variables. The most widely used is the volume of innovation product sales (or its share in the total enterprise output). Qualitative measures characterize the broader effects of innovation on the enterprise.

The surveys provide a comprehensive and open-ended approach to cooperation and knowledge exchange. The methodology inherits the ideas of multilateral networking interactions and broader open innovation practices, from classical industry–science–cooperation to informal instruments, such as crowdsourcing.

The *Oslo Manual*-driven surveys have been pioneered by European countries in the framework of the Community Innovation Surveys (CIS). Eurostat remains a major provider of quality data and the harmonized approaches for the practical implementation of the *Oslo Manual* guidelines. A detailed survey of CIS history can be found in (Arundel and Smith 2013). Inspired by the successful case of CIS, many countries established comparable surveys. The overview of international experience in innovation surveys is presented, for example, in (Bogliacino et al. 2012). All in all, the survey has been executed in more than eighty countries. The most comprehensive international comparisons of the innovation survey indicators around the globe are provided in the OECD Science, Technology and Innovation Outlook project[3] and published biannually in the Science, Technology and Innovation Scoreboard[4] reports.

In a range of countries, there are established procedures to access firm-level data (microdata). Several countries (e.g., Germany, Switzerland) have constructed long-term panel databases that facilitate intense research on causal relations between different aspects of innovation. Moreover, international microdata databases have emerged, for example, within the Eurostat CIS and under the umbrella of the OECD. It opens the floor to comprehensive comparative analyses, potentially aware of the cross-country differences, including the institutional and cultural aspects.

The weaknesses and limitations of innovation surveys have been widely discussed in the literature (Arundel et al. 2013; Cirera and Muzi 2020):

- A subjective approach that imposes too much interpretative burden on the respondents (e.g., classifying their routines within a classification that is exogenous to their perspective on businesses). The decision of what to call “innovation” may vary even within the same firm. Thus, the unified, clear, and detailed guidelines are a must to ensure robust and quality data collection.

[3] https://www.oecd.org/sti/science-technology-innovation-outlook/, accessed 16 January 2021.
[4] https://www.oecd.org/sti/scoreboard.htm/, accessed 16 January 2021.

- Limitations of the survey-based data collection (e.g., sampling issues, a higher probability of non-response for certain types of enterprises, other sources of self-selection biases, difficult verification of the data). Controls for sampling errors should be applied extensively, e.g., the "survey of non-responses and false negatives" that helps to correct the self-selection biases using the characteristics of the firms that return incomplete questionnaire or avoid the survey.
- Issues of international comparability, including the nuances of survey methodology and questionnaire design. To produce useful and comparable data, national offices should pay maximum attention to harmonization issues at all levels of methodology and implementation, and, by no means diverge from the state-of-the-art recommendations of the *Oslo Manual*. International organizations undertake efforts[5] to collect metadata on the national surveys and to audit the comparability of the national data for producing global benchmarks of innovation indicators.

These challenges are subject to detailed consideration by the communities of data producers and data users, including academic communities and policymakers.

Given the balance of strengths and weaknesses, innovation surveys are a promising source of data for catch-up development studies. The most common policy use of innovation survey results is benchmarking a set of aggregate indicators (e.g., the share of innovation firms, the intensity of innovation expenditure, and the share of innovation sales in total output) at regional, national, or international levels. A straightforward comparison of aggregate statistics may be challenged by the non-linear character of innovation strategies and the diversity of possible innovation behavior avenues. Firms generally identified as innovative (or innovation-active) may engage entirely different levels of innovation capabilities (e.g., varying in their readiness to perform in-house R&D or the choice of networking strategy). Innovation survey microdata (or firm-level data) helps to construct composite indicators (indicators that combine multiple characteristics of the firm) and analytical taxonomies of innovation strategies aimed at treating the excessive heterogeneity with optimum balance between the level of detail and interpretability.

Innovation surveys can provide empirical evidence to the frameworks and concepts native to technological upgrading discourse, e.g., Kim's (1980) three-stage formula of country's growing sophistication: "adoption, assimilation, innovation." Rich dimensionality of the data enables a range of flexible analytical approaches to address the catch-up at the firm, sectoral and national levels, which is discussed in detail in the next sections of this chapter.

[5] Innovation Survey Metadata collection efforts by OECD and UNESCO Institute of Statistics.

6.3 Measuring Innovation Capabilities with Innovation Surveys

6.3.1 Identifying Firms' Capabilities: Taxonomies Based on Innovation Survey Microdata

Innovation surveys brought powerful new tools for identifying and differentiating innovation capabilities in line with the "resource-based view on the firm" (Barney 2001) and the dynamic capabilities approach (Teece 2007). Central is the opportunity to examine, compare, and classify the firms within the economy in terms of their innovation resources, effort, and outputs, accounting for the heterogeneity of possible strategies and processes to implement innovations.

The idea of the diversity of innovation mechanics can be traced up to the conceptual demarcation of types of innovation by Schumpeter (Mode I—a setting where innovation is fueled by small firms and entrepreneurs and Mode II—where the development is driven by monopolistic giants, see (Dosi 1982)). This complexity was later formally acknowledged in the non-linear ("chain-link") model (Kline and Rosenberg 1986) that considered a broad range of practices and activities leading to innovation and proposed a general framework to consider both the in-house R&D-driven development of new products and processes and performance boost that resulted from the acquisition of new machinery and equipment as innovations, potentially equally meaningful for economic development. The diversity behind this unified conceptual model was later illustrated in Pavitt's seminal contribution (Pavitt 1984). The classification of firm-level cases of innovation by the development strategy and sources of knowledge resulted in a taxonomy of firm-level patterns of innovation processes. This study brought significant insight into an impressive level of difference in the sectoral models of innovation. Understanding types of innovating firms and their relations within the exogenous (but actively involved) environment proved to be a promising method of developing the systemic views on the national innovation capabilities. Specifically, Archibugi (Archibugi 2001) proposed to treat innovation taxonomies as a narrative, describing the mechanics of evolving innovation systems at a given time.

Innovation surveys fostered a generation of quantitively driven taxonomy studies that focused on inter-firm heterogeneity (e.g., Arvanitis and Hollenstein 2001; Castellacci 2008; Cesaratto and Mangano 1993; Evangelista 2000; Hipp and Grupp 2005; Hollenstein 2019, 2003; Marsili 2001; Sirilli and Evangelista 1998) and others). This approach succeeded in the qualitative case-studies and opened the floor for reproducible and portable methodologies for innovation heterogeneity studies. A few impactful research projects constructed taxonomies using the data from multiple countries and revealed the distributions of different innovation strategies across sectoral, geographical, and temporal contexts. Comprehensive effort enabled by the OECD (Frenz and Lambert 2009; Lambert and Frenz 2012;

OECD 2009) helped to emphasize core observations important for innovation capabilities' identification and measurement:

- Innovating firms are highly heterogeneous in their strategies, treating them in a unified way results in inconsistent, biased, and oversimplified characteristics of a country's innovation potential.
- National environments (and economic sectors within a single national economy) vary significantly in numbers of firms that implement different strategies. Innovation surveys help to identify what are the dominant types of innovation behavior, and to grade the national and sectoral environments by their "friendliness" to the advanced innovation capabilities.
- National and sectoral patterns identified from the innovation surveys demonstrate certain persistence over time (at least in the shorter term, e.g., between the consecutive waves of the surveys). It is an encouraging observation that promotes the consistency and reliability of the analyses based on firm-level taxonomies.

6.3.2 Identifying Innovation Capabilities at the Sectoral Level

Identification of innovation capabilities at the sectoral level is strongly associated with the "technological regimes" approach (Breschi et al. 2000; Dosi 1982; Malerba et al. 1997; Malerba and Orsenigo 1993). This approach implies that the sectoral characteristics, such as market structure, technological opportunities, appropriability conditions, and knowledge base, have a decisive impact on determining the strategies of individual firms, thus allowing to talk about a "regime" of innovation typical for the firms within the sector.

Taxonomies have been widely used to categorize sectoral differences in innovation capabilities. Earlier studies focused either on aggregate statistics or on unique datasets. At the same time, the emergence of harmonized innovation surveys and broadening access to microdata brought the cross-sectoral comparative studies to a whole new level of objectivity and detail.

Pavitt's taxonomy (Pavitt 1984) is the first famous effort of this type. It was derived by careful examination of 2,000 cases of innovation across industries in the UK, including manufacturing, services, mining, and agriculture. By classifying the strategies pursued by innovating firms, Pavitt emphasized four groups of sectors. He proposed a set of ordered relations between these groups regarding sources of new knowledge, technology, and the underlying means to implement innovation (such as the acquisition of machinery and equipment). The resulting set included science-based sectors that possessed the most advanced innovation capabilities; specialized suppliers; scale-intensive; and supplier dominated, the least sophisticated in terms of developing impactful technological innovation. The follow-up research, in particular, (Pavitt et al. 1989; Soete and Miozzo 1989) addressed the growing importance of the information and communication technology as well as the heterogeneity of services (formerly being equally classified as supplier-dominated). The next generation of studies broadened the scope of service industries under consideration (Castellacci 2008; Evangelista 2000; Miozzo and Soete 2001). However, the general perception of sectors beyond manufacturing and so-called knowledge-intensive business services (KIBS, (Miles et al. 1995)) as simple adopters of technology prevailed.

Innovation surveys and the firm-level data enabled more flexible approaches to explore sectoral regimes of innovation. Recent studies combine the reasoning behind sector-level technological regimes and inter-firm heterogeneity and implement a two-step procedure: firstly, focus on the heterogeneity of firms as opposed to aggregated characteristics of industries and derive the particular types of innovation strategies; secondly, classify the sectors given the propensities of the firms within the industry towards the emphasized patterns of behavior. Peneder (2010) follows this approach to develop a taxonomy of sectors by innovation intensity (which is close to the concept of innovation capabilities that is of interest in this chapter). His contribution uses firm-level data from the twenty-two EU countries. As a result, the industries are classified along 5 degrees of innovation intensity: high innovation intensity; intermediate-to-high innovation intensity; moderate innovation intensity; intermediate-to-low innovation intensity; and low innovation intensity. The methodology of the study is remarkably transparent, ready to be replicated in other countries, and at different periods due to the standardized data source. The results present the distribution of innovation capabilities across the sectors of the European economy.

As illustrated, taxonomies have been successfully applied to identify the levels of innovation capabilities across the industries. Additionally, the latest generation of these studies developed the methodologies that exploit firm-level data and help in understanding the complex composition of actors within sectors. These actors differ in terms of their performance, the sophistication of strategies, the general perception of the (competitive) environment, and thus potential reaction to the incentives (including the ones designed through innovation policy measures). The studies prove that the perception of sectors as homogenous regarding innovation patterns is misleading. There are examples of highly innovative (and vice versa—laggard) firms in every industry regardless of the expected sectoral labels. The resulting sectoral innovation capabilities depend on the ratio between the advanced and lagging-behind firms subject to direct measurement through the innovation surveys.

It is quite clear that the allocation of innovation capabilities across sectors is ultimately predefined across economies and not stable over more extended periods.[6]

[6] "Every long wave of capitalist development has generated a different typology of innovative firms. . . . But, of course, the quantitative and qualitative importance of each group of firms has

Therefore, the adequate approach to sectoral innovation capability studies would be a regular update of firm-level strategies within sectors, and thus, a revision of the taxonomies (or at least the classification of industries along with the taxonomy classes).

Observing the evolution of innovation capabilities across sectors is the key to understanding the genesis of the economy. However, existing taxonomy research rarely focuses on capturing dynamic or transformative processes. While Arundel and Hollanders (2008) emphasize the potential of the analysis of changes in the composition of the actor types (e.g., a growing share of advanced innovation firms) for understanding the performance of economic systems, as well as the dynamics of sectoral transformations, so far this area remains under-researched. Possible obstacles include limited access to the required amount of microdata over longer time horizons and a lack of comprehensive general theory and research programs behind generic taxonomic efforts. The former remains in the domain of organizational effort of the community of data producers (and the situation improves gradually). The latter may be changed dramatically, given the growing interest in the innovation taxonomies from the side of development studies.

6.4 Observing the Dynamics of Innovation Capabilities at National and Sectoral Levels: The Evidence from the Russian Innovation Survey

6.4.1 Methodology to Measure Innovation Capabilities Using Composite Indicators of Output-Based Innovation Modes

The Oslo Manual Framework provides means for constructing new indicators that combine the power of the firm-level data to identify diverse innovation strategies and the taxonomy approaches to classify various levels of innovation capabilities for satisfying the needs of economic catching-up and technological upgrading studies. This section proposes a methodology of measuring innovation capability using composite indicators that relies on the "output-based innovation modes" taxonomy (OECD 2009). This taxonomy closely follows the logic of Kim's progressive accumulation of capabilities ("adoption—assimilation—innovation" formula of technological upgrading process (Kim 1980)). It is based on the original contribution of (Arundel and Hollanders 2008) and addresses the issues of innovation novelty (are products new to the firm or the market—national or international) in combination with capabilities of innovation development (whether the firm exploits its resources,

considerably changed within capitalist evolution. . . . This suggests that the same taxonomy may also be used to explore the parallel long-term evolution of corporations and of economic activity" (Archibugi 2001).

specialists, and innovation culture, or relies on out-contracting development activities). As opposed to data-driven approaches (e.g., cluster analysis), it is constructed using the top-down (or "cut-off" (Peneder 2003)) classification principle, which implies a strict definition of the classification rule and allows replicability of the analysis given different context and time frames.

The "output-based innovation modes" taxonomy of innovation capability levels classifies each firm using the following three dimensions:

- Positioning against global markets: whether the firm operates in the international markets and considers them essential.
- Novelty of resulting innovation: whether the introduced innovations were new to the market or new to the firm only.
- In-house effort: whether the firm developed the innovation based on its intramural activities or the innovation resulted in adoption without (or with modest) in-house creative input.

Combining three dimensions results in a mutually exclusive classification of firm-level innovation capabilities that includes five levels of increasing sophistication and potential: non-innovation companies, technology adopters, national imitators, international imitators, national innovators, and international innovators (Table 6.1).

These dimensions are quantifiable using the data derived from the commonly used innovation survey design. Thus, using the firm-level data of the innovation survey, it is possible to classify each observation as the implementor of one of the five mentioned "output-based innovation modes." Then, a distribution of the firms across the levels of sophistication of innovation capabilities can help to understand the specificity and the potential of the innovation development within the observed population (either at national or e.g., regional or sectoral level of analysis). For example, a higher share of the most advanced innovation mode—"international innovators" indicates that the target population acts at an impressively high level of innovation capability, possibly acting as a locomotive of the upgrading processes. On the contrary, the dominance of the simplistic modes evidences for the lack of innovation capabilities, which automatically affects the potential development trajectory of the target firm population.

The original publication presented such estimates for a range of economies as one of the outcomes of the OECD Innovation Microdata Project.[7] The joint contribution of fifteen countries that performed estimates using the national microdata allowed

[7] The OECD Microdata Project: http://www.oecd.org/sti/inno/oecdinnovationmicrodataproject.htm/. Accessed 16 January 2021.

The project guided by the OECD Working Party of National Experts on Science & Technology Indicators (NESTI) in 2006–09 aimed at exploring the potential of firm-level data on innovation from multiple national contexts. The project followed a decentralized design that joined the research teams of nearly twenty countries within a unified analytical procedure. The coordination at the steps of data cleaning, indicator construction, and econometric modeling helped to overcome the limitations and restrictions in accessing the data. The results and interpretations were presented in (OECD 2009).

Table 6.1 Innovation modes definitions and descriptions

Mode	Definition	Description
International innovators	Introduced new-to-international market technological innovation. Innovation activities are in-house or mostly in-house.	New-to-international-market product innovations implemented mostly by the firm itself. Potential for radical innovations.
National/local innovators	Operate on the national market only. Introduced new-to-market technological innovation mostly developed in-house.	Successful product innovations—new to national and local but not international markets, implemented mostly by the firm itself.
International imitators	Operate on the international market. Introduced new-to-firm technological innovation. Innovation activities are in-house or mostly in-house.	Minor innovation activity implemented mostly by the firm. Resultant product and process innovations already available at the firms' markets. Capable of technology borrowing using their own resources. Firms are active in the international market
National/local imitators	Operate on the national market only. Introduced new-to-firm technological innovation mostly developed in-house.	Minor innovation activity implemented mostly by the firm. Resultant product and process innovations already available at the firms' markets. Capable of technology borrowing using their own resources. Firms are active in the national/local markets
Technology adopters	Not developed innovation in-house. Operate on either national or international markets.	Development of technological innovations using the competencies of external organizations (irrespective of novelty level)

Source: OECD 2009.

the construction of an international comparison of the distributions of the innovation modes. It helped to observe the diversity of the national contexts in terms of underlying innovation capability levels. Figure 6.1 incorporates Russia into the original comparison.

As opposed to comparing the levels of innovation activity (shares of innovation-active enterprises in total number of surveyed firms), the comparison presented in Figure 6.1 helps to capture the diversity of the national innovation capabilities. It provides an illustration to the question: "When a firm is innovating, what innovation strategies would it usually pursue." When for a majority of countries innovation strategy is strongly associated with developing innovations novel to the international market, several countries indicate other compositions of priorities for innovating firms, for example Japan emphasizes the importance of national market innovation, when Russia and Brazil focus on imitation and technology adoption as the dominant innovation strategy.

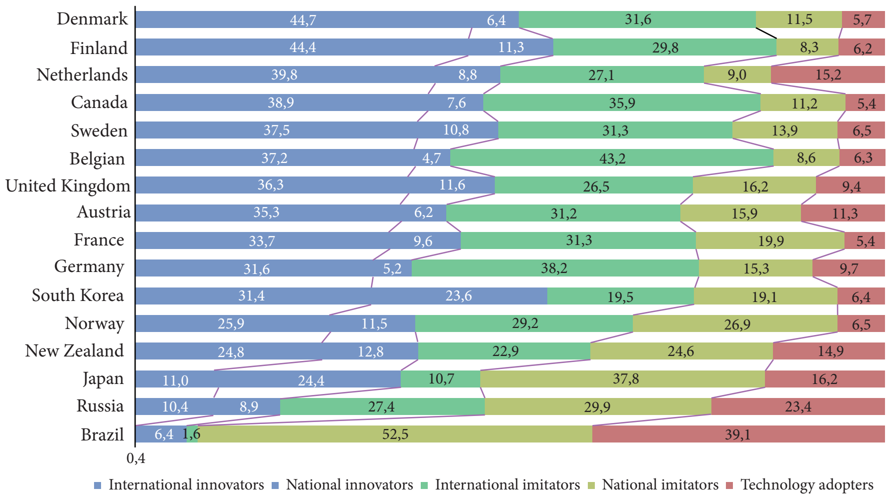

Figure 6.1 Innovation modes across countries (% of innovation companies)
Source: Russia—2015, from (Roud 2018). Other countries—2008 (OECD 2009).

The OECD effort brought persuasive evidence on the diversity of innovation capabilities across the countries. However, the original contribution was focused on a static international comparison of the national innovation capabilities. To the author's best knowledge, no follow-up updates in a similar design were performed. Also, the cross-country comparisons within the original contribution don't consider the potential use of such measurements for the studies of catch-up and technological upgrading trajectories.

The methodological claim of this section is to encourage further use of the proposed indicators in two ways. Firstly, to serve as a comprehensive metrics of technological upgrading, this methodology needs to be extended in the dynamic dimension. Tracing the presence of different innovation modes over more extended periods of observation would capture the economy's trajectory. Secondly, applying the composite indicators of the "output-based innovation modes" at sectoral levels can contribute to estimating the between-industry variation of the innovation capability levels based on the in-depth analysis of the within-industry diversity.

Identifying the areas of innovation capability concentration would provide robust evidence for the discussions on the country's current stage of upgrading and the available windows of opportunities.

The next section pilots this approach using the data for the Russian Federation.

6.4.2 Innovation Capabilities at the National Level

To assess innovation capabilities using composite microdata-based indicators, a country should ensure that a consistent innovation survey is carried out, following the up-to-date international guidelines both for methodology and data collection procedures.

Russia runs innovation surveys as a regular part of the statistical observation since 1994 within the activities of the Federal Statistical Service (Rosstat).[8] The data collection is annual and performed on a mandatory basis for medium and large enterprises. Small enterprises are observed within a sample-based biannual survey. The design follows the *Oslo Manual* (being updated to the most recent editions) and is harmonized with the EU Community Innovation Surveys.[9]

This section discusses the trends observed with composite indicators of output-based innovation modes. The analysis relies on a pooled cross-section of firm-level data that covers enterprises with more than twenty employees from mining, manufacturing, and utilities (NACE rev. 1.1 C, D, E) and represents sixteen years (2000–15).[10] The total number of observations is 326,492, of which 34,390 are innovative (that means it can be classified as one of the five output-based innovation modes, as discussed in Section 6.3.3). The sample covers roughly 85 percent of the total output of the industrial production sector in Russia.

Pooling the data from several survey waves allows us to observe trends in firms' distribution across output-based innovation modes on the horizon of sixteen years (Figure 6.2). As opposed to most of the countries that participated in the original

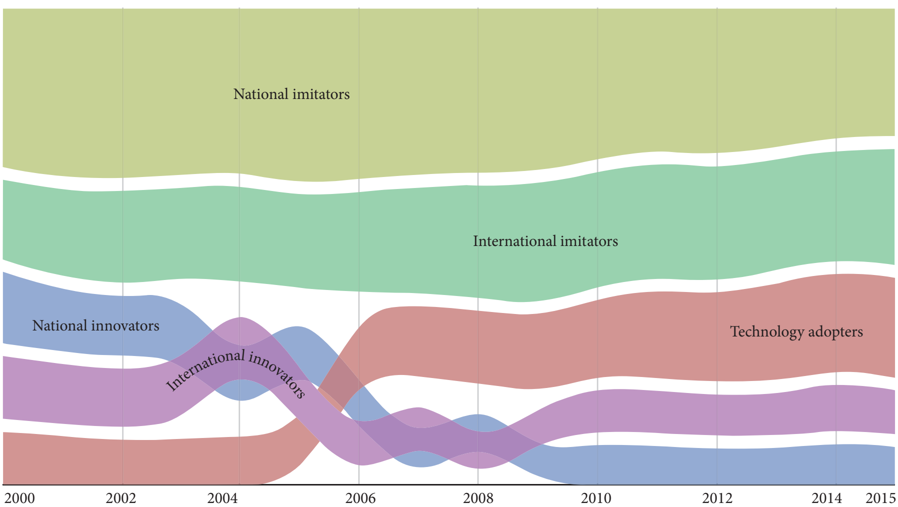

Figure 6.2 Innovation modes over the years (% of innovative companies in mining, manufacturing, and utilities)
Source: (Roud 2018).

[8] https://gks.ru/. Accessed 16 January 2021.
[9] http://www.gks.ru/wps/wcm/connect/rosstat_main/rosstat/ru/statistics/science_and_innovations/science/
[10] Provided by the Institute for Statistical Studies and Economics of Knowledge, National Research University Higher School of Economics.

comparison performed by the OECD (see Figure 6.1 in the previous section), Russia demonstrates a strong tendency towards imitation- (or adoption-) based strategies. The fraction of firms that developed strong innovation capabilities remains low.

The proportion of firm strategy types is robust over long periods. It supports the consistency of the analysis (high volatility would reduce the meaningfulness of the derived trends). The overall path dependency and inertia confirmes the limited scale of the transformation processes within the national innovation system of Russia over the observed period.

Output-based innovation modes reveal trends of upgrading that are otherwise hard to observe. The indicators identify a stable cluster of advanced companies with high innovation capabilities at international or national markets and can develop new-to-market innovations. The share of these firms remains stable (but low) and seems to be non-sensitive to the economic downturns or other shocks. At the same time, the indicators capture the tendency of simplification of innovation strategies. The share of enterprises that follow the technology adoption strategy with no in-house capability building is rising over time and has become dominant in recent years. It can be interpreted as a signal of adverse economic processes accompanied by losing (as opposed to accumulating) innovation capabilities or a technological downgrading.

It seems logical to rate the national environments by their "structure," linking the country's success directly with the higher share of the "advanced" modes. However, the actual performance of the modes (as well as the resulting contribution into the economy) may differ from the behavior expected by the *ex-ante* labels (see, e.g., debate on the performance of Science-Technology-Innovation strategies vs. doing-using-interacting strategies given the economy's distance from the global technological frontier (see Jensen et al. 2007)). In-depth studies of microeconometric properties of the innovation modes may bring extra insight to what the allocation of the strategies means for the country's development. As derived in Roud (2018), the intensity of innovation expenditure and the efficiency of turning innovation input to output (innovation sales) significantly differs across the innovation modes. Structured econometric models allowed the ranking of the innovation strategies in terms of intensity and efficiency of innovation and the identification of the differences of the most impactful barriers hampering innovation and the experiences of using and benefiting from the existing innovation policy-support measures:

- Generally low propensity to innovation observed by the aggregate statistics is furtherly decomposed by types of innovation strategies. It appears that the innovating firms tend to execute the least advanced innovation strategies (imitation and adoption). Advanced innovation capabilities are less required for the success at local markets under the conditions of the rent-extracting competition regimes (widely publicly discussed but rarely illustrated).
- At the same time, the least advanced modes demonstrate lower efficiency of the innovation process (in terms of transforming expenditure to innovation sales), thus explaining the observed limited amount of innovation outcomes given a considerable amount of resources spent.

- Technology adoption (without any in-house capability building) is the most cost-intensive strategy and has the lowest efficiency of transforming investment into innovation sales.
- Firms at different levels of innovation capabilities have a completely different perception of the country's institutional bottlenecks and the demand for policy-support measures. Internationally oriented firms identify problems with local administrative barriers and the flaws of the regulation (e.g., imports and exports). Those focused on domestic markets mainly reference issues with within-country standards, lack of qualified personnel, and weak innovation infrastructure. Non-innovative firms reference low demand for innovation and underdeveloped in-house capabilities as the main obstacles to launch innovation projects.
- Less sophisticated innovation modes mainly benefit from direct support in the form of grants and subsidies, primarily treating this channel as another source of finance. Companies that introduce innovations new to the international market indicate the importance of the state-coordinated new complex innovation projects. Interestingly, the most advanced modes report the lowest efficiency of the existing policy-support framework, while the firms with more simple strategies are considerably more satisfied with the state effort. Another essential highlight—innovation modes oriented at the national and international market—demonstrate the opposite attitudes towards the existing system of technical regulation and standards. Thus, benefiting one group would discriminate against the other.

Thus, the composite indicators of output-based innovation modes provide useful data to the observers of the country's innovation capability building pathways. The natural assumption that different types of innovation actors are exposed to varying barriers for successful innovation and establish differentiated demand for the innovation policy-support measures finds robust empirical grounding. Complex indicators based on firm-level data allow us to recognize and quantify the mix of actors that coexist at the given moment within the national economic environment and to understand the potential and limits of an existing or prospective innovation policy framework.

6.4.3 Sectoral Dynamics of Innovation Capabilities

Innovation capabilities are unevenly distributed across sectors. This allocation evolves over time, making some sectors more innovation-intensive and leaving others behind. Innovation surveys help to capture the processes of innovation capability building by providing the data on the types of innovation strategies engaged by the firms within sectors.

The composite indicators of the output-based innovation modes provide the necessary optics to trace sectoral trajectories of capability accumulation.

This approach is illustrated below using the Russian Innovation Survey database presented in the previous section.

The classification procedure described in Section 4.1 applied at firm level to the whole sample of the enterprises and then aggregated at sectoral level allows the evaluation of the shares of six innovation modes (non-innovative, international innovators, national innovators, international imitators, national imitators, technology adopters) across twenty-six sectors of industrial production (aggregated at the level of 2-digit NACE rev 1.1 codes, C, D, E with several 3-digit code groups following the definitions of the OECD/Eurostat technology level classification of industries) for the time horizon of sixteen years (2000–15). It results in 416 industry-year pairs further treated as points of observation. For all of these points, there are estimates of the number of firms following each of six innovation modes. Additionally, several economic indicators of performance are estimated: mean productivity (proxied by firms' total output to the aggregate number of employees), mean export intensity (total output abroad to the aggregate number of employees), and the productivity gap—distance between 10 percent top-performing and 50 percent less-performing firms.

The next step is classifying the sectors according to the level of innovation capabilities, similar to Castellacci (2008) and Peneder (2010). The procedure implies clustering the industry-year pairs according to the distribution of the firms across six output-based innovation modes. For this, the hierarchical cluster analysis was performed. The heuristics based on the dissimilarity measures allowed the identification of five classes of typical innovation capability distributions. Each industry-year pair falls into one of these five classes based on the observed propensity of firms at the given industry and the given year to each of six innovation modes.

The following step is deriving interpretation for the clusters based on their profiles (Figure 6.3). The comparison between the average observed shares of innovation modes within the cluster profiles identifies five possible states of the industry-level capabilities: *Non-innovative* industries, with the minimal total number of innovating firms regardless of strategies; *Barely innovative* industries, with higher numbers of imitators at the national level and technology adopters; *Modestly imitative* industries—characterized by higher shares of imitators at national and international levels and a detectable fraction of innovators; and *Actively innovating* industries, with the highest share of innovation enterprises overall, highest shares of international innovators, and more significant numbers of all other types of innovating firms.

Figure 6.4 presents the dynamic trajectory of industry-level innovation capabilities on the horizon of sixteen years.

As observed, only a fraction of the observed industries is in the *actively innovating* state. The list of these industries is rather stabl: by 2015 it includes manufacture of aircraft and spacecraft, manufacture of office machinery and computers, manufacture of coke, refined petroleum products, and nuclear fuel. At specific years the manufacture of radio, television, and communication equipment joins this list. These industries demonstrate the maximum level of innovation capabilities relative to

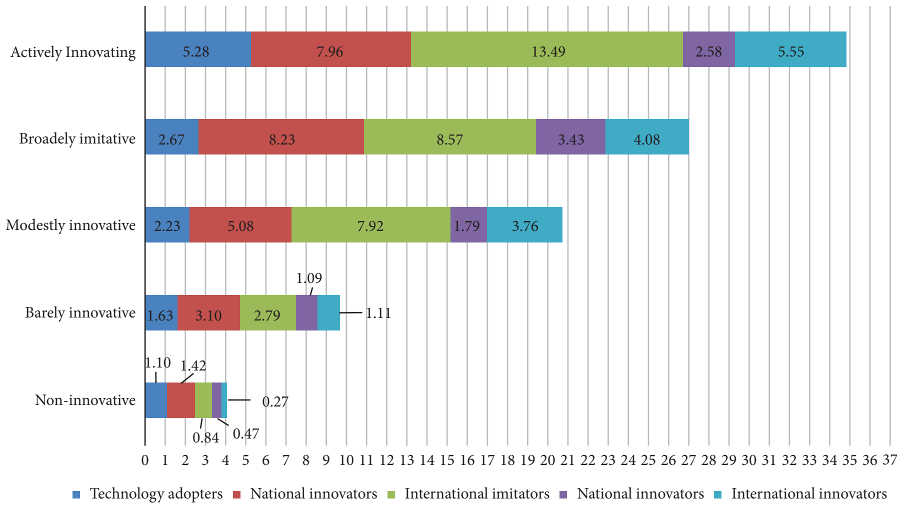

Figure 6.3 Classification of industries by innovation capability levels. Cluster profiles derived using hierarchical cluster analysis*

*For each of five clusters of industry-year pairs, the diagram presents the average percentage of firms with each of five output-based innovation modes within the industry in the given year. The percentage of non-innovative firms is omitted. Including it totals to *100* percent. Statistical tables are available on *demand.*

others. The membership to this cohort remains stable over sixteen years and demonstrates the highest share of innovating firms aimed at global markets.

The next level of innovation capabilities or *broadly imitating* state unites the industries on their way to further strengthening their positions: manufacture of radio, television, and communication equipment, manufacture of medical, precision, and optical instruments, manufacture of pharmaceuticals, and medicinal chemicals. The boundary between this cluster of industries and the most advanced "active innovation" is rather vague: there are frequent examples of industries traveling between the clusters.

The group of follow-up industries is in the *modestly imitating* state. This group had four to seven members in different years. These industries demonstrate the observable potential for global imitation.

By 2015 nearly a half (12 out of 26) of the observed industries in Russia are classified as *barely innovative,* growing from four of twenty-six in 2000. Most of these newcomers are industries that upgraded their capabilities from the *non-innovative* level.

Additional descriptive indicators allow us to speculate on the link between the industry levels of innovation capabilities and the economic performance of these industries (Figure 6.5).

Industries with higher innovation capabilities demonstrate higher productivity. Advanced levels of innovation capabilities also correspond to a smaller productivity gap between the firms acting at national productivity frontier and the laggard ones. The productivity inequality is also small for the "non-innovative" industries. However, the reason is the overall low efficiency of companies. In terms of export

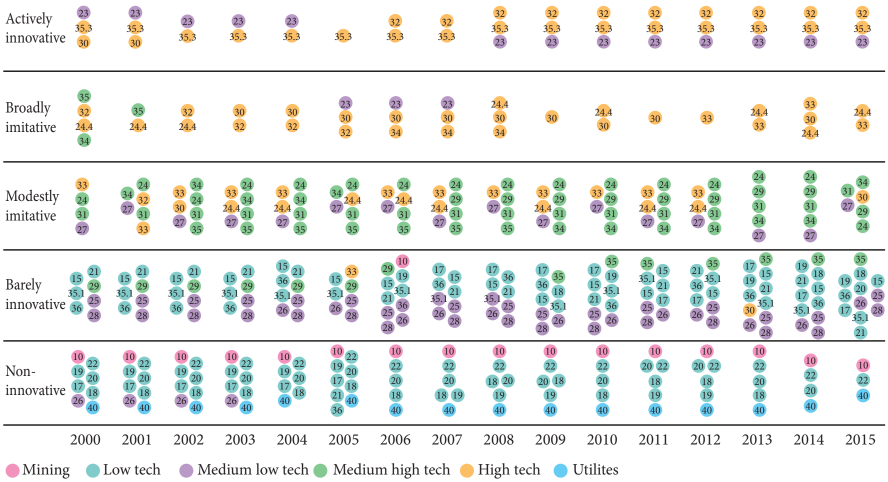

Figure 6.4 Industries by innovation capability level over sixteen years*

Circles correspond to industry groups (NACE rev 1.1 codes): 10 – Mining; 15 – Manufacture of food products, beverages, and tobacco; 17 – Manufacture of textiles and textile products; 18 – Manufacture of wearing apparel; 19 – Manufacture of leather and leather products; 20 – Manufacture of wood and wood products; 21 – Manufacture of pulp, paper and paper products; 22 – Publishing and printing; 23 – Manufacture of coke, refined petroleum products and nuclear fuel; 24 – Manufacture of chemicals and chemical product; 24.4 – Manufacture of pharmaceuticals, medicinal chemicals; 25 – Manufacture of rubber products; 26 – Manufacture of plastic products; 27 – Manufacture of basic metals and fabricated metal products; 28 – Manufacture of other non-metallic mineral products; 29 – Manufacture of machinery and equipment n.e.c.; 30 – Manufacture of radio, television, and communication equipment; 31 – Manufacture of electrical machinery and apparatus n.e.c.; 32 – Manufacture of office machinery and computers; 33 – Manufacture of medical, precision, and optical instruments; 34 – Manufacture of motor vehicles, trailers, and semi-trailers; 35 – Manufacture of other transport equipment; 35.3 – Manufacture of aircraft and spacecraft; 36 – Manufacturing n.e.c.; 40 – Utilities. Colors correspond to the OECD industry classification by technology level.

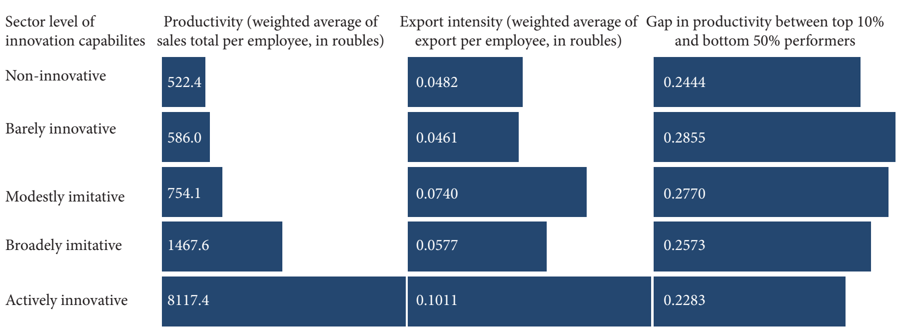

Figure 6.5 Innovation capability levels and economic performance of industries

Note: Cross-level differences are statistically significant (F-test for the cross-group difference by each of the three variables, based on 416 industry-year pairs. Statistical tables are available on demand).

intensity, there is a definite "premium" for the sectors with the highest innovation capabilities. Moreover, the sectors with considerable levels of innovation capabilities ("broadly imitative" and "modestly imitative") show higher integration into the global value chains compared to the firms with minor innovation capabilities ("barely innovative" and "non-innovative").

With this evidence, it is possible to quantify the character of the upgrading dynamics of the Russian Federation. At the period of observation, many industries demonstrated the lowest levels of innovation capabilities. Only a fraction of sectors focuses on proactive innovation and successfully contributes to the global markets. A range of follow-up industries are stable in their performance and have been successfully integrated into the global value chains as imitators and technology adopters. The most observable tendency is the migration of industries from the non-innovative to a somewhat more capable category.

Overall, the innovation survey-based indicators of innovation capabilities depict Russia's performance as mostly stagnant. The core of advanced industries remains nearly the same for sixteen years of development. However, there is evidence of positive dynamics of the initial stages of innovation capability building—most of the industries moved from the "non-innovative" to "barely innovative" state.

The resulting empirical classification of industries confirms the economic intuition—higher innovation capabilities pair with better economic performance, lower productivity gaps between the frontier and laggard firms, and higher integration into global value chains.

This evidence is essential for assessing the historical path and the potential opportunities for the discussions on the country's catch-up and upgrading strategy. Industries with the highest levels of innovation capabilities are natural sources of country-relevant best practices and role models subject to be upscaled. These industries share most aspects of the national institutional environments; thus, the cultivation of these local competences could be more sustainable than copying from abroad. The follow-up industries with higher shares of firms capable of participating in global value chains are the best available candidates for further upgrading. Further analysis of the regulation pitfalls, barriers, and bottlenecks relevant for these industries might have the most significant effect in terms of strengthening the country's innovation capabilities. Sectors with low innovation capabilities raise red flags signaling of moderate problems in industrial organization, the efficiency of competition, and growth potential. These industries should be approached with a portfolio of crisis management policies aimed at understanding the scope and nature of systemic failures relevant to these economic activities.

6.4.4 Discussion in the Context of Russia's Technological Upgrading and Economic Catch-Up Agenda

Composite indicators of output-based innovation modes contribute to a more profound understanding of the upgrading dynamics of Russia and help to identify the potential pitfalls and perils of reductionistic views on the mechanisms of developing the country's innovation capabilities.

General agenda of economic catching-up has been central for the post-soviet Russia's development discourse. There has been clear recognition of the decisive role of science, technology, and innovation in establishing new sustainable growth models and facilitating the structural change (Gershman et al. 2018). Preserving the high-tech industries and R&D complex (research organizations and universities) inherited from the Soviet period was the central objective of the policies after the 1990s (Gershman and Kuznetsova 2016). Significant efforts by the policymakers have been related to attempts to increase the efficiency of the national innovation system (Gershman et al. 2018; Gokhberg et al. 2018; Gokhberg and Kuznetsova 2011; OECD 2011; Simachev and Kuzyk 2018). The gap between the supply of innovation and the market-driven demand has been inherited from the top-down model of the planned economy and remains persistent. The national innovation system-building efforts included establishing a set of development institutions aimed at supporting and promoting the innovation activities of different actors (e.g., the Russian Venture Company, Rosnano, Skolkovo), investment into infrastructure (establishing the networks of business incubators, technology parks, and technology transfer centers). Specific initiatives targeted facilitation of interactions of different actor types, for example, fostering cooperative projects between companies and R&D organizations (Roud and Vlasova 2020) and promoting the innovation within major state enterprises (Gershman and Thurner 2016). In 2018 the agenda of innovation was formally stated at the highest level of the strategic policymaking by listing "facilitation of the technological upgrade and increasing the share of the enterprises introducing technological innovation" in the President's decree on the National Development Goals to 2024 on a par with "promotion of digitalization of the economy."

However, despite the impressive effort, the effects of the innovation policies in Russia remain modest. Given the nominal existence of numerous strategic documents and support measures, and significant multi-year expenditures, innovation policies do not produce detectable impact (acceleration of growth, diversification of the economy, an increase of productivity, technological modernization, increased share of non-resource exports, etc.).

Systemic analysis of the national innovation system performance enhanced by new composite indicators of innovation capabilities brings in new evidence to the discussion on the causes of limited efficiency in innovation policy governance in Russia.

First, the dynamics of innovation capabilities provides a solid illustration that the core of advanced innovators and active participants of the global value chains remains stagnant and does not create noticeable change over sixteen years of observation. Many of the examined industries demonstrate only a basic ability to innovate (that is, the dominant share of innovation-capable firms remains minimal in these industries as such, decreasing the momentum of growth and limiting the potential to development). This means that all the policies immediately aimed at promoting advanced innovation (e.g., those to facilitate active industry–science cooperation) are at risk of targeting a minimal set of enterprises. In contrast, others will not even express their interest in the policy measures not explicitly tailored to their needs.

Second, there is a definite tendency that the share of firms with baseline innovation capabilities is growing, distributed among different industries. As shown, the efficiency of these innovation "newcomers" remains the lowest compared to more advanced innovation modes. At the same time, these "baseline" innovators may go unnoticed by the policymakers biased towards "high-tech myopia" and having excessive expectations on the level of innovation novelty worthy of state support. Ignoring the initial levels of innovation capabilities accumulation is likely one of the most significant factors hampering the efficiency of catch-up policies.

Third, the gap between the firms acting at the national productivity frontier and the laggard firms is shrinking too slowly, which has systemic consequences for efficient policymaking. The extrapolation of this process might lead to the growth of economic inequality of industries, and widening gaps in productivity and technological level between leaders and "lagging behind," bringing the risks of value chain breaks. The policies should target at upscaling the revealed cases of sectoral regimes favorable for innovation, being aware of the intra-sectoral heterogeneity of firms and differences in their capabilities and needs.

Composite indicators of output-based innovation modes provide the quantification of the dynamics of innovation capability accumulation processes and help to reveal the diversity of actors between and within industries. It allows the formulation of a set of recommendations to increase the efficiency of innovation and technological upgrading policies in Russia.

Given the limited scale of the innovation across the economy, the first priority of the development agenda should be to improve the business climate and institutional environment to stimulate innovation-driven competition. The logic of policies should move away from "supporting the best" to the idea of promoting mass innovation in all the industries in order to stimulate the processes of accumulating a basic level of innovation capabilities. This can be implemented through the development of horizontal instruments to stimulate innovation. These instruments must take into account actual strategies of innovative behavior (in the case of Russia—the dominance of technology adoption and local imitation) and possible trajectories of company innovation capabilities development (manifest incentives and support for switching from passive adoption to in-house development, from local to international imitation, etc.). The target for the policy instruments must be involvement of a wide range of companies, especially small and medium-sized ones, including in sectors of their mass presence (services, creative industries) beyond the usual suspects from "high-tech," as the economic effect of the increased momentum of innovation could be an immediate reward for government effort. The efficient policy framework should include a cross-cutting policy evaluation system that relies on the ex-ante and interim estimates of the demand for the policy measures from different types of actors the ex-post post estimates expressed in the stimuli to accumulate innovation capabilities for different starting conditions and business models.

6.5 Concluding Remarks

Finding reliable, robust, and internationally comparable indicators for innovation capabilities remains a non-trivial task both for researchers and decision makers. By definition, economic catch-up and upgrading are associated with successful transformative change. The evolution of complex economic and technological systems depends on the country's potential to encourage development and adoption of innovation, to foster dissemination and scaling-up of advanced practices (Geels 2002; Geels and Schot 2007). Maintaining the momentum of change is crucial to exploit the available windows of opportunities (Lee and Malerba 2017) and to avoid traps of intermediate success (Lee 2013). Thus, the promotion of innovation capabilities remains central to effective catch-up and upgrading strategies (Radosevic and Yoruk 2018).

Internationally harmonized innovation surveys based on the *Oslo Manual* Framework is the most comprehensive statistical effort to measure the changing nature of innovation capabilities rigorously. Two decades of data collection led to the creation of large-scale databases on the firm's innovation activities in a broad range of countries. However, the most promising potential of innovation surveys as a source of evidence for catch-up and upgrading studies and policymaking is yet to be unleashed.

The surveys enable the construction of composite indicators based on firm-level data that are particularly suitable to address the heterogeneity of innovation strategies and to observe the processes of capability accumulation at national, regional, or sectoral levels through coherent and reproducible procedures. Indicators that emerge from the internationally harmonized innovation surveys help to operationalize and measure the upgrading as a process of accumulating innovation capabilities. It can be translated into the language of measurable indicators as a systemic shift of the innovation actor's strategies towards the more sophisticated types of behavior.

The insight brought through these indicators may provide valuable evidence for planning and evaluating national policies for technological upgrading and catch-up, which is especially essential for the developing economies. A generalizable lesson is that understanding the availability and the diversity of actors at different levels of innovation capabilities and the specificities of their demand on policy support is mandatory to develop efficient policy instruments. The analysis presented in the chapter illustrates that even a large-scale policymakers' effort may remain unfruitful given the lack of adaptability of the policy frameworks.

Furthermore, promoting the use of internationally harmonized data on the firm's strategies and capabilities allows news ways to addressing path-dependence, a central feature of transformative processes in complex institutional systems. The research on institutional development tends to explore two extreme cases of system dynamics: lock-in and revolutionary change (Hart 2009). The first means stability and continuity of institutional arrangements observed for longer timespans (Bergek et al. 2008; Freeman 1995) detectable at national (North 1994) or regional levels (e.g., "place dependence" discussed by Martin and Sunley (2006)). The second case is traditional for ex-post analysis of major socio-economic (or political) shocks. The shocks disrupt the routines and move the systems to new trajectories (Freeman and Louçã 2001) subject to becoming as inertial as pre-shock tendencies. Fewer studies (e.g., (Hart 2009)) concern the dynamics between these extrema, that is gradual development and co-evolution of actors and systems, referred to as "bounded change" (Hall and Thelen 2008; Streeck and Thelen 2005; Thelen 2004). Firm-level indicators that focus on the heterogeneity of actors are a valuable aid for further research of "bounded change" and investigation of the "black box" mechanics of competitiveness, which, in turn will lead to the next generation of evidence-based policy frameworks of catch-up and upgrading.

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PART II

TECHNOLOGY CAPABILITY UPGRADE AND SECTORAL CATCH-UP

7
Macro and Micro Foundations for Technology Upgrading and Innovation

The Case of Shipbuilding and Offshore Industry in Brazil

André Cherubini Alves, Nicholas S. Vonortas, and Paulo Antônio Zawislak

7.1 Introduction

The question of how less developed economies build their pathway to prosperity has been of interest to research for quite a long time. Reaching the "developed" status requires countries to catch up by building technological capabilities (Abramovitz, 1984; Lall 1994; Bell and Pavitt 1995) and eventually technologically upgrade on innovation capabilities to compete in global markets (Radosevic and Youruk 2016). Nevertheless, few middle-income countries have been able to join the developed world since 1960, suggesting that there is no simple formula or simple factor to this process (Gill and Kharas 2015). Instead, emerging countries often find themselves stagnated into a middle-income trap (Gill et al. 2007; Griffith 2011; Lee 2013; Agénor 2017).

Recent literature has called attention to mission-oriented policies in setting the directions of technological change and market dynamics through innovation. More than serving as market regulators driven by a view for correcting market failures, in this view, governments can help create and shape markets through targeted, innovation-led policies (Mazzucato 2013, 2015). The tools used by the government for this purpose are, however, still up for debate (Ergas 1987; Brown and Mason 2014; Foray 2018; McKelvey and Saemundsson 2018). It seems that upgrading is a much harder task than policies can possibly and intentionally induce. It is highly dependent on idiosyncratic and complex combinations of the "institutional landscape," techno-economic "windows of opportunity," and the ability of individual agents to take advantage of such landscape and windows to create new trails of development (Lee and Malerba 2017). Cases of failure are usually more frequent than successful ones, seemingly even when conditions seem right. Under such perspective, what needs to be put together to prevent the failure of a development initiative? Which are the building blocks of a winning policy?

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In this chapter, through a detailed case study on the innovation and industrial policy of the Brazilian Shipbuilding and Offshore sector, we describe and analyze the institutional setting put in place to boost technological and industrial development. The investigation highlights the necessary core elements—the *macro* institutional-market governance, the *meso* industry techno-economic-coordination structure and the *micro*-level techno-organizational capability and learning mechanisms—to be intertwined by the policy.

The policy was motivated by the discovery of supergiant oil fields in ultra-deep waters in the coast of Brazil (called the Pre-Salt) in the mid-2000s. Based on the commercial prospects of the oilfields' exploitation, the Brazilian Government foresaw the possibility for catching-up and upgrading, especially in the offshore oil production segment. The high and urgent demand for offshore production platforms and oil tankers coming from Petrobras (the Brazilian Oil Company) and a long waitlist shipyards' order books around the world, motivated the search for national alternatives. Exploring the Pre-Salt layer and its potential for rebuilding the local shipbuilding industry was argued to represent Brazil's "passport to the future" in terms of job creation, technological upgrading, and innovation. Local content policies, tax incentives, trade-barriers, special funding by the Brazilian Development Bank and the commitment of Petrobras to be the ultimate buyer of technology and vessels developed and assembled in Brazil suggested the "perfect" window of opportunity for Brazil to re-enter the market to become a major power.

Against all expectations, the strategy has not fully succeeded. Even though the set of policies inaugurated was able to mobilize a large number of actors and resources around the country, the industry ultimately failed to catch up and innovate to the extent required by the circumstances.

We argue that technological upgrading strategies and policies in developing countries are meant to cope with the imprecision of "building innovation capabilities for market creation" versus "market creation for building innovation capabilities." Due to bounded rationality and uncertainty behind all coordination decision-making processes (Simon 1997), it is impossible to foresee the exact upcoming shape of the market as well as the exact scope of the required innovation capabilities. Uncertainties increase with the complexities associated with the need for technology mastering and industry coordination which ultimate generate high-capability building costs (Alves 2015).

The central thesis of this chapter is that these capability building costs arise from systemic frictions originated from institutional, technological, and coordination-based issues which prevent the catching-up process. These frictions often hinder learning and thus inhibit the effective implementation of policies for technological upgrading. Finding the right balance between policy intentions and the actual potential of economic agents to learn and meet the task is difficult. In this sense, contrary to the idea that imitators' relative costs to build capabilities tend to be lower than innovators' (Perez and Soete 1988), macro-, meso- and micro-level uncertainties (such as government mismanagement, latent moral hazard, and opportunism) can significantly increase capability building costs to imitators.

The remaining of this chapter is organized as follows. Section 7.2 builds our analytical framework based on three core elements. Section 7.3 presents the procedures to gather evidence on the specific case study to support the arguments presented in this chapter. Section 7.4 unfolds the case of the shipbuilding industry in Brazil on the basis of the analytical framework described earlier. This section is divided into a brief history of the sector in the country, the recent macro institutional and industrial setup that provided a unique window of opportunity, and the outcomes at the very micro-level where catching-up and upgrading were supposed to occur. Sections 7.5 and 7.6 contain the final discussion and overall conclusions of the study.

7.2 Macro and Micro Foundations for Technology Upgrading and Innovation

Understanding the reasons that underlie the different growth rates among national and regional economies has been on the research agenda of economists since the very beginning of the filed, nevertheless, no simple formula exists. Innovation, however, is widely recognized as the key element in this process and goal worth pursuing as policy (Schumpeter 1912; Solow 1956; Lundvall and Maskell 2003; Fagerberg and Srholec 2009). This process pertains to the economic dynamics requiring and at the same time allowing the building and nurturing innovation capabilities by economic agents (Klein 1997).

This is of key importance to latecomer economies where the embryonic levels of extant capabilities often require economic agents to go through a process of catching-up first to try to eventually forge ahead (Abramovitz 1986). This, however, is not a straightforward process as catching-up does not occur in a linear way (Lee 2018). Moreover, the complexity of economic and institutional settings in different regions makes technological upgrading a multidimensional process that transcends individual measures such as R&D investment (Radosevic and Yoruk 2017).

Earlier frameworks suggest that different national models of development should be supported by intertwined pillars such as the mode of regulation, accumulation regime, and the technological paradigm (Aglietta 1979; Lipietz 1987; Boyer 1990). They have attributed the different technological cycles and the country-specific configuration to the dynamics of technological trajectories, the organization of industrial sectors, and the institutional conditions of the market (Freeman and Perez 1988). More recent studies propose a set of dimensions to measure technological upgrading and innovation such as the intensity and the types of the targeted technology (scope), the breadth of technological upgrading and its infrastructure (scale), and the interactions of the industry with the economy (Rodosevic and Yoruk 2017). Building capabilities creates intrinsic dynamics that self-reinforce firm and social knowledge creation, positively influencing national levels of competitiveness (Fargerberg and Shorolec, Chapter 2, this volume).

Inspired by all of them, we propose a step forward: to consider the macro, the meso, and the micro foundations behind the scope, the scale, and the bonds of technological upgrading and innovation. Any catch-up policy, in order to bring about technological upgrading and innovation, should consider the institutional-market governance (the macro foundation), the industry techno-economic coordination structure (the meso), and the existing techno-organizational capabilities and learning mechanisms (the micro), as shown in Figure 7.1.

The following sub-sections explain how each one of the three core elements contributes to technological upgrading and innovation.

7.2.1 Institutional-Market-Governance

Institutions have long been recognized as an important factor in shaping the techno-economic environment (Nelson 1991; North 1991; Lall 1992; Edquist 1997; Malerba 2006). Institutions promoting technical-economic growth often partake in the form of mission-oriented programs (Bush 1945; Nelson 1959 Arrow 1962). Historical mission-oriented programs in the twentieth century can be traced back to the post-war development in the USA with the creation of National Science Foundation, R&D investments in defense and space exploration (Mowery 2010; Pisano and Shih 2012), and the computer industry (Langlois and Mowery 1996). Such heavy-handed approaches are especially important for developing countries, where mission-oriented policies can target "embryonic" sectors and markets subject to lesser uncertainty about the desired policy objectives. Even though policies for innovation are often focused on the future, in developing countries traditional sectors often need to focus on earlier

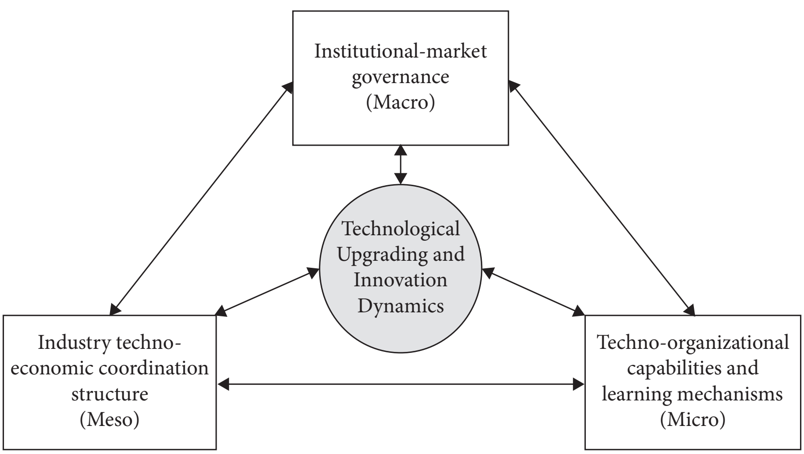

Figure 7.1 Macro, meso, and micro foundations for technological upgrading and innovation
Source: Authors.

stages of catching-up, which may eventually lead to leapfrogging opportunities (Lee and Lim 2001; Lee, Chapter 5, this volume).

Catching-up relates to the ability of a country to narrow the productivity and income gap vis-à-vis a leading country (Abramovitz 1986; Fagerberg and Goding, 2005). While this process has sometimes been simplified to a matter of speed in a "fixed race track" where technology is unidirectional and pre-determined (Perez 1988), more recent research has pointed out that catching-up does not follow a linear path and that latecomers usually take alternative paths to build their own (Lee and Lim 2001), since catching-up requires followers to chase a moving target (Lee 2018).

Successful catching-up requires a mix of conditions and opportunities to take place. Lee and Malerba (2017) and Lee (2018) highlight that catch-up cycles usually happen around windows of opportunity of three types: new technology; new market demands from consumer and users; and public policy. In the case of the latter, these windows are often intertwined. One of the primary ways of creating new markets for innovation is through public procurement (Edquist and Zabala-Iturriagagoitia 2012; Edquist et al. 2015). Governments can often initiate the catching-up process by procuring and opening markets (Gao, Chapter 14, this volume). However, while the "government can create the right conditions, ultimately management decision will determine what happens" (Pisano and Shih 2012, p. 20). Both government policies and investment decisions of private enterprises will determine what capabilities are fostered and where (Lundvall and Maskell 2003). High levels of learning and of technological and marketing capabilities are a key requirement for successful responses by latecomer firms (Lee and Malerba 2017).

7.2.2 Industry Techno-Economic Coordination Structure

Different from catching-up targets set by macro policy, technological upgrading depends on a broader concept that involves several meso dimensions that go far beyond general goals or specific research and development (R&D) activities. It takes into account structural dimensions for change such as industrial, technological, and organizational interaction with local and global actors in the form of investment flows and technology accumulation activities (Radosevi and Youruk 2017).

In this sense, windows of opportunity are necessary but not sufficient for creating sustainable market growth. Markets rely on the concrete interplay of producers and consumers from which the organization of the industry will emerge. While the institutional setup can temporally create a market, it should also foster the conditions to leverage existing capabilities and build new ones that allow firms to constitute an enduring market. In fact, a precondition of market creation is to build capabilities, which are often unavailable in the case of latecomers, and are also difficult to master and costly to develop.

If, by institutionally generating market reserves and incentives, governments intend to reduce transaction costs allowing national actors to internalize and make feasible (formerly unavailable) capabilities and technological interfaces, it is vital that those local actors (e.g. firms, science & technology institutions, regulatory agencies, etc.) be able to execute their complementary roles in order to concretely allow knowledge to be absorbed, operated, and developed. To really reduce transaction costs and allow capability building, these systemic relations depend on established structures, such as national and sectoral systems of innovation (Nelson 1993; Malerba 2002; Lundvall and Maskell 2003). In short, the industry techno-economic coordination structure works as the necessary link between the policy goals (which aim at catching-up), and the concrete agents responsible for leveraging and building capabilities.

The mismatch between policy intentions and the possibilities of available local capabilities creates a fuzzy horizon for technological upgrading, which frequently results in unsuccessful technology policy efforts. In developing country contexts, avoiding a paradox of negative returns to R&D investment requires coordination capabilities such as managerial skills, as a first step towards building technological capabilities (Cirera and Maloney 2017).

7.2.3 Techno-Organizational Capabilities and Learning Mechanisms

The literature on building technological capabilities has a long tradition. Technological capabilities have been defined on the one hand as "the ability or proficiency to make effective use of technological knowledge" (Westphal et al. 1985, p. 171) and as the capabilities needed to generate and manage technical change (Bell and Pavitt 1995). Technological and organizational capabilities can be considered the basic step toward upgrading as firms are unlikely to compete effectively if they are unable to decide on their investment on equipment and processes to reach minimum levels of efficiency (Lall 1992). Capabilities are first driven by firms' knowledge of the production process and evolve by a path-dependent process of complementary investments and learning-by-doing (Jacobides and Hitt 2005).

Usually, this process follows, as Kim (2001) argues, the building of production capabilities first and innovation capabilities later. Literature on catching-up of manufacturing firms from developing nations uses a stereotypical path from imitation to innovation as follows. First firms enter the market as Original Equipment Manufacturers (OEM) by licensing the production of foreign technology. Over time, firms develop engineering capabilities and can become Original Design Manufacturers (ODM). Eventually successful firms may enter markets with their own products as Original Brand Manufacturers (OBM) (Hobday 2000). Lee, Baek, and Yeon (Chapter 4, this volume) argue that catching-up results from the ability of companies and countries to transition from "implementation capabilities" based on efficiency and learning-by-doing to "design capabilities" based on differentiation and learning-by-building.

This is important as beginning with the latter is unlikely if one wants to gain competitiveness in an existing industry.

While a useful pedagogical model, however, the above masks the fact that building technological capabilities also requires organizational capabilities relative to how firms efficiently orchestrate internal resources and assets (Dutrénit 2000) and specific learning mechanisms designed to both absorb external knowledge and to develop new ones through research and experimentation (Bell and Figueiredo, 2012). Moreover, a whole set of innovation capabilities that cope both technological and business drivers are to be fostered (Zawislak et al. 2012). In this sense, catching-up and technological upgrading are highly dependent on the effectiveness of learning where absorptive capacity helps reduce the cost of building capabilities (Cohen and Levinthal 1990).

The inability to master innovation capabilities and thus to orchestrate technological interfaces undermines the possibility of conducting economic transactions in the future (Alves 2015). Complexity in the knowledge and in the number of necessary technological interfaces can generate several difficulties in building capabilities.

7.2.4 Capability Building Failures and Costs

We argue that effective technological upgrading requires the interrelation and interplay between the three core elements above to a balanced whole. Successful catching-up processes rely on a series of institutional programs and tools that creates the fundamental industrial conditions for technology upgrading. Yet, the concrete technology upgrading is directly dependent on which and how capabilities are in fact built and mastered at the micro-level. Institutional voids, lack of coherent industrial-coordination structure and shortage of techno-organizational capabilities for effective learning generate frictions that are costly and bound to failure.

These frictions arise from similar sources predicted by transaction cost economics such as government mismanagement, moral hazard, opportunism, and bounded rationality about the behavior of individual agents (Williamson 1985). Beyond the mere transaction or production costs are technology transfer costs—"the costs of transmitting and absorbing the relevant firm specific knowledge" (Teece 1977)—and costs related to coordination and supplier-switching costs (Monteverde and Teece 1982). These are akin to what Langlois (1992) calls "dynamic transactions costs," that is, the "costs of persuading, negotiating and coordinating with, and teaching others" or, simply, "the costs of not having the capabilities when you need them" (p. 113). Capability building costs are *dynamic learning costs* that must be taken into consideration by policies for capability building and upgrading as they will influence the economic scope and the rate at which new industries can and will dynamically grow.

7.3 Research Methods

This study is the result of a three-year research project on industrial organization dynamics intended to identify the strategies for building capabilities and a chain of technological interfaces in the shipbuilding and offshore sector in Brazil. The research mapped the main shipbuilding clusters in Brazil as well as the institutional support systems in order to identify how different players interact, cooperate, and choose among available technological packages what made sense to vertically integrate domestically.

We conducted an in-depth literature review on the history of shipbuilding in Brazil and the recent mission-oriented policy framework that was set up to underline the industry's re-emergence. Secondary data sources also included specialized literature such as publications by the Institute for Applied Economic Research (IPEA), by PETROBRAS, by the National Shipbuilding and Offshore Association (SINAVAL), and by the National Organization for the Oil Industry (ONIP). We then moved to analyze a concrete case with the outcomes of such policies (Table 7.1).

Primary data for putting together the story of the recent re-emergence of the Shipbuilding and Offshore sector in Brazil was obtained through eighteen interviews and on-site visits of shipbuilding sites, whereby we observed the evolution and challenges from project development, project coordination, and construction, pared with parallel policy efforts from creating the market to actually building it (Table 7.2).

In order to understand the dynamics of capability building and challenges, the research involved the detailed description of the boundaries and interfaces in one of the most emblematic shipyards codenamed SHIPYARD A. This part of the research involved three weeks of visits, interviews, and data collection on site. The shipyard used in the case study was producing at the time a hull to be later integrated in SHIPYARD B in the region of Rio de Janeiro.

7.4 Technological Upgrading and Innovation in the Brazilian Shipbuilding and Offshore Industry

The Brazilian shipbuilding industry has a long history reaching back to the sixteenth century in connection to small vessels and marine arsenals. Private investment, however, started practically in 1846 in Niteroi (Rio de Janeiro) influenced by the English Industrial Revolution. Entrepreneur Barão de Mauá transformed a little foundry into the biggest shipyard in the country at the time.

The first policy-based boost of the sector arrived in the 1950s during the presidency of Jucelino Kubitsheck and the "Plano de Metas" which intended to accelerate progress and economic growth of "50 years in 5." During this period, the Merchant Marine Fund (FMM) was created alongside the National Development Bank (BNDES), aiming at promoting the renewal and increase of the national fleet, reduction of both ship imports of ships and charter costs of foreign ships, and stimulation

Table 7.1 Levels of analysis, research, method, and data sources

LEVELS		Research conducted	Sources of data
National (N)	MACRO Institutional-Market Governance	• on the evolution of shipbuilding in Brazil from its early emergence to the later decline; • A description and analysis of the recent institutional setup to allow the re-emergence of shipbuilding and offshore sector in Brazil.	• Previous Literature • Information obtained in sectoral conferences and symposiums. • Documents provided by PETROBRAS and Industry representative institutions SINAVAL
	MESO Industry Techno-economic Coordination Structure	• A description of the industrial configuration and coordination structure • Mapping of the shipbuilding clusters	
	MICRO Techno-organizational Capabilities and Learning Mechanisms	• Description and analysis of the general interface plan of the Shipbuilding Project • Description and analysis of the *dynamics* of capability building and challenges	• Dataset and documents provided by the firm; • Interviews and on-site observations

Table 7.2 List of organizations and interviews

Company and Location	Interface	Title of the interviewee
PETROBRAS (Main Client) *Rio de Janeiro*	Planning (Head Quarters) Engineering (CENPES) Construction Management (ESTALEIRO BRASFELS - SHIPYARD B)	1. Local Content President Assessor 2. E&P R&D 3. Interface Manager
ESTALEIRO RIO GRANDE—ECOVIX (SHIPYARD A) *Rio Grande*	Engineering • Detailed Engineering • 3D	4. Engineering Director 5. Chief of Detailing Engineering 6. 3D Manager
	Planning	7. Strategic Planning Manager
	Procurement	8. Procurement Director
	Structure Construction • Structure • Block Assembly	9. Chief of Construction 10. Chief of Structure Division 11. Block Assembly Manager
	Advanced Finishing • Outfitting • Piping • Paint • Architecture	12. Chief of Advanced Finishing Division 13. Outfitting Manager 14. Piping Manufacturing Planning and Control Manager 15. Paint Manager 16. Architecture Manager
ULTRABLAST *Rio Grande*	Paint	17. Production Planning and Control Manager
ABS *Rio Grande*	Certifier	18. Surveyor

of ship exports (Foster, 2013). Over the next twenty years, foreign direct investment resulted in the setting up of major shipyards in Rio de Janeiro. Ishibras from Japan and Verolme from the Netherlands established operations in Rio de Janeiro alongside the national shipyards Caneco, Mauá, and Emaq. Another shipyard, Só, was established in Porto Alegre during the same period. By 1975 Brazil had reached second place in shipbuilding orders worldwide, behind only Japan.

A major bust in the cycle followed as a result of economic problems facing the country in the next decades. Tight monetary policy resulted in lesser subsidies to the industry, and the removal of large local content requirement eliminated the generous terms offered to foreign customers. Disinvestment led to delays, cost overruns, and technological downgrade in the sector. The Brazilian fiscal crisis and the inability to compete either in terms of quality or in terms of costs led to the total decline of the sector by 1980 (Cho and Porter 1986). As a result, the Brazilian shipbuilding industry had eroded significantly by the early 1990s.

The industry would eventually re-emerge in the 2000s as Brazil was able to balance its fiscal deficit and manage inflation. A major role in this re-emergence was played by the new off-shore oil discoveries. The prospects of oil found in the "Pre-Salt" layer—the big offshore area along the sea coast of Rio and São Paulo—were the major push elements for rebooting shipbuilding. The estimated deposits of 15 billion barrels of oil equivalent (BOE), potentially placing Brazil among the top ten oil producers in the world, was the green light for new market creation. This is the part of the story we concentrate upon herein. In this section we present the case and how the macro, meso and micro core-elements interplayed resulting in the successes and failures.

7.4.1 Setting the New Institutional-Market-Governance Framework (MACRO)

As the deepest oil fields ever discovered until now, the Pre-Salt Oil reserves required significant technological advancement in order to push back the frontier of drilling and oil recovery from ultra-deep waters. Following a variety of complex strategies for access, adaptation, and creation of new technologies (Furtado and Freitas 2000), the Brazilian state-owned oil company, Petrobras, eventually emerged at the forefront of deep-water oil exploration and production. From 410ft in 1977, the company reached depths of more than 8000ft in 2010 (Furtado and Freitas 2000; Petrobras 2009). Sub-sea technologies require the work of specialized professionals in different domains of engineering, geology, and geophysics. So much so that the importance and complexity of these challenges have been named as the Brazilian "space-race" in analogy to the American-USSR space race during the 1960s. Technological development and the "race" to explore and produce, in turn, created high demand for different types of vessels to sustain operations. The relative costs and long wait list of orders at the time created the incentives for the country to find a solution and build ships and oil rigs in Brazil.

In 2002 Petrobras announced it was going to buy two offshore oilrigs (P-51 and P-52) from overseas companies as part of its *Program for Offshore and Support Vessel Fleet Renovation* initiated in 2000. The announcement generated a strong counter-reaction from labor unions arguing against the external purchase of these two platforms. The unions demanded that the platforms should be constructed domestically, generating jobs to local labor. President Luiz Inácio Lula da Silva, sensitized by those issues, changed course and promoted the idea of domestic production of the platforms. This triggered a series of legislative acts and policy changes summarized in Figure 7.2.

A new public bid was called later that year, requiring the two platforms to be built in Brazil (Foster, 2013). A legislative Act[1] created the National Program for Mobilizing the Oil & Gas Industry (PROMINP) aiming at maximizing the participation of

[1] Decree Nº 4.925 of 19 December 2003. http://www.planalto.gov.br/ccivil_03/decreto/2003/d4925.htm//, accessed 18 January 2021.

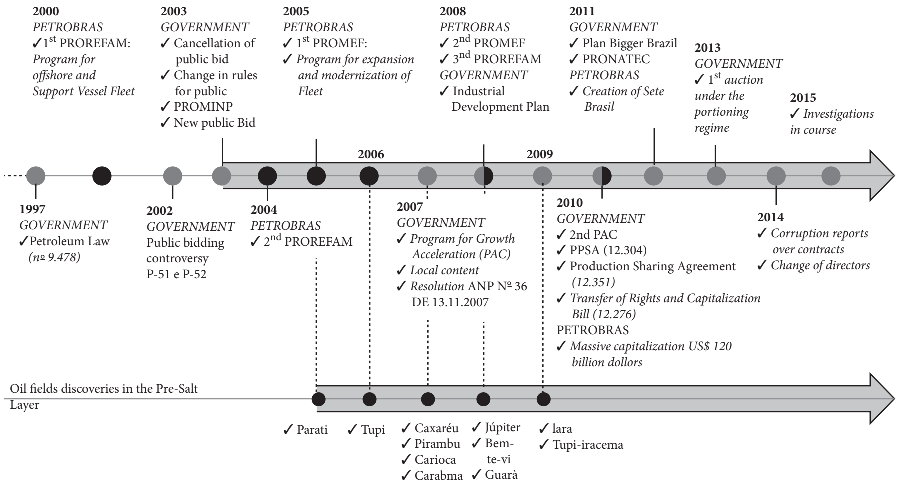

Figure 7.2 Chronology of policies targeting the Brazilian shipbuilding industry
Source: Alves 2015.

national suppliers of goods and services to the Oil & Gas industry. This organization was supposed to map the national capabilities and provide training in several related fields of shipbuilding to the oil industry. Furthermore, in 2007, the Brazilian government instituted the Program for Growth Acceleration and placed the shipbuilding industry as one of the key national strategic sectors to generate wealth and create jobs (De Negri, 2013). In the same year, the National Oil Regulatory Agency created a resolution[2] for minimum local content requirements.

In 2010, Petrobras announced the biggest capitalization in history, amounting to 120 billion dollars borrowed to fund the exploration, development, and production of the Pre-Salt fields. The purchasing power of the company was directed to national shipyards in order to stimulate the national supplier base to meet the demands for renewal of their fleet of platforms, tankers, and support boats. In 2011, Petrobras alongside other major construction companies created SeteBrasil SA, a company responsible for the drilling operations of the Pre-Salt fields. The company placed several orders of drill ships to various domestic shipyards.

The demand for oilrigs, tankers, and support vessels came from companies already involved in the offshore oil exploration and production activities. Petrobras was placed at the center of this endeavor. The National Oil Agency (ANP) created the Local Content resolution in 2007. This resolution required that every concessionaire that would be producing oil in the Brazilian offshore fields must acquire a minimum of 65 percent of goods and services from national suppliers. The National Organization of the Oil Industry (ONIP) certified suppliers in order to participate. Local content

[2] ANP Resolution Nº 36, de 13.11.2007.

policy created a local market reserve for national suppliers, thus, providing incentives for local suppliers to gradually build capabilities and gain capacity.

The existing oil and offshore industry and the local content resolution set the foundations of the current Brazilian legislation defining three exploration regimes: *production sharing; concession; and transfer of rights regime.*[3] The *production sharing agreement* stated that all oil from the Pre-Salt fields was the property of the state. The state-owned oil company is guaranteed to participate in the exploration while it may not be the main operating firm in the field. The operating firm to be contracted through a public bid is responsible for exploring and extracting the oil and paying for all operational expenses, in exchange for part of the value from the oil fields. The operating firm absorbs all costs and risks from exploring the specific field and does not have any right of restitution or compensation in case the oil field is not tradable. In the *concession regime*, the extracted oil is the property of the operating firm during the timeframe stipulated in the contract in exchange for financial compensation to the state. This compensation comes in the form of taxes and royalties. Finally, the *transfer of rights agreement* stated that the government may give to Petrobras the rights over the activities of exploration and production in certain areas of the Pre-Salt fields with up to five billion barrels and Natural Gas at the company's own expense and risk. It was a way to compensate for the company's capitalization effort to supporting industry.

With the demand side institutionally set local content requirements alongside incentives such as tax exemption and direct financial support for equipment producers provided the first step to promote the supply side. By linking oil-producing firms to national shipyards and with the engineering, procurement and construction (EPC) firms through contracts, a national market for shipping vessels and parts was stitched together to foster capability building all along the national supply chain. Complementary national training programs involving universities and technical schools aimed at mapping the national suppliers and at providing the necessary training in different fields.

The established set of laws, resolutions, and incentives was intended to reduce the comparative cost disadvantages of Brazilian suppliers vis a vis foreign competition and to stimulate the entry of new national players into the supply chain. Credit facilitation also allowed firms to obtain lower rates on loans to invest in activities related to the shipbuilding industry. Table 7.3 presents all resolutions to stimulate capability building and finance for innovation.

The idea of setting up a new institutional-market-governance framework for shipbuilding was to reduce transaction costs and enable economic viability for capability building. As aforementioned, the concrete leverage and building of technological capabilities is a *sine qua non* condition for technology upgrading, the major driver for catching-up. However, also as stated before, capabilities need a sort of "right environment," an industry techno-economic coordination structure, to thrive.

[3] Lei 9.478/97 (Lei do Petróleo), Lei 12.351/10 (Lei da Partilha de Produção), Lei 12.304/10 (Lei da criação da PPSA), Lei 12.276/10 (Lei da Cessão Onerosa).

Table 7.3 Policy incentives to stimulate the supply side

Incentives	Description	Legislation
Local Content	Local content requirements for vessels used in the activities of exploration and production of oil and gas in the Brazilian offshore oil fields.	ANP Resolutions 36 a 39/2007
Fiscal	Exemption of tax (IPI) for industrial production on parts and materials for the construction of ships in domestic shipyards. Zeroing of PIS/PASEP and COFINS taxes on equipment for the marine industry.	Act 6.704/2008 and Law 11.774/2008
Finance	Facilitating financing conditions to the sector through the Navigate Brazil Program, which introduced changes in access to credit for shipowners and yards, increasing the participation of the Merchant Maritime Fund (FMM) from 85% to 90% in the operations of the shipbuilding industry and increase in the maximum loan term from 15 to 20 years.	Re-edition Provisory Act 1.969/67
	Establishment of differential interest rates and participation in financing with FMM resources for those contracts that ensure local content rates of over 60% or 65%.	Resolution CMN 3.828/2009
	Creation of the Shipbuilding Guarantee Fund (FGCN) with the purpose of ensuring risk credit to financing operations for construction and production of vessels and the risk of performance of Brazilian shipyards.	Law 11.786/2008
Training	The institution of the Program for Mobilization of the National Oil and Natural Gas—PROMINP, which aims to enhance the participation of national goods and services industry, competitive and sustainable manner, the implementation of oil and gas projects in Brazil and abroad.	Act Nº 4.925/2003.

7.4.2 Defining the Industry Techno-Economic Coordination Structure (MESO)

With the institutional conditions set for the creation of a market and the establishment of an industry, Petrobras was used as the main engine for building it. It was the crystallization of the industry coordination structure and its unfolding in the domestic value chain. Three main roles were attributed to Petrobras: to secure demand, to orchestrate suppliers, and to invest in R&D.

As a state-owned company, Petrobras is responsible for the operational activities in Brazilian oil production and, in this mission, was also responsible for securing the demand through the acquisition of platforms and support vessels, ordered in Brazilian shipyards. Petrobras uses its subsidiary Transpetro for the transportation and storage activities of the oil products, which demanded a large crude-carrier fleet such as tankers and LNG carriers. SeteBrasil, specialized in the exploration and drilling activities, was responsible for placing the orders for the drill ships. Table 7.4 presents the size and values of orderbook as they were expected by 2012.

Petrobras was also responsible for managing the overall contractual interfaces, which guaranteed the effective orchestration of shipbuilding local and global

Table 7.4 Expected shipbuilding orders and investment by type for 2013–18

Vessels Type by Program	Number	Investment	Average cost/vessel	Investor
Support Vessels PROREFAM 1, 2 and 3	223	R$16.7 billion	R$75 million	PETROBRAS
Platforms FPSOs	22	R$53.9 billions	R$2.45 billion	PETROBRAS
Large Crude Carriers PROMEF 1 and 2	49	R$6.8 billion	R$139 million	TRANSPETRO
Drill ships	29	R$54 billion	R$1.8 billion	SETE BRASIL
Total		R$131.4 billion		

Source: Neto (2014). Data from 2012 reports of contracted orders.

suppliers as well as the shipyards. A major complex product system like this required staff to be placed in different shipyards to inspect and make sure contracts are being respected in terms of technical requirements and delivery schedule. The minimum local content requirements for different vessels—varying from 45 percent up to 70 percent of local sourcing—depend on the technological complexity, availability, and time to master the necessary technologies by local suppliers. Petrobras managed these requirements closely. The company had mapped all potential suppliers in Brazil for every single piece of technology, equipment, ship parts, and materials detailed in the engineering projects, providing it with a pretty good understanding of the gaps in the national industry. The company had also documented in several books the different pieces of technologies, which described the technology and informed what could be built in Brazil and what had to be outsourced abroad.

R&D investment was another core pillar to the strategy. The goal would be achieved by building innovation capabilities all along the value chain, from the main contractor (Petrobras) until the "last" supplier. Petrobras participated, at different degrees of involvement, in developing all process steps of shipbuilding—engineering, procurement, construction, and commissioning. Projects would be broken down into separate modules and integrated in different sites as shown in Figure 7.3.

The initial engineering processes for complex product systems such as shipbuilding involves defining the general technical description document, the Basic Engineering Project and the Detailed Project. Petrobras participation in these processes varied according to project complexity and interest. Generally, the company had to provide the general technical description to the shipyards or to the operating firms, reflecting the requirements for each platform or vessel to be built. The general technical description was elaborated at the company's Research Center (CENPES). When oil fields were chartered to a third-party operating firm, Petrobras provided the GTD leaving the full coordination and construction responsibility to the chartered firm. When Petrobras was the main operating firm, it could choose on the basis of project complexity. The higher the complexity of the project, the higher Petrobras involvement in coordination and intervention would be.

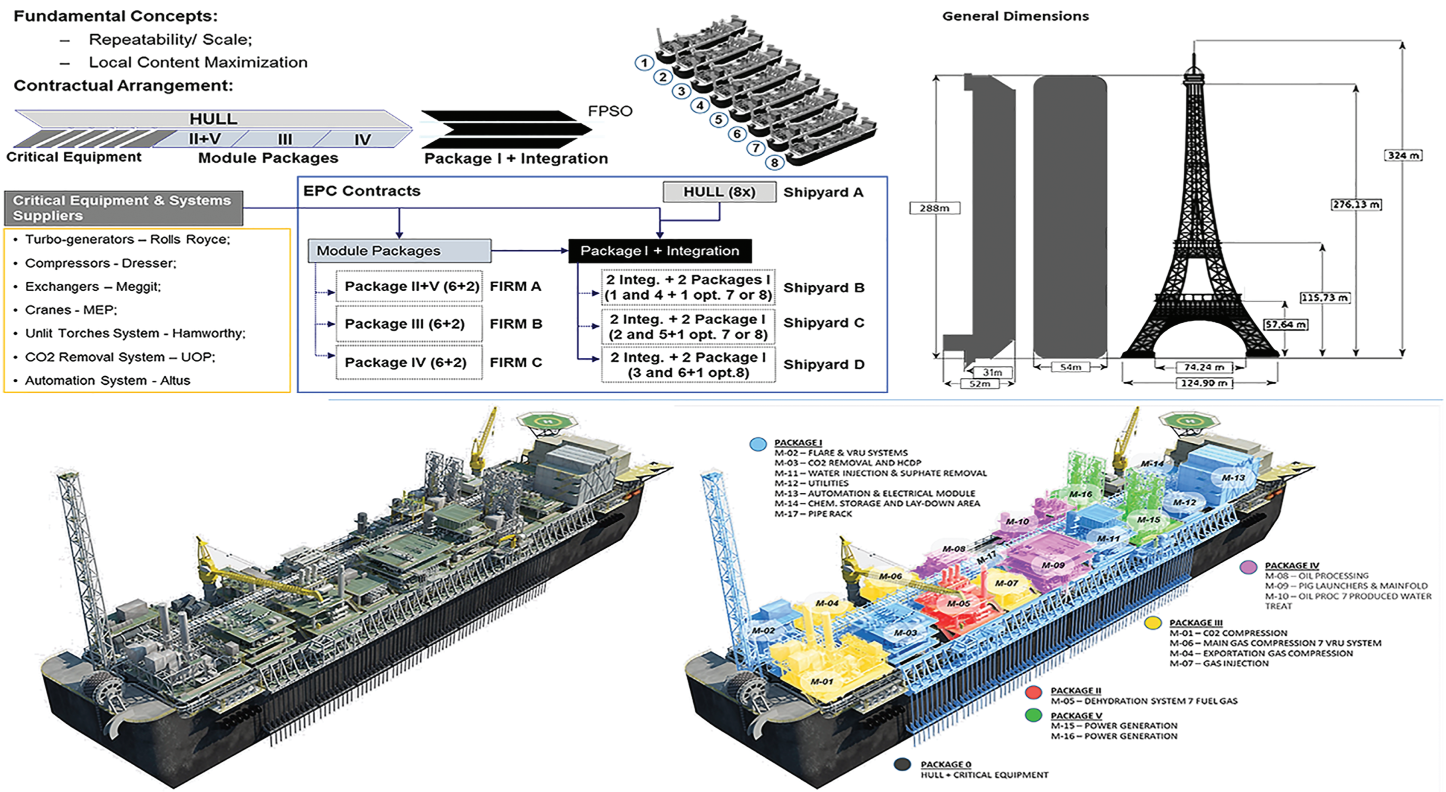

Figure 7.3 General view of the industry coordination structure

The overall success rate in terms of quality, delivery time, and costs was higher with chartered contractual mode.

The prospects and ambitious construction plans of Petrobras unleashed the interest of various states in benefiting from the construction of shipyards. Even though there was already shipyard infrastructure available from earlier phases of the Brazilian shipbuilding, a series of new shipyard projects were announced in different states bargaining to guarantee a part in the production chain. These new shipyards came to be called "virtual shipyards" as soon as they were based on actual orders and were going through the process of obtaining licenses to begin construction and finely operate.

Figure 7.4 maps the locations of these yards. The initial requirement for the shipyard operator was to either be an experienced firm or to show proof of an international partnership with an experienced company in the shipbuilding industry.

With little previous experience in the sector most domestic companies willing to participate in the public bids needed to show proof of their engineering, procurement, and construction capabilities based on their record in coordinating complex projects, and to also commit to establish technological partnerships with recognized shipbuilding firms in order to engage in technology transfer. Since shipbuilding in Brazil had nearly disappeared by 1990, new shipbuilding companies were almost all being built from scratch, combining local capabilities on other segments, such as industrial or construction. International partners came from Japan, South Korea, China, and Singapore providing special technological know-how.

Apparently, the industrial techno-economic structure, by the means of development and production activities, was established and would function under an integrated coordination effort, managed by Petrobras. However, the full functioning of this

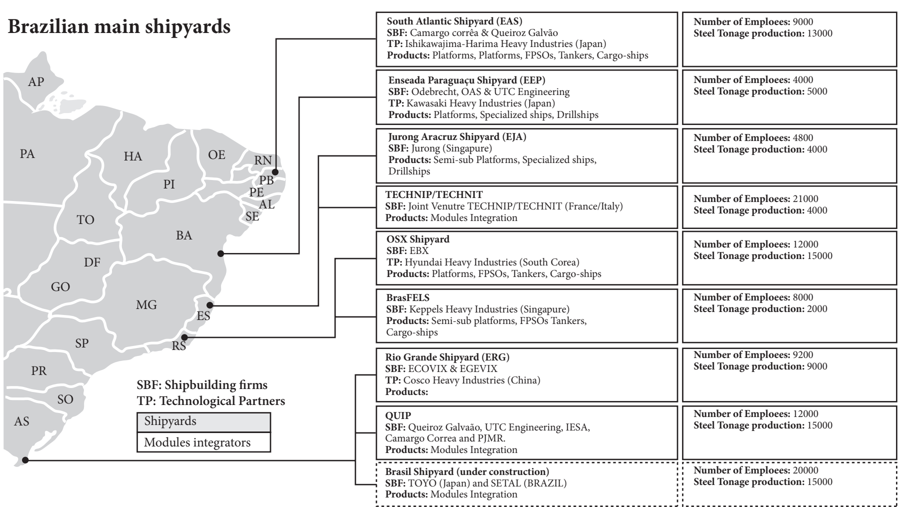

Figure 7.4 Distribution of Brazilian main shipyards

Source: Adapted from Alves and Zawislak 2014.

structure, under the logic and the dynamics of an effective supply chain, would depend on the leverage of existing techno-organizational capabilities and, especially, the building of new innovation capabilities at the micro-level. The example cases of specific shipyards are used to illustrate the micro-level technological and organizational capabilities and learning mechanisms in the nascent sector.

7.4.3 Techno-Organizational Capabilities and Learning Mechanisms: Shipyard A (MICRO)

Shipyard A was one of the biggest in Brazil and had been prepared to build large oil production structures such as FPSO (*floating production, storage and offloading*) and semi-submersible platforms. The shipyard site had been built with a significant investment at 350 meters long, 133 meters wide, and 13.8 meters deep drydock, with two large gantry cranes of 600- and 2,000-tons capacity (the biggest in Latin America). The company responsible for running the shipyard was an engineering, procurement, and construction (EPC) firm with experience in large infrastructure projects such as roads, bridges, damns, industrial complexes (e.g., refineries, petrochemicals, etc), yet little experience in shipbuilding. These EPC companies were noteworthy for having capabilities to mobilize large contingents or resources like labor and materials; however, their technological base was in civil engineering rather than shipbuilding. For this reason, companies were required to establish technological partnerships with recognized shipbuilding firms in order to engage in technological transfer. Shipyard A was controlled and run by Brazilian engineering and construction company Engevix Construções Oceanicas (Ecovix). The shipyard established an initial technological partnership with the Chinese shipbuilding company COSCO. A few years after its founding, a Japanese consortium led by Mitsubishi Heavy Industries Ltd and another four companies (Imabari Shipbuilding Co., Ltd., Namura Shipbuilding Co., Ltd., Oshima Shipbuilding Co., Ltd., and Mitsubishi Corporation) agreed to acquire 30 percent of the shipyard's capital stake with the goal of providing advanced technology and operational expertise for mutual prosperity.

The Japanese consortium entered at a crucial moment as the shipyard was struggling to increase productivity andefficiency, and meet its deadlines. While COSCO provided technical support for the detailed engineering, the Japanese consortium focused on technology and operation management to increase productivity and quality, and reduce waste, cost overruns, and delays.

The goal was to establish and improve effective learning mechanisms. To build FSPO and platforms is a typical complex product system (CoPS) where knowledge and innovation endeavors are supposed to be accomplished during the production process. Since the targets were relatively tight because of the technical process itself (it can take more than eighteen months to get an FSPO done and twenty-four months for a platform) and Petrobras' schedules, learning by interacting and partnering was the quickest solution. Of course, beyond the absorption capacity needed to take advantage of the partnerships, the traditional learning by doing was expected as an outcome. When performing the various productive activities, firms ought to build technological capabilities on the job.

The construction projects undertaken at this site were the most challenging of this recent phase of the Brazilian shipbuilding industry. Petrobras ordered eight identical FPSOs called Petrobras 66, 67, 68, 69, 70, 71, 72 and 73 (illustrated in Figure 7.3). The shipyard was responsible for building the identical hulls. Constructing the entire hull of FPSOs is not a common choice among shipbuilders. Usually, these types of vessels result from existing hulls of old tankers that are renovated and later converted into a FPSO. The project aimed at combining complexity with scale by building exact FPSO units. Hence, this project was an attempt to plan and organize the majority of the construction chain from hull to modules within Brazil, respecting the 70 percent local content that was determined by the Brazilian National Oil Agency (ANP).

The upcoming products, the platforms, have the capacity to produce 140 thousand barrels of oil per day for approximately twenty-five years. The set of production events was planned to reach economies of repetition favoring suppliers. The construction process was then divided into "packages" of modules distributed across different firms as described in Figure 7.5. Shipyard A was responsible for building the hulls, while other firms were responsible for building and integrating modules at different locations. The contractual arrangement specified that firms responsible for building modules of each package could be eligible to make others, depending on their performance in the previous ones. The same applied for companies responsible for integrating modules to the hull.

A shipbuilding construction project is generally divided into *Engineering*, *Procurement*, *Construction*, *and Commissioning*. The production plan integrates engineering and procurement to organize and schedule the productive sequence. Engineering involves the activities from defining the platforms' technical specifications, basic engineering design, detailed project design, 3D modeling, to final drafts and instructions for production. Engineering alongside procurement involves the decision around what parts should be made at the yard and what should be bought from external suppliers. Procurement, involves all activities related to finding, selecting, and contracting suppliers for services, materials, or equipment. Construction follows, divided into two groups of activities: *structure* building by cutting, welding parts into blocks, and blocks into the bigger structure. The other group of activities refers to the *advanced vanishing* involving outfitting, piping, electric, information, and telecommunications (EIT), heating, ventilation and air-conditioning (HVAC), architecture. and painting. Finally, commissioning involves the testing of every system of the vessel. Figure 7.5 presents the detailed techno-organizational sequence of activities involved in the hull construction.

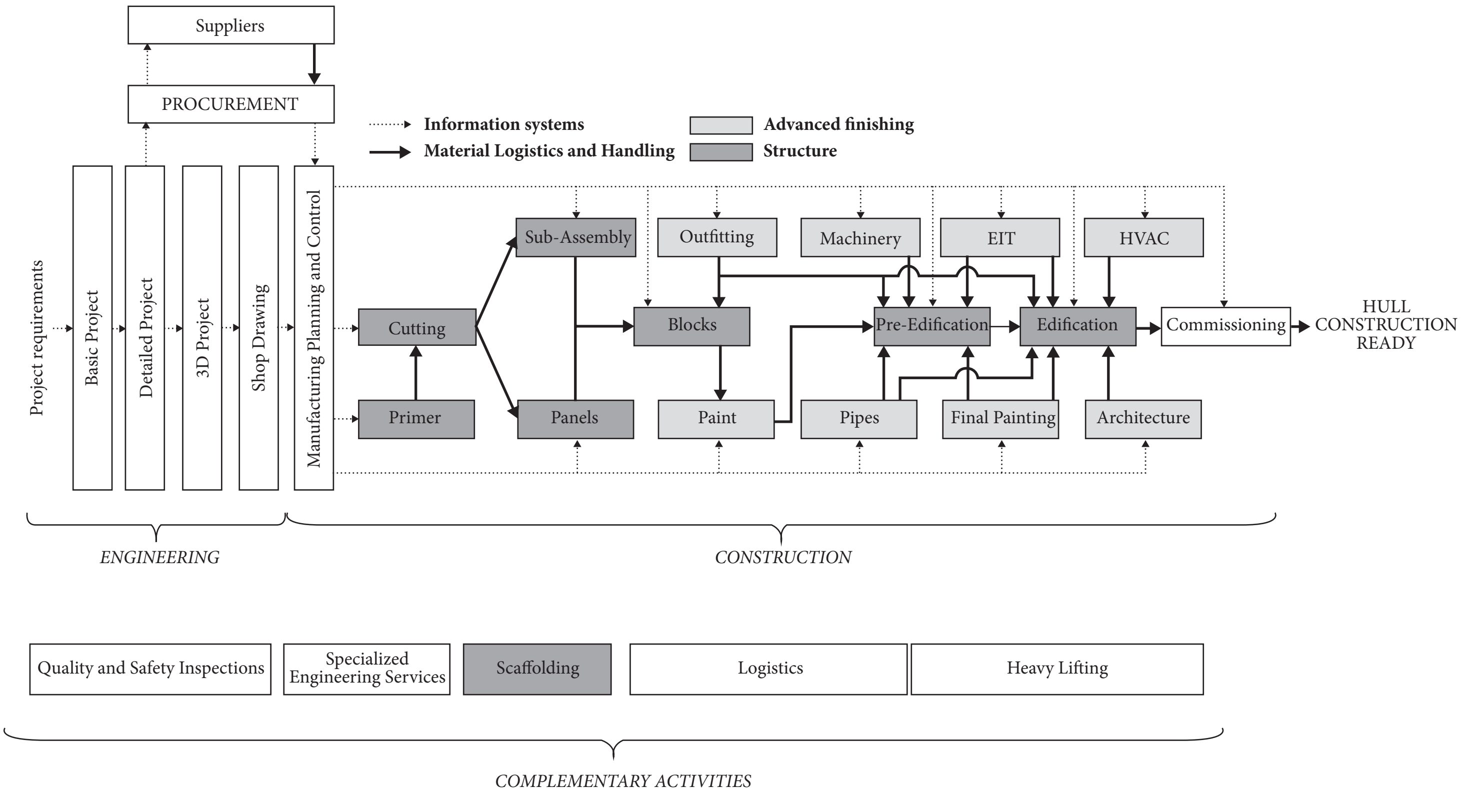

Figure 7.5 General view of the technical sequence of engineering, procurement, construction and commissioning

Source: Alves (2015).

7.5 Frictions and Capability Building Costs

The micro activities involved in hull construction, as listed in the previous section, are non-trivial. Such orchestration is highly complex and requires a high level of precision. During the four weeks spent in SHIPYARD A, interviews were carried out across technological interfaces.

The excerpts below are indicative of some of the challenges encountered in the process of building the necessary capabilities, catching up, and upgrading. We analyze specifically three sources of frictions, which created capability building costs and, thus, hinder the technological upgrading and the expected consequent catching-up. While the industry was triggered by a top-down MACRO institutional and policy setup, many of the issues started to emerge at the MICRO level. In this section, we present failures following a bottom-up perspective.

7.5.1 Techno-Organizational Frictions

Techno-organizational frictions resulted from inherent knowledge gaps from companies operating shipyards. These knowledge gaps encompassed different sections of the techno-organizational interfaces, that is, engineering, procurement, and construction. Thus, building the necessary techno-organizational capabilities proved to be a greater challenge than planned.

It is important to note that the incentives provided by government did allow the shipyard infrastructure to be built with relatively updated equipment and machinery. However, operating capabilities required bridging knowledge gaps through technological transfer, partnerships, and often co-coordination with international companies. For instance, basic engineering design had to be hired by a Swedish company.

7.5.1.1 Engineering Capabilities

> We contracted a Swedish company to draw the basic engineering design for this type of FPSO. Today we do not have the experience to do a Basic Engineering design for shipbuilding. In Brazil, the Navy is the only organization capable in this technology, but other than them it's hard to find any other firms with these capabilities. Moreover, PETROBRAS requires the Basic Design Project to be done by a company with proved experience in designing this type of project with proved construction success. The detailing and shop drawings are done by SHIPYARD A with help of COSCO from China. (Engineering Director – SHIPYARD A)

Knowledge gaps were also observed in the transition from detailed engineering to 3D modeling and shop drawings.

> Everyone would like to use 3D modeling as the main platform, however it takes a little more time to finalize the project because it has more details including materials and processes. Not to mention that this type of software requires people

> training and discipline so everyone can work together. However trained people on this type of technology are rarer while it is relatively easier to find trained people on 2D tools such as AutoCAD. (3D Project Engineering – SHIPYARD A)

Given the availability of labor and the ease of training, two streams of techniques competed in the project design and detailing eventually producing errors, misalignments, re-work, and costs.

7.5.1.2 Procurement Challenges or Capabilities

Matching technical capabilities under relative competitive prices on a world basis was a continuous struggle even with all the fiscal and local content incentives. This was a major source of cost escalation.

> The major difficulty is when we need to identify suppliers that are not international. Brazil still lacks a supplier base. So, we usually have to stick with the few big companies that are around. Specially here in Rio Grande, this is very problematic.
>
> For example, in Brazil there is only one steel company (Usiminas) that process the type of steel plate we need. The company is still missing some equipment to make the size of the steel plates that we needed with the right thickness and quality. On top of all that they could not reach the competitive price [. . .] It seems now that they have reached the technical condition and the price is finally coming together, but it still is very difficult to compete with China [. . .] Usiminas intends to catch up and we will support them, but we will not pay more for it.
>
> (Procurement Director – SHIPYARD A)

In that context, the building of the necessary capabilities has shown to happen also beyond the boundaries of the project and the directly assigned companies.

7.5.1.3 Construction Capabilities

The company responsible for Shipyard A faced coordination struggles from the planning stage while deciding which activities to outsource and which ones to integrate. Inspired by the automotive industry, the initial plan was to outsource most of the activities to subcontractors. However, costly coordination led to a change of course towards vertical integration.

> Originally the yard was designed to outsource almost everything. Only the structure was planned to be assembled here [. . .] Subcontractors would work as an industrial condominium [. . .] like in the automotive industry. As the project went on, we realized that the company, which had other partners, was more concerned with earnings and without the commitment to meet schedules. The company wasn't able to deliver what it was supposed to and, in the order, that we wanted. Then we decided to cancel the contract and integrate most of the construction process.
>
> (Interview – Chief of Structure Division – SHIPYARD A)

Additionally, external pressures from Petrobras resulted in sudden decisions to subcontract and fire workers, which often created instability and hindered the learning process and capability building.

> We weren't supposed to have this much subcontracted labor, but we had a peak of demand and we had to hire more people to meet the schedules. However, lots of people already have gone out. PETROBRAS made a strong request to speed up the process, and the only alternative was to increase the labor force.
>
> (Interview – Chief of Structure Division – SHIPYARD A)

Local legal and permit issues, which lead to complicated logistics, also brought about frictions and extra costs.

> We have companies interested in investing in this segment here, but they are discouraged once they have to get permits from Fepam (Local environmental agency) which, in some cases, takes 2 years to get the approval. Some of the environmental inspectors are very rigorous, especially here in the municipal area where we are. [...] We are very interested in having a piping firm close by. In galvanizing there were many people thinking about coming, but no one actually came. Now we have a cost of sending the spools to Sao Paulo and bringing them back.
>
> (Interview – Engineering Director – SHIPYARD A)

Another emblematic example of this was exactly the piping construction and assembly, a key element for oil platforms.

> Piping is not only a problem of this shipyard, but a general problem of Brazil [...] First, the project is complicated. Few people really know about pipe building. There are many companies doing it, but few people really know. Piping has specific problems of flexibility analysis that we have to be very rigorous about in the engineering phase. Pipes are "alive" in a sense that they vary in size depending on temperature and pressure conditions. It moves with the ship's movement [...] It is a process that requires high precision. If you assemble a little crooked, it will leak when placing enormous pressure on it.
>
> (Interview – Engineering Director – SHIPYARD A)

However, lack of production capacity in the shipyard required the firm to both outsource part of pipe production as well as send those produced in the shipyard to receive chemical treatment to a supplier located in São Paulo (1.5 thousand kilometers away).

> There is a part of the scope of piping that we manufacture here. Another part of the scope that is manufactured outside. We have pipes that are galvanized and coated, others that are manufactured, galvanized and coated. There is an external company in the state that does the coating. Some pipes we buy from Jambeiro, in

> São Paulo. They make the pipe, then send to Metalcoating for painting, and they send to us. Jambeiro fabricates the spools and also does the hydrostatic test.
> (Interview – Pipe Manufacturing Planning and Control Manager – SHIPYARD A)

7.5.1.4 Labor Productivity and Qualification

Key to all technical and coordination capability issues was the inability to reach higher levels of labor productivity and quality requirements. Cultural aspects and labor lack of discipline as well as turnover were some of the reasons found to explain the frequent frictions and difficulties in building a learning curve.

> I do not know why our labor does not seem to improve productivity. Culture may be one aspect to it. We've had some Mitsubishi welders from Japan here to train our labor. The Brazilian welder at the shipyard is currently burning 1.5 to 2 solder rolls per day. The Japanese arrived here and burned 5-6 rolls per day [...] The frustration by some Brazilian workers sometimes led them to try to boycott the Japanese work instead of learning.
> (Interview – Chief of Advanced Finishing Division)

After the first few years of operation there was growing disbelief in the actual ability of the shipyard to really build up the necessary capabilities.

> I've worked for Shell, Chevron, ExxonMobil out there and I think I've learned a lot. There was always a specialist to every ship segment. I often sat with those responsible for the structure's construction to learn. Here I visited a recently built block and, although I'm relatively young, I have a load of things to teach the guys, whereas, in other places I worked I just learned. In fact, these other international shipyards were already much ahead of the standard requirements. Their construction process was much more advanced. Here, however, I honestly do not see how we can get there. (Interview – ABS Surveyor)

Finally, continuous external interventions and pressure for schedule and cost led to high labor turnover, which also contributed to creating frictions rather than the stability necessary to run operations smoothly.

> The labor turnover is very high. At times I see some improvements, at others, I see production making the same mistakes again. I keep having meetings to talk about the same things on welding. Supervision sometimes is absent, there are too many people and I think there is a lack of commitment of each workman to do their best. We have discipline problems (there have been cases of marihuana use on the ship). Moreover, the yard is running straight, after a while (all of a sudden) "boom" there is a contractor with 3000 new employees! No company can handle this type of sudden change. (Interview – ABS Surveyor)

Micro-level analysis presented how difficult it was to generate organizational stability in order for the learning curve to be built. External factors did play a role in generating theses frictions; however, lack of experience in the specific technological base combined with project complexity made the catching-up process very difficult to achieve.

7.5.2 Industry Techno-Economic Coordination Structure Frictions

Techno-economic elements such as the way the coordination structure itself was put in place, how the qualification of the labor force dealt with the operational challenges, and the actual planning of the technical projects are keys for success.

Petrobras was entitled to monitor and coordinate most efforts in building supplier capabilities in the country. Given the 65 percent local content requirement imposed by the National Oil Agency (ANP), several studies were conducted which made the company confident in the ability to leverage the Brazilian supplier base.

> When the national oil agency says we must have 65% of local content, we have to analyze every screw that goes into the project as to what extent they can be made in Brazil. If it can't be made in Brazil, what are the reasons? We have several studies with the Brazilian Development Bank (BNDES) and Petrobras on competitiveness of Brazilian industry published in 2008 and updated in 2011 where we analyzed 25 segments in the domestic industry . . . so we know what each segment can provide in terms of local content. In addition, we have our manufacturing inspectors who reside or visit frequently our suppliers, so we constantly monitor the industry.
>
> (Interviewee – presidential assessor for local content at PETROBRAS)

Besides controlling for local content requirements, Petrobras also ran frequent on-site inspections at every shipyard to make sure quality, schedule, and costs were being met according to the contracts. Interface managers did theses strict checks.

> We are present at each construction field on a daily basis. We coordinate each of the contracts here (at the module integrator). My day to day is to stay with the Detailed Project in hand at the office in Rio where I follow the project's progress. Once a week or when there is a special demand, I come to the yard to see the physical progress. (Interview – Interface Manager from PETROBRAS)

However, the complexity of projects tested Petrobras' initial coordination and controlling structure. Soon after the projects started, the on-site coordination structure was perceived to be undersized, which led the company to heavily increase its presence on different shipyards.

> Before this project, we were connected only to a general management with different managerial departments. There was a project management and the supply department. As soon as we walked in the previous structure, it was clear that the structure was undersized. Today, even with the "boom" of projects we are still undersized. (Interview – Interface Manager - PETROBRAS)

Moreover, according to Petrobras,

> Shipyards would have to live with two fronts of work. On the one hand, cutting steel to build ships, while earth-moving and launching concrete foundation for the yard's infrastructure…in light of this, it was understood that the competitiveness of the industry was linked to the capacity of the workers to carry out simultaneous activities. (Avila et al., 2019)

However, carrying out both activities often generated undesirable delays and costs.

Finally, besides local content requirements, technological development requirements for Petrobras' orders also increased projects complexity. Petrobras' oil fields to be explored were usually bigger and deeper which increased the technical specifications of platforms.

> There are two building strategies. When Petrobras will not be the operating company in the field, we charter to another company. So Petrobras issue a general technical description (GTD) of the vessel, but the operating firm will be the one responsible for contracting the shipyards to build the platform […] When Petrobras will be the operating company in the field, the oil platform usually has a greater number of specifications. In this case, we need to specify not only "what" the platform has to have, but "how" it has to be done. This leads to a set of 1000 technical documents. Then we hire the shipyard to do the detailed engineering and construction based on our requirements.
>
> (Head of Engineering at CENPES)

This greater complexity of Petrobras' orders, combined with the local content obligations, resulted in a greater need for on-site supervisions where mistakes were often spotted, generating pressure in the shipyard, rework, and delays. Conversely, however, when oil fields were chartered (Figure 7.5) and the operating company was the one responsible for building the platforms, orders built in Brazil were delivered on time and at a lower cost.

> When Petrobras charterers field, the chartered company is responsible for following our technical requirements and dealing with the shipyard. In our experience, when we do this, ships are usually delivered on time…we believe this happens because the Petrobras projects tend to be more complex and Petrobras has to obey more regulations. (Head of Engineering at CENPES)

In short, three basilar elements, that is, the coordination itself, the qualification of work, and the projects, turned out to have been underestimated, generating important techno-economic frictions. The above-mentioned undersized coordination, the exiting qualification of work below operational standards and requirements, and the undersized projects (technical specs versus actual size of oil fields) led to delays and extra costs.

7.5.3 Institutional-Market-Governance Frictions

Whereas the institutional setup was initially intentioned to create a temporary market-governance context for the industry to emerge, such a complex project involving a large number of contracts combined with having a public company leading the project resulted in a blurry line between industrial policy for development and political interests. With a handful of companies capable of mobilizing resources, bids and contracts were distributed somewhat evenly among them, often involving breaking down contracts with political bribes and commissions paid to politicians and their respective parties.

The lack of technical and organizational capabilities somehow "obliged" different players to act opportunistically in order to sustain their business positions, creating the path for moral hazards. In 2014 what came to be known as the "Car Wash Operations" (Box 7.1.), initiated a process of corruption investigations involving the deviations of money from contracts with various companies in the oil and gas sector

Box 7.1 "Car Wash Operations"

The *Car Wash Operation* has been the biggest criminal investigation conducted by the Brazilian Federal Police relating to the biggest money laundering scheme in the history of the country (Valarini and Pohlmann 2019). The scheme involved the main construction companies operating in the shipbuilding sector which formed an illegal price-fixing cartel, Petrobras and political parties. The criminal investigations started in 2014 and led to over 1,340 criminal search and seizure warrants, and over 290 preventive or temporary arrests, involving senior managers and directors of construction companies, as well as politicians from six political parties, including ministries, senators, congressmen and women as well as the former president of the country, Lula da Silva. According to the Federal Public Ministry, the car wash operation has returned around 4 billion reais that were deviated from the public safe (Petrobras and Union)*

*Numbers of the Car Wash Operations according to the Federal Public Ministry: http://www.mpf.mp.br/grandes-casos/lava-jato/resultados/, accessed on 08.17.2020.

which were hired to build refineries, drilling rigs, oil tankers, and platforms. This is allegedly one of the biggest corruption scandals in history (Watts 2017).

The upcoming results are, other than technical and operational inefficiencies, corruption and scandals. Somehow, the "car-wash" scandals end by becoming evidence of an institutional "debacle." The highly expected "passport to the future" based on this complex institutional arrangement went off. This weak institutional framework, personalistic political moves by the government, generated even more institutional instability. The outcome of this process two years later after investigations started culminated with several politicians and company's representatives found guilty and arrested, including former president Luiz Ignacio Lula da Silva, arrested in 2018. In 2016, President Dilma Rouseff got impeached for alleged administrative misconduct. While the impeachment process itself was not directly related to the Car Wash Operation, the volume of corruptions scandals was often used as an argument to justify it. Surprisingly, such issues created a contextual storm and a "window of opportunity," not for catching up, but for an institutional change in Brazil with regards to the fight against corruption (Castro and Ansari 2017).

7.6 Policy Outcomes and Discussion

Relatively low levels of output and high costs of construction stunned the industry and rendered it unable to catch up with international competition. The abovementioned frictions and capability building costs led to the lack of competitiveness, while the corruption scandals—with Petrobras at the core—culminated in a strong dive of the sector.

About a decade after policies for the sector were implemented, the results started falling apart. From near despair in the 1980s to the fast rise in the 2000s, the industry peaked in 2014 reaching 82 thousand jobs. By 2016 the industry was accounting only for 46 thousand employees. According to Sinaval's latest[4] data the projected employment in the sector for 2020 has dropped further to 15 thousand. Figure 7.6 presents the labor and productivity evolution over the years in the Brazilian shipbuilding industry.

With very few exceptions, public bids for shipbuilding in Brazil were won by a handful of domestic firms. These tended to be civil engineering firms specialized in complex infrastructures projects such as roads, bridges, dams, industrial complexes (e.g., refineries, petrochemicals, etc). They were the only ones with capabilities to mobilize large contingents of resources such as labor and materials. However, infrastructure projects have a quite different technology base from those of shipbuilding. One could state that the necessary techno-organizational capabilities in fact were not built.

Among the reasons for the decline were insufficient engineering teams, systems, and tools, lack of a nearby supplier base, delays, and frequent rework. Important to

[4] http://sinaval.org.br/empregos/, accessed on 17.8.2020.

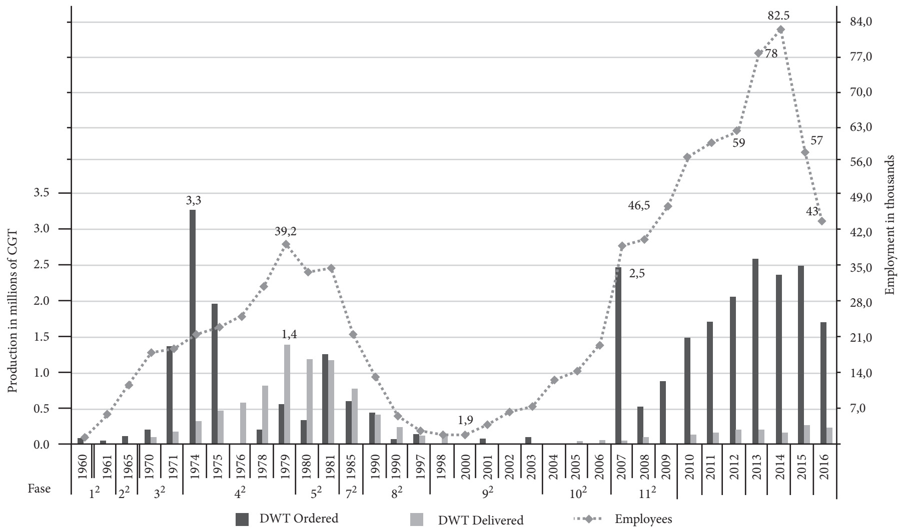

Figure 7.6 Labor and productivity evolution over the years in the Brazilian shipbuilding industry

Source: Updated from Barat, Neto, and Paula (2014); based on Clarksons Research (2018) and Sinaval (2016) data.

note is that leading shipbuilding nations organize a major part of the value chain into close regional clusters (Pires et al. 2007). All these resulted in cost escalation, which prevented the building of capabilities due to frequent changes in the project while trying to respond to the pressure for building fast within the deadlines. Given the low level of the existing local capabilities, the window of opportunity was not long enough.

The internal dynamics of orchestrating various interfaces and the need to acquire technological and organizational capabilities prevented the shipyards from achieving full production capacity. Without reliable organizational capabilities, production capacity had severe difficulties in meeting market demand. While many shipyards have been equipped with state-of-the-art facilities and the necessary assets to operate, the ability to master the necessary routines involves a high level of knowledge and skills, as well as organizational capabilities. The lack of capacity to learn quickly and deliver on time led to a constant fragmentation of contracts, generating more instability to the entire chain.

In a specific case of SHIPYARD A, in spite of all the difficulties, a learning curve started to build up after the coordination of the operations had gained the expertise by the Japanese Consortium of firms that entered as shareholders of the shipyard's controlling firm Ecovix. Petrobras also understood that its constant pressure and interference at the shipyard was also creating problems. In 2015 (a year later), the shipyard had reduced its workforce by 38.9 percent and vertically integrated some of the production interfaces. The change in the total labor structure and the increase of knowledge transfer with the Japanese partner began to stabilize operations from engineering to production. Table 7.5 shows these differences. While in October of 2014 the number of employees was 11,413, a year later it reached 6,973.

Aggregate productivity of the shipyard also suffered somewhat due to financial problems, dropping from 3.600 tons of processed steel per month in October of 2014 to 3.014 tons per month a year later (a reduction of 16,28%). Average productivity per worker increased by 34.38 percent which indicates some learning curve gains. Peak production of 4,800 tons was reported for 2014. The participation of an international shipbuilding group in a local shipyard improved capability building. This provides an indication of positive prospects by the engagement of international shipbuilding companies in these facilities paired with public efforts to select and train local labor in order to build up domestic capabilities. Given the obvious capability constraints of incumbent firms, with no specific experience in the area, much deeper and more pervasive alternatives to capability building should have been foreseen.

Despite the progress at the shipyard achieved after the arrival of the Japanese consortium, the increasing scrutiny of the Car Wash Operation due to the corruption investigations involving the contracts with the Brazilian shareholder Ecovix, led the Japanese investors to decide to exit the joint-venture and declare the deal as loss.[5] The shipyard latter announced several lay-offs and eventually the complete shutdown of the operation. With a debt of 2.4 billion dollars, Ecovix filed for bankruptcy protection for its creditors, including Petrobras and COSCO. The Chinese partner who had already produced Petrobras 68 (one of the eight FPSO's hulls that were ordered in the original plan—see Figure 7.3), also received the transfer of Petrobras 70 to be completed at the Cosco Shipyard in China. Another two shipyards in China also inherited the remaining orders to be completed. Beihai Shipyard with Petrobras 67 and Yahtai CIMC Raffles with Petrobras 71. FPSO's Petrobras 72 and 73 were discontinued.

Table 7.5 Variation in productivity after one year of technological transfer

Indicator	October 2014	October 2015	Variation
Total Number of Employees	11,413	6973	−38,9%
Direct Labor	7516	4727	−37,11%
Indirect Labor	3897	2246	−42,37%
Number of Total Sub-Contracted Firms	92	57	−38,04%
New Sub-Contracted Firms	–	16	
Number of Sub-contracted workers	3.743	980	−73,82%
Production in Steel Process Tonnage Month	3600	3014	−16,28%
Average productivity per employee (tonnage per worker)	0.32	0.43	34,38%

Source: Based on data provided by Shipyard A relative to October of 2015.

[5] Mitsubishi-led group existing stake in Brazil shipyard—report. (https://www.reuters.com/article/mhi-brazil-ecovix/mitsubishi-led-group-exiting-stake-in-brazil-shipyard-report-idUSL1N14P0RU20160105/, accessed 17.8.2020).

7.7 Concluding Remarks

Developing economies face unquestionable challenges to escape from the middle-income trap, succeed in catching-up and technologically upgrade their industrial and social capabilities. Overcoming this challenge often requires the opening of special windows of opportunities that arise from institutional, market, or technology changes. However, these windows are not unidirectional and entail the working of interdependent layers, macro *institutional-market-governance*, meso *industrial-techno-coordination structure,* and micro *techno-organizational firm capabilities and learning mechanisms.*

The Brazilian shipbuilding example teaches that policy for capability building and innovation can and did foster an intuitional and market window of opportunity for firms to catch up on capabilities and eventually open new paths for innovation in the sector. However, industrial-techno-coordination and techno-organizational capabilities were lacking in order to effectively absorb knowledge and catch up.

This is even more problematic in a complex industry such as shipbuilding as complexity increases the probabilities of frictions across the whole chain. In order to escape from being trapped and really take advantage of market entry incentives created by governmental institutions, latecomer economies must figure out faster ways to develop capabilities at the lowest possible cost or be smartly selective in the choice of specific packages that make technological and economic sense to regions. These elements should be arranged and balanced out in order to generate positive "dynamic-stability" so capabilities can be built up.

Otherwise, bounded rationality (translated into the lack of former capabilities) and uncertainty (expressed, for example, by undersized coordination decisions) may not only hamper the building of the necessary capabilities, but also give rise to unexpected moral hazard that looks how to circumvent the lack of capabilities (and thus keep contracts), for example with bribery and corruption.

To conclude, these results are based on a single case of a policy for industrial dynamics and capability building "experiment" in Brazil within the very institutional, social, and economic idiosyncrasies of the country. It would be necessary to be juxtaposed with similar experiences from other emerging economies in the energy sector and beyond for wider applicability of the results.

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8

Technological Learning Strategies and Technology Upgrading Intensity in the Mining Industry

Evidence from Brazil

Paulo N. Figueiredo and Janaina Piana

8.1 Introduction

Although economic convergence between emerging and advanced economies depends on several factors (De Gregorio 2018), technology upgrading is important for overcoming the slow growth that prevents some middle-income countries from reducing their income gap with high-income economies, that is, economic catch-up (Lee 2013, 2019; Radosevic et al. 2019; Radosevic and Yoruk 2019). Technology upgrading intensity is understood herein as the accumulation of technological innovation capabilities up to the world-leading level or technological catch-up (Bell 2007, 2009; Radosevic and Yoruk 2016; Lacasa et al. 2018). Technology upgrading intensity of emerging economies depends largely on how and the extent to which their firms and industries, known as latecomers, respond to certain windows of opportunities by engaging in effective technological learning strategies (Lee and Malerba 2017; Figueiredo and Cohen 2019). Therefore, technology upgrading is relevant for scrutiny at the firm and industry level, particularly for countries in the middle-income and technology trap.[1]

Research on latecomer firms' and industries' technology upgrading dates back to the early 1970s, particularly exemplified by the seminal studies of J. Katz, C. Dahlman, M. Bell, S. Lall, and C. Cooper (for compilations and reviews, see Katz [1987]; Bell [2006, 2007, 2009]). Over the past two decades, we have witnessed a rejuvenation of research in this area, which seems to reflect the leading technological and commercial position of some latecomers in the global market (Bell and Figueiredo 2012; Radosevic and Yoruk 2019; Lee 2013, 2019).

[1] As suggested by the related literature (e.g., Lall 1992; Bell and Pavitt 1993; Lee 2013; Radosevic and Yoruk 2019), the concepts of technological catch-up and technology upgrading are intrinsically linked. Therefore, we use these terms interchangeably.

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Lee and Malerba (2017) explain successive industry leadership changes in terms of "catch-up cycles" (where catch-up means closing the gap in *market share* between incumbents and latecomers). Combining the notions of "windows of opportunity" (Perez and Soete 1988) and component changes in sectoral systems of innovation (Malerba 2004), Lee and Malerba (2017) argue that different windows of opportunity (technological, demand, and institutional) and incumbents' and latecomers' strategic responses influence industrial leadership changes and successive latecomers' catch-up. These catch-up cycles differ across industries, as demonstrated by studies of memory chips (Shin 2017), steel (Lee and Ki 2017), cameras (Kang and Song 2017), mobile phones (Giachetti and Marchi 2017), regional jets (Vértesy 2017), and wine (Morrison and Rabellotti 2017). These studies provide robust evidence of the role of windows of opportunity combinations and incumbents' and latecomers' strategic responses—particularly concerning a firm's innovation strategies—in affecting industrial leadership change and *market* catch-up cycles. However, we still know little on how these micro-level learning-based innovation strategies emerge and how they affect technology upgrading or *technological* catch-up in latecomer firms.

Building on Lee and Malerba (2017), Miao et al. (2018) undertake a systematic review of extant studies of East Asia's firms to develop an overarching framework that identifies precursors of technological catch-up, both external (institutional environment and technological regime, including windows of opportunity) and internal (firms' learning and catch-up strategies). They recognize the prominence of recent technological catch-up studies that use panel and simulation analyses and are based on R&D and patent statistics, as proxies of innovation capabilities, and in-house and/or collaborative R&D, merger and acquisition, and international flows of scientists, engineers, and inventors, as learning channel proxies, of high-tech or science-based assembled products manufacturing (e.g. electronics, telecom equipment) and services firms.

However, the prominence of these proxies for technological innovation capability generates unintentionally biased approaches to technological catch-up research. It excludes types of non-R&D capabilities (e.g. design and engineering) and other types of analysis, which are relevant to industries in different contexts with technological catch-up stages (see Bell 2007, 2009; Bell and Figueiredo 2012, for a discussion). These biases mirror the biases in innovation studies and policy debates, which associate innovation with R&D and patenting activities in large "high tech" manufacturing and service firms (see Lundvall et al. 2008; Lundvall 2012; Martin 2016, for a critique). Nevertheless, Miao et al. (2018) recommend future studies to identify diverse learning channels through which latecomer firms can upgrade their technological innovation capabilities.

Seeking to move a step further and conceptualizing technological upgrading or development as a multidimensional construct, Lacasa et al. (2018) and Radosevic et al. (2019) employ a broader understanding of innovation, well beyond R&D and patenting. They argue that dominant metrics overlook a range of technological activities that are typical of latecomer firms. These and the related studies seek to adopt broader perspectives on changing patterns of technology upgrading and factors affecting firms' technological capability creation in different countries, such as South Korea, Brazil, Poland, India, China, Bangladesh, and the Mercosur in firms and industries such as nuclear (Choung and Hwang 2019), electrical motors and oil and gas (Bernat and Karabag 2019), mobile telephony (Dey et al. 2019), water heating (Busch et al. 2019), pharmaceutical (Kale, 2019), clothing (Yoruk 2019), defense (Bernat and Karabag 2018), solar power (Shubbak 2019), and automotive (Obaya et al. 2018). This also includes the role of industry–university collaborations in technological upgrading, examined through R&D and patenting (Fischer et al. 2019).

These studies illuminate the greater importance of organizational capabilities and inter-organizational knowledge interactions in technology upgrading. However, the majority of these studies do not examine micro-level (firm and/or intra-industry) learning strategies underlying technology upgrading. They also do not explore the role of macro-level changes (windows of opportunity) in triggering firms' and industries' innovation strategies based on learning and technological capability development efforts to upgrade technologically. Figueiredo and Cohen (2019), based on evidence from Brazil's forestry and pulp industry, explain technological catch-up through a combination between firms' effective responses to windows of opportunity and learning strategies effectiveness. Nevertheless, there is a dearth of empirical studies examining the learning dimension of micro-level innovation strategies in response to windows of opportunity and their impact on technological upgrading, particularly in under-researched industries such as those that are intensive in natural resource in resource-rich developing economies. We seek to provide a contribution in this direction by examining these issues in Brazil's mining industry.

Academic researchers, policymakers, and the general public—even in resource-rich developing economies where natural resource-intensive industries form a major part of GDP and exports—tend to view natural resource-intensive industries negatively. These industries are deemed "low-tech," "commodity-makers," and even seen as a "curse", disregarding the windows of opportunities that are opened by these industries and from which resource-rich economies could benefit (see Katz and Pietrobelli 2018; Crespi et al. 2018).[2] However, underneath standard classifications of "low tech" (OECD 1999), there are relevant innovation activities (Robertson et al. 2009), complex process technologies (Lager 2017), and several opportunities for learning and innovation (Morris et al. 2012). Technological upgrading in so-called "low-tech" industries may be significant in the economic catch-up process (Bell 2009). Unlike what one might assume, natural resource-intensive industries, such as mining, play an important role in the transition to a low carbon society (Ali et al. 2017; World Bank 2017) (see Section 8.2).[3]

[2] It is not our purpose to engage in the long-standing "resource curse" debate, as there are several studies addressing this theme.

[3] For a discussion on the experience of other countries in technology upgrading in natural resource-intensive industries, particularly in mining, see Figueiredo and Piana (2016, 2018).

Brazil's mining industry offers a rich empirical reservoir to explore the issue of technology upgrading intensity. As one of the world's largest producers and exporters, the Brazilian mining industry, through its leading firms and other sectoral systems organizations, holds a leading technological and market position in the global market. Unlike most mining-intensive producer developing/emerging economies, where there is a prevalence of multinational enterprises (MNEs), in Brazil, the bulk of the mining industry is dominated by domestic private firms. Thus, Brazil is an instigating empirical context in which to examine technology upgrading. In this chapter, we examine the following research question: How has the interplay between windows of opportunity and leading firms' technological learning strategies affected technology upgrading intensity in Brazil's mining industry, thus shifting this industry into a globally leading position? We address this question through a micro-level (intra-industry) qualitative and empirically grounded study based on evidence from leading mining firms and some of its partners, gathered from extensive fieldwork. The remainder of this chapter is organized as follows. Section 8.2 provides an overview of Brazil's mining industry; Section 8.3 contains the theoretical background, followed by the methods in Section 8.4. Section 8.5 presents our findings, which are subsequently discussed in Section 8.6.

8.2 Natural Resource-Intensive Industries and Mining: A Brief Overview

Unlike assembled products industries (e.g., automobile, telecom equipment), natural resource-intensive industries, such as mining, are characterized by geographic specificity as well as localized and idiosyncratic knowledge due to local environmental, ecological, and geological conditions (Mazzoleni and Nelson 2007; Andersen et al. 2015; Katz and Pietrobelli 2018). In the case of mining, local specificity is even higher, as no two mineral deposits are the same, which prevents the use of standardized solutions (Scott-Kemmis 2013). Therefore, it is not possible to examine these industries by considering universal production functions, which differentiate them from assembled products or conventional manufacturing (e.g. aircraft and electronics) (Katz and Pietrobelli 2018).

Although considered "low-tech" by standard classifications (OECD 1999), such industries include firms with considerable innovative capabilities undertaking new-to-market and new-to-world innovations (von Tunzelmann and Acha 2005), opportunities for interactive learning and innovation (Andersen et al. 2015), and knowledge-intensive linkages with other organizations (Torres-Fuchslocher 2010). Natural resource-intensive industries, such as mining, have become more knowledge intensive and can potentially become a platform for innovation and growth in natural resource-rich developing economies (Lederman and Maloney 2007; Morris et al. 2012; Marin et al. 2015; Crespi et al. 2018).

Being intense in *natural* resource (e.g., geological conditions, mineralogical characteristics), we refer to the mining industry as a natural resource-*intensive* industry.

One could consider the mining industry as purely a commodity-based one—*part of it is*. However, there are major technological areas as well—for example exploration (research and prospecting), mining, mineral processing, engineering services, and logistics, involving a broad spectrum of technological activities ranging from operations to several types of innovation activities, such as minor adaptations in equipment, production systems and software, design and engineering, and different levels of R&D (Figueiredo and Piana 2016, 2018; Morris et al. 2012; Morris and Fessehaie 2014; Scott-Kemmis 2013; Urzúa 2013). Historically, most technological innovations in the mining industry have been driven by geological challenges to maintain satisfactory levels of cost and productivity to meet mineral demand given the decline in ore content and increasing mineralogical complexity (Peterson et al. 2001). New challenges exist in the requirements to address environmental, health and safety issues, labor shortages, and social responsibility (Barnett and Bell 2011).

Data abundance, low computing costs, and advances in digital technologies (machine learning, artificial intelligence, Internet of Things [IoT], and big data), as well as biotechnology, and nanotechnology combined with environmental and social pressures have opened opportunities for learning and innovation through challenges in mining production (Pietrobelli et al. 2018; Katz and Pietrobelli 2018). Examples include advanced business decisions, autonomous, self-controlled devices and processes, flexible business operations adaptation, human resource planning, and machine-learning algorithms to predict tasks (Gružauskasa et al. 2018),[4] helping to boost productivity and mitigate social and environmental impacts (Humphreys 2018; Mueller et al. 2019; Tribal 2018), and industry reorganization to support knowledge-intensive mining services (KIMS) (Scott-Kemmis 2013), as in Australia (Scott-Kemmis 2013), South Africa (Kaplan 2012), and Sweden (Nuur et al. 2018).

The mining industry is relevant to the transition into a low-carbon society and the UN development goals. Based on comprehensive dataset analyses and demand forecasts, Ali et al. (2017), in a study published in *Nature*, argue that mineral resourcing and climate change are intrinsically interconnected: First, climate change cannot be tackled without an adequate supply of raw materials to produce clean technologies; and second, because global population is expected to cross 8.5 billion by 2030, there is an important mineral resource dimension in the provision of infrastructure, entailing science and policy to meet development goals.

Accordingly, a framework has been developed to estimate mineral demand in a low-carbon future in light of the 2015 Paris Agreement on Climate Change (World Bank 2017). The report focuses on wind, solar, and energy storage batteries as high-potential technologies to deliver future low/zero greenhouse gas (GHG) emission levels. It examines which mineral and metal demand is likely to rise to deliver a carbon-constrained future. Thus, it indicates important windows of opportunity for

[4] The 39th APCOM (Applications for Computers and Operations Research in the Minerals Industry) conference entitled "Mining Goes Digital" presented innovative IT-related papers from resource estimation and geostatistics, mine planning, robotics, equipment automation, autonomous guidance, and many other integrative aspects of digital transformation in the minerals industry (see Mueller et al. 2019).

natural resource-rich developing countries in terms of innovation and growth based on their mineral endowments in a low-carbon energy transition.

However, controversies regarding the growth of the mining industry and its environmental and social impacts exist. One of the most visible impacts is the collapse of tailing dams, which are even more likely due to climate change effects. Eliminating all catastrophic incidents remains a challenge in the environment, health, and safety. Since 2014, there have been seven failures significant enough to make international news (Canada, Mexico, Brazil [twice], China, USA, and Israel). Some of these have resulted in human casualties; all caused extensive environmental and social damages. These tragedies erode community confidence and give rise to more stringent regulations and heavy levies, making mining activities more costly, although there are new guidelines to avoid them (Ali et al. 2017; Roche et al. 2017).

Brazil has a diversified mineral basis, involving the production of seventy-two minerals, of which twenty-three are metallic, forty-five non-metallic, and four energetic. It is one of the world's largest mineral producers, especially of iron ore, bauxite, zinc, copper, niobium, and several of the mineral resources required to supply carbon-constrained technologies. Brazil's reserves of rare earth metals are second only to China; both countries hold nearly 60 percent of the world's reserves. By 2017, Brazil's mining industry accounted for 1.4 percent of its GDP and 13 percent of exports, occupying 0.5 percent of Brazilian territory, and producing more than two billion tonnes/year. In value terms, Brazil's mineral production increased from USD five billion in 2001 to USD 32 billion in 2017.

The industry is highly concentrated, with most of its output being generated by less than ten large firms, including extensive local Brazilian mining companies (DNPM 2014; IBRAM 2019). Unlike other resource-rich developing economies where MNEs dominate mining, domestic firms lead in Brazil. For example, Vale is Brazil's leading mining firm, accounting for more than 50 percent of the total domestic mineral production. It is the world's largest iron ore, pellets, and nickel producer, whereas Votorantim Metais (now Nexa Resources) is one of the world's largest zinc producers.

8.3 Theoretical Background

8.3.1 Windows of Opportunity

Extant studies and our fieldwork insights suggest that windows of opportunity and firms' leadership behavior may trigger, or condition, firms' innovation strategies relative to technology upgrading. The notion of windows of opportunity in the context of catch-up was introduced by Perez and Soete (1988), who argue that technological discontinuities, in the form of radical technological innovations, create advantageous opportunities for latecomers. Lee and Malerba (2017) further identify changes in various components of a sectoral system of innovation (Malerba 2004) that open new windows of opportunity for latecomers to engage in technology upgrading or catch-up, involving dimensions such as: *technological* (the emergence of a radical technological innovation); *demand* (change in users'/consumers' existing and potential demands and needs, upturns/downturns of business cycles); *institutional* (changes in public policies (e.g., fiscal incentives, regulations), and the provision of research and educational infrastructure).

Following Figueiredo and Cohen (2019), we consider a fourth dimension, *idiosyncratic problems*, which arise due to local specificities and knowledge idiosyncrasies inherent to natural resource-intensive industries. They may cause unexpected difficulties in innovation processes, triggering specific local searches and experimentation, potentially leading to a novel technological development. In the mining industry, they may involve geological, environmental, and health and safety challenges, and the maintenance of satisfactory cost levels in the face of decreased ore content and increasing mineralogical complexity (Barnett and Bell 2011; Peterson et al. 2001).

8.3.2 Firms' Technological Learning Strategies

Firms from emerging economies (latecomers) generally start from a condition of being initially imitative and with a low-level technological innovation capability (Bell and Figueiredo 2012). To engage and compete in global markets, their innovation strategies—as responses to windows of opportunity—tend to be based on learning processes to *create* and accumulate their own innovation capability (Bell 2009; Lee and Malerba 2017; Scott-Kemmis and Chitravas 2007). Some firms may not even identify windows of opportunities (Pavitt 1990), others may opt not to respond (Giachetti and Marchi 2017), whereas still more may respond by implementing innovation strategies oriented to catch-up (Lee and Malerba 2017; Vértesy 2017). This involves deliberate learning and technological innovation capability-building efforts, although with differing degrees of effectiveness (Figueiredo and Cohen 2019). Innovation strategies vary within and across firms within the same industry over time, as they respond to windows of opportunity, leading to different impacts on technological upgrading and industrial leadership (Vértesy 2017).

Drawing on the above perspectives, on Freeman and Soete's (1997), and on our own fieldwork insights, we identify the following types of *technological learning strategies* as firms' responses to windows of opportunities: (i) *offensive*: learning and capability building efforts to achieve leading market and technological positions in the global market through R&D and engineering-based innovation activities, internationalization, and technological diversification; (ii) *defensive*: learning and innovation capability-building efforts to be prepared to quickly follow global technological leaders (fast-followers) through technological innovation activities, with relatively complex to more complex new-to-the-country or near-world-leading level innovation activities; and (iii) *imitative:* learning and innovation capability-building efforts to implement minor changes in existing technologies and new-to-the-firm innovation activities. In practice, elements of these strategies may overlap in the same firm and industry (Hobday et al. 2004), although this mix may not reflect deliberate choices. In some cases, the imitator may aspire to become a defensive innovator. A defensive strategy may be involuntary, as a new entrant may overtake a world-leading firm.

To implement these learning strategies, latecomer firms draw on different knowledge inputs (Bell and Figueiredo 2012, for review). However, the technological catch-up and innovation literatures tend to emphasize one type of knowledge input to the detriment of others. Knowledge generated in public organizations, such as R&D institutes and research groups in universities—or even in the R&D units of firms—is often deemed as the main input for firms' innovation capability-building. Sources of innovation capabilities that are more decentralized in firms and closely linked organizations, and, thus, pervasively distributed across and embedded in production activities in the economy are prioritized less (Bell 2009). This seems to reflect the emphasis of most recent technological catch-up studies on patents and R&D as proxies of innovation capability (see Miao et al. 2018).

There are dichotomous perspectives in innovation studies (Martin 2016) that associate "high-tech" firms with science-based interactions (with universities and research institutes) ("analytical knowledge"), and "low-tech" firms with engineering- and experience-based interactions (with suppliers and users) ("synthetic knowledge") (Asheim and Gertler 2005; Fu et al. 2013). These perspectives limit our understanding of learning processes and overlook the blurring distinctions and complementarity of these types of knowledge (Lundvall and Lorenz 2007; Lundvall 2012). Accordingly, low-tech firms and natural resource-intensive firms are deemed to lack knowledge-intensive learning strategies and relevant innovation activities.

As claimed in extant studies (Bell 2009), it is time to recognize the fundamental importance of a complementarity between knowledge inputs for innovation capability-building by including knowledge generated through (i) formal R&D-based activities within firms and research institutions and (ii) knowledge generated through experimentation, design, and engineering within firms and closely related organizations whose activities are pervasively embedded in and around production activities in the economy. Thus, we pursue herein a comprehensive perspective on firms' learning strategies.

To that end, we draw on the framework developed in Jensen et al. (2007) and Lundvall and Lorenz (2007) that reconciles the tension between two major knowledge inputs (also learning modes or strategies) for innovation: the "science, technology, and innovation" (STI) and the "doing, using, and interaction" (DUI) at the level of firms and the economy. These studies argue that, at the level of research, there is greater emphasis on the STI-mode through training of scientists and R&D linkages.

"The vast majority of quantitative survey-based studies of innovation simply have little to say about the relation of DUI-mode learning with innovative performance" (Jensen et al. 2007, p. 681). Simultaneously, they argue that DUI learning is insufficient to secure firms' competitive performance. Their empirically grounded seminal study suggests that firms that combined both learning strategies were more likely to innovate new products than firms that relied primarily on one or the other. However, they do not state that both learning strategies operate in harmony with each other, and, thus, "[I]t is a major task for knowledge management to make strong versions of the two modes work together in promoting knowledge creation and innovation" (p. 690).

Several empirical studies apply the DUI/STI framework in different industries (see Apanasovich 2016, for a comprehensive meta-analysis). However, there are some limitations. First, most studies are based on large samples of firms, cross-sectional design, and econometric analysis. These methods do not capture in-depth evidence of *how* firms and industries use the STI and DUI learning strategies to implement their innovation activities. Second, most studies have been undertaken in advanced economies, particularly in Scandinavia, where innovation capabilities tend to be assured. Even the rare studies centered in developing economies (see Apanasovich 2016) are not concerned with *how* these two modes of learning contribute to the creation and accumulation of capabilities. One exception is Figueiredo et al. (2020) who examine the role of STI/DUI learning strategies in the innovation capability-building process of a subsidiary of a biotechnology MNE.

Third, there are scarce studies addressing this DUI/STI framework in latecomer natural-resource intensive industries. For instance, Isaksen and Karlsen (2010) and Simensen (2018) examine these learning modes in Norway's oil and gas industry, concluding that this industry relies more on DUI learning to innovate. However, they do not examine the impact of these learning modes on innovation capability accumulation. These findings reinforce the well-trodden argument that natural resource-intensive industries are not likely to develop knowledge-intensive links with other sectoral systems organizations.

Nevertheless, Lundvall and Lorenz (2007) suggest that, based on aggregated data, in both "high" and "low tech" industries, firms that combine strong versions of DUI and STI learning modes are more innovative than those that practice only one of them. By combining insights from the abovementioned studies with those from our fieldwork, we operationalize the notion of STI/DUI knowledge inputs underlying firms' technological learning strategies through the framework in Table 8.1. The two knowledge forms, as inputs for firms' technological learning strategies are accessed, externally acquired, internally created, and shared through the use of various DUI and STI learning mechanisms. They are interactive, involving different types of intra- and inter-organizational relationships. The intensity and manner of use of the DUI/STI learning mechanisms reflect the imitative, defensive, or offensive innovation strategies adopted by firms.

Table 8.1 A framework to examine mining firms' technological learning strategies and their related knowledge inputs

	Forms of knowledge inputs	**Related learning mechanisms**	**Definitions and examples**
Technological learning strategies: imitative, defensive and offensive	Doing, using and interacting (DUI)	Design, engineering, and experimentation	Various types of learning by doing and types of tests, trial-and-error, and experimentations as part of design and engineering related to the use and adaptation and/or development of new production processes, software development, industrial automation, product adaptation, and technology evaluation, individually and/or with partners, especially with suppliers.
		Interactions with users	Knowledge exchange with lead users to improve products, equipment, software, and production processes.
		Interactive training and experimentation	Various training forms (classroom, on-the-job) and experimentation (e.g. skill or knowledge-building as a by-product of particular innovative experiments); some depend on formally managed processes of exposure to experience-rich opportunities (e.g. searches, non-R&D experiments and field tests, observation tours, technical visits and supervised operations' training in other mines (technical visits) and suppliers' facilities; external training contracted through the acquisition of service and/or new technologies and production systems.
		Interactive informal training	Learning from observing procedures of installation and operations by suppliers and from informal conversations, where one more experienced employee passes the information to another about operation processes.
		Short/medium-term courses duration	Participation in industry meetings and short training courses to master geological/engineering routines and their underlying knowledge bases with specialized suppliers and training centers.
		Technical assistance and consulting services	Knowledge interactions to undertake the diagnosis and formulation of solutions regarding specialized areas, especially with suppliers. They are associated with responses to mining firms' specific demands.
	Science, technology and innovation (STI)	Hiring expertise	Access to new knowledge through the hiring of varied forms of expertise (e.g., new graduates or experienced professionals, from suppliers, competitors or from different industries) to engage in different types and levels of innovative activities.
		Participation in scientific meetings	Active participation in local and/or international scientific conferences and related events (e.g., papers presentation).
		Long-term courses	Postgraduate degree courses (e.g. MSc and PhD) in local and international institutions.
		In-house incipient R&D	Applied research and experimental development activities internally and/or in collaboration.
		In-house formal R&D	Applied research and experimental development projects and search for technological innovations.
		Collaborative R&D	Basic and/or applied research and/or experimental development in collaboration with local and/or international universities and research institutes.

Source: Drawn from related literatures and fieldwork evidence.

8.3.3 Technology Upgrading Intensity

Technology upgrading can be examined from three dimensions (Radosevic and Yoruk 2016; Lacasa et al. 2018): (i) *global interaction*; (ii) *breadth* or structural change in technological activities (e.g., diversification); and (iii) *intensity* or accumulation of technological innovation capabilities. We particularly examine the third dimension as an outcome of the interplay between windows of opportunity and firms' technological learning strategies.

In this study, technology upgrading intensity is the accumulation of progressively higher levels of technological innovation capability, and, consequently, up to the world-leading level (Bell and Figueiredo 2012; Lee and Malerba 2017; Lacasa et al. 2018; Radosevic et al. 2019). Firms' capabilities involve a stock of knowledge-based resources found in human capital, techno-physical systems, and organizational systems, which are symbiotically linked (Bell and Pavitt 1993; Bell 2009; Leonard-Barton 1995). These capabilities reflect what firms can actually do technologically (Jacobides and Winter 2012; Dosi et al. 2000): through these capabilities, firms may implement production activities and innovative activities, with increasing levels of complexity and novelty.

Concerning the operationalization of technological innovation capability, there tends to be a bias in the technological catch-up literature towards standard proxies (R&D indicators and patents) (see Miao et al. 2018 and our earlier discussion). This bias also appears in a stream of studies linking latecomer firms' innovation capabilities with breakthroughs from research institutions (World Bank 2010), where the cross-sectional studies use standard proxies (Walz and Marscheider-Weidemann 2011). The use of these proxies also contributes to classifying industries according to technological complexity levels (from low to high-tech). Relying solely on these perspectives may neglect non-R&D capabilities (e.g. design and engineering) (Patel and Pavitt 1994; Laestadius 1998; Bell 2009, 2012) and lead to false-negative conclusions about technological innovation capability accumulation (Ariffin 2010).

To overcome these problems, we operationalize the technological capability construct through a "revealed capability" approach (Sutton 2012), that is, firms' capabilities are revealed in their technological *activities*. Put differently, firms' capabilities are the observable outcome reflecting the symbiotic relationship between the capability dimensions as firms' technological *activities*. Consistent with studies taking this approach (see Bell and Figueiredo 2012, for review; Hansen and Ockwell 2014; Figueiredo and Cohen 2019), we distinguish between production capability and innovation capability; the latter is disaggregated into the "basic," "intermediate," "advanced," and "world-leading" levels.

8.4 Methods

This study was part of broader research projects implemented from 2012 to 2015, with a follow-up in 2017–18, examining technological capability-building, innovation, and sustainable growth in Brazil's natural resource-intensive industries, including mining.

This study adopted a qualitative and inductive approach, operationalized through a case-study research strategy, and substantiated by fieldwork. This methodological approach is appropriate to improve the understanding of an under-researched phenomenon, the details of which could be missed by aggregated analyses based on quantitative methods (George and Bennett 2005; Yin 2009).

8.4.1 Selected Firms and Related Organizations

We selected firms representing information-rich cases that could substantiate the research question and simplify the analysis (Patton 2002) while providing relevant examples of the issues and enhancing analytical generalization (Yin 2009). The selected firms represented the two most important Brazilian mining firms (Vale and Votorantim Metais), accounting for nearly 60 percent of Brazilian mining output during the studied period (Brasil Mineral 2018). Additionally, the study considered other organizations that collaborated with the leading firms' technological capability-accumulation processes (Table 8.2).

8.4.2 Data Collection Process

Substantiation of the research question demanded detailed and long-term intra-industry and intra-firm qualitative evidence. Accordingly, extensive fieldwork was performed involving multiple sources of evidence and data-collection techniques (Table 8.3). Extended stays in the field increased the evidence-gathering quality (Miles and Huberman 1994). Each interview lasted approximately two hours and was recorded. Because this study examines technological capability accumulation over a relatively long period, efforts were made to collect evidence of previous decades entailing (i) consultations of firms' archival records and other secondary sources; and (ii) snowballing interviews to identify retired staff from firms and research institutes. Access to these primary and secondary sources proved essential in gathering evidence to substantiate the research questions' issues.

8.4.3 Analysis Process

The analysis involved recursive and laborious stages. The first stage began in the field. As we conducted interviews, we mentally established associations among the issues highlighted by the research questions. The second stage involved careful organization and assimilation of all qualitative material gathered during fieldwork. In the third stage, we standardized all interview transcripts to facilitate reading and coding: each researcher read and flagged all interview transcripts and related field material for early classification of different evidence types.

Table 8.2 The selected organizations

Selected organizations		Details
Brazilian leading mining firms	Vale	Created in 1942 as Cia Vale do Rio Doce (CVRD), a state-owned company. It was privatized in 1997. In 2007 it was renamed as Vale. It is Brazil's largest mining firm and the world's largest iron ore producer and exporter.
	Votorantim Metais	Created in 1956 as Cia Mineira de Metais within the Votorantim Group, a large Brazilian conglomerate. In 1996, it was renamed Votorantim Metais (hereafter, Votorantim). In 2016, it acquired the Peruvian Milpo to become Nexa Resources, one the world's largest zinc producers.
Local SMEs suppliers	Geoambiente	Created in 1994 as a startup focusing on geotechnology services
	Useligas	Created in 2002 as a foundry and machining firm, specializing in manufacturing and equipment recovery for mining and other industries.
	Verti Ecotecnologias	Created in 2004 from a university spin-off of the Federal University of Minas Gerais, focusing on R&D in environmental management services.
	Terravision	Created in 2007 from a corporative spin-off of Brandt, an environmental studies firm, to focus on geoprocessing and remote sensing.
International supplier	3M	Created in 1902 in USA, 3M offers a wide selection of peripheral products to the mining industry and has a global network of innovative subsidiaries. Beginning of operations in Brazil in 1946.
Research center and universities	Mineral Technological Centre (CETEM)	Public research institute created in 1978 supporting the development of Brazilian mining technology.
	Federal University of Ouro Preto—School of Mines (UFOP)	Created in 1876, the School of Mines pioneered geological, mineralogical, and metallurgical studies.
	Federal University of Rio Grande do Sul—Engineering School (UFRGS)	Created in 1934, it undertakes teaching and research in mining, metallurgical, and materials engineering.

Table 8.3 Data collection techniques and sources of evidence

Organizations	Data collection techniques	Quantity	Main sources/details
Mining firms	Formal interviews	63	Group 1: Directors (e.g., of mineral projects, technology, and intellectual property). Group 2: Managers and coordinators (e.g., general manager of technology and intellectual property, R&D, mine infrastructure development and innovation, project engineering, mineral exploration manager, and human resource). Group 3: Engineers, supervisors, analysts, technicians, specialists, and researchers (e.g., geological data acquisition infrastructure, senior engineer, and laboratory supervisor).
Research centers and universities		12	Researchers and professors in the field of geology, mine engineering, chemistry, and production.
Suppliers		8	Presidents, analysts, administrators, consultants, specialists, managers, directors, and other professionals in different areas.
Industry-related organizations		2	Consultant of geology, marketing, and relationship coordinator.
Mining firms and suppliers	Direct observations	11	Interactive tours (e.g. Vale: Technological Institute, Mineral Development Center, Mineral Technological Center) non-participant observations or attendance of internal presentations, workshops, conferences, and seminars with suppliers.
Mining firms, suppliers, research centers and universities	Informal meetings	15	Fortuitous meetings with professionals of the organizations (e.g. during lunch, coffee, fraternization, and events).
	Archival records consultations		Presentations of organizations, records in archives, technical files, training records, annual reports, bulletins, institutional videos, historical publications, books, academic articles, and others.

In the fourth stage, we built data matrices based on specific research question issues: (i) firms' technological activities (as a proxy for technological capability accumulation), as the issue to be explained; and (ii) explanatory factors (windows of opportunity and technological learning strategies). To facilitate the analysis, we considered Lee and Malerba (2017) and Figueiredo and Cohen (2019) to organize evidence into three phases in Brazil's mining industry technology upgrading process: (i) emergence (early-1940s—mid-1960s); (ii) gradual catch-up (late-1960s—late-1990s); and (iii) forging ahead (early-2000s—mid-2010s). In the final stage, we elaborated narrative sketches from the interpretation of the data matrices. Elaboration of these narratives improved understanding of the relationships among our research questions issues (Dougherty 2002). Elaboration of these sketches evolved into the presentation of our findings.

8.5 Findings

We organize our findings based on the phases described in the previous section. Within each phase, we describe evidence of the interplay between windows of opportunities and firms' technological learning strategies and technology upgrading.

8.5.1 Emergence Phase (Early-1940s—Mid-1960s)

8.5.1.1 Windows of Opportunity

By the 1910s, there were notable technological advances in mining, iron, and steel-making activities in Europe and the USA, while in Brazil, these activities were incipient. There were only two medium-sized firms producing pig iron through imported raw material: small family businesses making iron casting through small charcoal furnaces. By then, the existence of vast reserves of iron in south-eastern and western Brazil were known due to studies by the Ouro Preto School of Mines, created in 1876. In the south-eastern state of Minas Gerais, the reserves were distant from demand centers. The technology and firms needed to exploit these resource were also lacking. WWI functioned as a window of opportunity for the emergence of Brazil's large-scale mining industry. It created severe difficulties for iron and steel imports, leading to a scarcity of these products in an economy with growing demand. To reduce external dependency, domestic efforts were underway to exploit the mineral reserves (Soares e Silva 1972).

Following federal government's incentives, several foreign firms established their operations in Brazil. By the late-1920s, the British firm Itabira Iron Ore Co., which exploited iron reserves in Minas Gerais, had become a monopoly, sparking nationalist opposition. Starting in 1930, the Getulio Vargas government nationalized all mining businesses and created a new Mining Code separating the soil property from the underneath mineral reserves. These measures, together with WWII, became important windows of opportunity for the creation of Brazilian large mining and steel firms. The nationalist and pragmatic Vargas leadership permitted the USA to install a military base in the north-eastern Brazilian coast in exchange for a USD 20-million loan and technology transfer/assistance from US Steel Co. to create the first Brazilian large-scale steel-making firm, the Cia. Siderúrgica Nacional, in 1941. It then arranged UK's handover to Brazil of Itabira Iron and Ore Co.'s assets and a USD 14 million loan by the USA to structure the first large-scale Brazilian mining firm, the Cia. Vale do Rio Doce (CVRD), in 1942, securing the UK and USA to buy CVRD's exports.[5]

In the 1950s, iron ore demand continued to grow because of the reconstruction of countries involved in war and an arms race led by the Korean War (1950) (CVRD 1992) as well as Brazil's fast economic growth influenced by the Plan of Targets and the import substitution (IS) policy, stimulating basic industries. As production grew, idiosyncratic problems appeared. A new window of opportunity opened: reduced iron ore content led to decreased quality of ore produced in Brazil, which was worsened by generation of excess tailings. In parallel, diffusion of the basic oxygen furnace (BOF) technology in the steel industry—a technological window—required high-quality iron ore loads and more stringent chemical and granulometric specifications for the steelmaking process. Additionally, in the early 1960s, Vale's leadership sought to double the company's exports. As such, the Tubarão Habour (state of Espírito Santo) was built and a long-term contract with ten Japanese steelmakers to supply 50 million tonnes of iron ore over fifteen years was signed (creating a demand window). Responses to these windows of opportunity entailed technological learning strategies to implement early innovation activities.

8.5.1.2 Firms' Technological Learning Strategies and Technology Upgrading

It was not until the early 1950s, that Vale demonstrated actions reflecting its responses to windows of opportunity. Vale's strategic focus was on operational modernization and market expansion, with some engagement in innovation activities, whereas Votorantim sought to consolidate its position in basic industries (cement, chemical, and steel), becoming a basis for entry in the mining industry. Elements of *imitative strategy* were predominant through learning efforts to create production capabilities. However, learning efforts were made to engage in minor improvements and develop local technical solutions in response to demand pressures and idiosyncratic problems, respectively. This affected technology upgrading. These efforts were made through the use of learning mechanisms related to DUI/STI knowledge forms.

8.5.1.3 DUI Learning Mechanisms

One of the major barriers to increasing production for meeting growing demand was the lack of capabilities for basic mining operations. Most workers who had been hired by Vale in the 1940s were not used to large-scale industrial operations: about 70 percent worked in agrarian activities in rural areas, whereas 30 percent were from small family businesses (CVRD 1992). One of the learning strategies used by Vale and other firms involved informal training through observation of installation procedures and equipment operations by suppliers and knowledge sharing through informal interactions with more experienced employees. Training also involved technical visits and observation tours to overseas operations accompanied by

[5] For the sake of simplicity, hereafter we will refer to this firm simply as Vale (Table 8.2).

representatives of equipment manufacturers. This strategy limited some engineers and managers because of language barriers (Germany 2002).

By the 1950s, seeking to enhance their initial production capability to meet growing iron ore internal demand (stimulated by the Plan of Targets) and exports, firms turned to suppliers for technical assistance and consulting services. For example, Vale hired US technicians to assist the then rudimentary mining of rolled hematite and experts in designing a plan to scale up production (Germany 2002). It also contracted the mining firm Parsons, Klapp, Brinckerhoff, and Douglas to plan a mining process from crushing and ore loading on conveyor belts to warehouses, and then boarding silos on railway wagons (CVRD 1992). As production volume grew and the BOF steelmaking technology diffused, serious customer complaints emerged. Accordingly, Vale interacted with local and external users to exchange knowledge on the required specifications for iron ore for better processing in steel mills. Vale also created a mineral-processing laboratory to enhance interactions with users to achieve proper granulometry for materials.

8.5.1.4 STI Learning Mechanisms

As production expanded, new idiosyncratic problems emerged. Among them were the accumulation of a fine fraction of hematite (pieces inferior to the half-inch) with no economically viable use and scarcity of high-content hematite. To tackle these problems, firms engaged in learning strategies such as learning by hiring and research activities. The Ouro Preto School of Mines was a major supplier of expertise, which included engineers, geologists, and technicians for mining and steelmaking operations. Simultaneously, Vale, in partnership with the Development Council, a federal agency, created a research fund to investigate the use of the itabirite of Minas Gerais. Vale began in-house R&D activities, although incipient, with the Armour Research Foundation at the Illinois Institute of Technology (USA) to explore possibilities of use of hematite and itabirite fines and ultrafines (considered waste) that accumulated in the mines (CVRD 1992; Vale 2012).

That research project demonstrated the potential to produce 4 million tonnes/year of itabirite concentrations. This discovery triggered the creation, in the early 1960s, of the Vatu Steel Co. Vale conducted initial R&D activities on pelletizing and other agglomeration processes, and technical studies for the installation of pelletizing plants, supported by universities and research institutes from the USA, Europe, and Japan. This research initiative worked as an essential knowledge acquisition process for building Vale's pelletizing plants. During this period, firms implemented relatively complex changes in dominant technologies based on incipient in-house R&D to solve the specific problems related to the Brazilian geological and mineral context. In 1968, Vale demonstrated the technical–economic feasibility of the hematite and itabirite fines treatment, ensuring the use of the existing vast itabirite reserves, as described by an R&D manager: "The development of this technology of concentration of the fines and ultrafines by Vale's Technology Research Centre enabled us to produce 45 million tonnes of pellets a year."

8.5.2 Gradual Catch-Up Phase (Late-1960s—Late-1990s)

8.5.2.1 Windows of Opportunity

During the late-1960s and 1970s, windows of opportunity opened for Brazil's mining industry, which triggered new learning strategies. Competition in the global mining industry increased due to the start of operations of Australia's Pilbara reserves. Regarding idiosyncratic problems, Brazil faced forecast of mines exhaustion by the 1990s. There was little knowledge about the Brazilian geological potential for exploitation along with obsolete mine infrastructure. These issues triggered some government actions that led to new institutional windows of opportunity.

The Brazilian government supported geological research and technological upgrading of mining through the first and second national development plans (1972–74 and 1975–79) and public and private investments. The National Non-Ferrous Metals Industry Development Program sought to make Brazil self-sufficient in non-ferrous metals and generate export surpluses, seeking, for instance, a major increase in zinc exploration and production (Conselho de Desenvolvimento Econômico (1975:9). In parallel, the government supported the creation of new undergraduate courses in geology in Porto Alegre, São Paulo, Ouro Preto, and Recife; the establishment of CETEM, a public research institute (Table 8.2) at the Federal University of Rio de Janeiro to undertake world-class mineral research; and the Natural Resource Research Co, a state-owned firm, under the Ministry of Mines and Energy. These institutions sought to intensify the discovery and use of mineral and water resource and provide venture capital to mining companies (CVRD 1992; Vale 2012). Additionally, Vale's Technological Research Centre and state-owned enterprise, Docegeo, a subsidiary of Vale, were created for mineral research.

During the late-1960s and mid-1970s, a critical window of opportunity opened for growth and technological development of Brazil's mining industry: the discovery of the massive Carajás reserves (in the Amazonian state of Pará, Northern Brazil). Early identification of the Carajás reserves occurred in 1966 through a major mineral exploration program in Brazil led by the Cia Meridional de Mineração, a subsidiary of the US Steel Corp. This event was followed by the Brazilian government's implementation of Project RADAM (Radar Amazon) during the early-1970s. This project sought to map out Amazonian soils through soil pit information, aerial photography, and geologic maps. It gathered data, including satellite imagery, micro-meteorological observations, near surface and upper-air atmospheric conditions, and surface biophysical and hydrological measurements, which revealed the immense richness of Carajás: iron ore resource involving approximately 18 billion metric tonnes containing 65 percent iron and significant deposits of bauxite, copper, gold, manganese, nickel, tin, niobium, and other minerals. The initial design and engineering projects for Carajás were undertaken by a joint venture between Vale and US Steel Engineering and Consultants (VALUEC). The exploitation of the Carajás reserves involved a joint venture between Vale and US Steel, the Amazonia Mineração. However, Vale soon acquired US Steel's share in this venture, becoming the sole operator of the Great Carajás Project (Machamer et al. 1991; CVRD 1992).

However, Brazil lacked the financial resources to fund the Carajás Project. Vale's leadership set the ambitious goal of operationalizing Carajás. A loan from the World Bank to fund the project was secured. The company was pushed to expand production from 10 million tonnes (early 1960s) to 56 million tonnes (1970s). Logistics operations were considerably expanded with the creation of new subsidiaries. By the late-1960s, Vale had the world's third-largest shipping fleet. During the 1980s, the Brazilian economy was marked by recession, hyperinflation, and external debt, which exposed the limits of state ownership of industries such as mining. Vale's leadership responded to that macro-economic condition by supporting an extensive technological research program to develop new products for new market demands. That program involved USD 200 million during the 1980s and helped diversify Vale's portfolio of mineral production. By the early-1990s, following the phase-out of the IS policy regime, the federal government launched the National Privatization Program, culminating in Vale's privatization in 1997 (Vale 2012). These events from the 1980s and 1990s opened new windows of opportunity to engage in defensive (with some elements) of offensive technological learning strategies.

8.5.2.2 Firms' Technological Learning Strategies and Technology Upgrading

Evidence suggests a mix between elements of defensive and imitative technological learning strategies. During the 1970s, Vale engaged in diverse projects to produce bauxite, aluminium, manganese, titanium, phosphate, fertilizer, magnetic ferrite, forests, cellulose, and pellets. This reflected a combination of Vale's leadership view on expansion and its response to market demand. Soon, the company transformed itself into a large state-owned business conglomerate, encompassing more than two dozen controlled and affiliated companies. It also developed a broad technological research program to produce new types of products to meet market demands. Votorantim expanded into zinc production through the acquisition of Companhia Mineira de Metais (CMM). The economic hardships of the 1980s and early 1990s, downturn in the mining and world economy, and stabilization of world steel production contributed to stalling the aggressive strategies in both Vale and Votorantim of the previous decades. They emphasized an imitative strategy for cost reduction and a productivity increase program with significant staff reduction. These changing strategies were reflected in the use of learning mechanisms.

8.5.2.3 DUI Learning Mechanisms

In the 1970s, facing limitation in technological innovation capability in the area of exploration (mineral prospecting and research), and to respond to the Carajás challenge, leading firms such as Vale engaged in learning efforts. These efforts included technical visits to mines in South Africa, the USA, Australia, and Canada. They also sent their professionals for short- and medium-term technical courses at the Brazilian Institute of Mining (IBRAM) and National Department of Mineral Production and industry-related organizations. Technical assistance and consulting services were also used. For example, from 1971 to 1974, Docegeo implemented the

First Triennial Geological Prospecting Program involving several types of specialized engineering services and technical assistance from the USA, UK, South Africa, Canada, and Australia, and especially from the US firm Terraservice Geological (Furtado and Urias 2013). Docegeo's relationship with Terraservice triggered other learning mechanisms (see the next section).

Operations expansion entailed intense design, engineering, and experimentation. For example, Vale redesigned the Cauê mine plant using equipment imported from Germany, which was adapted and enhanced by Vale's technicians and engineers, together with suppliers, to meet local geological conditions. Similar efforts were made by other firms to enter into zinc operations. CMM with Metallurgica Atlas, a subsidiary of the Votorantim Group, implemented design, engineering, and experimentations to adapt and develop equipment and machinery to produce electrolytic zinc ingots (Caldeira 2008).

Following the start of the Great Carajás Project, Vale intensified the use of technical assistance and consulting services. It pioneered the adoption of the following technologies in Brazil: (i) computerized planning and quality control in the mining with application of geostatistics; (ii) rock mechanics applied to slope stability; (iii) controlled deposition of tailings; (iv) lowering water tables in mines; and (v) transport of ore and sterile by belts in both directions. This learning effort was made through broad agreements with foreign suppliers and specialized engineering firms, through which Vale had the best available technical experts to train its technicians and engineers for using and further adapting those technologies (Germany, 2002).

8.5.2.4 STI Learning Mechanisms

The hiring of both local and foreign expertise was intensified. Following the end of the Triennial Geological Prospecting Program, Docegeo hired all the international experts who had worked on this project. Later, foreign professionals were replaced by new graduates from Brazilian geology schools: by 1973 foreign experts represented 30 percent of Docegeo's professionals; by 1980 this was reduced to 5 percent. By the early 1980s, Docegeo encouraged newly hired Brazilian graduate technicians and engineers to take post-graduate courses in Brazilian and foreign universities in economic geology and geochemistry. They were urged to present papers in local and international scientific meetings in France, Canada, the USA, South Africa, Australia, Romania, and Belgium (CVRD 1992). CMM's professionals were encouraged to take master and doctorate courses at Brazilian universities for generating patents, as a Votorantim manager recalled:

> During my master's degree, I demonstrated that it was possible to increase the yield of zinc using autoclaves and was granted a patent for that process. In my doctorate work, I showed how to turn silica residue into cement, leading to another patent.

Vale structured and strengthened its Technological Research Centre to undertake R&D activities in various minerals, such as manganese, gold, coal, aluminium, copper, titanium, and silicon. CETEM also intensified its R&D supporting the industry as well. With CMM, it engaged in R&D to develop a process of concentrating oxidized zinc ore, a rare type of ore worldwide. A similar project was underway with Mineração Areiense to develop a concentration process by flotation (Branquinho 2014).

To reduce foreign dependence, CETEM engaged in-house R&D in metallic copper, which was soon demanded by local firms. Together with Mineração Caraíba, CETEM sought to pioneer the development of a hydrometallurgical process in Brazil. To this end, in-house research efforts were combined with technical visits (DUI learning) to several copper-producing centers such as in Chile and Peru. These learning efforts paid off, as Brazilian firms achieved exceptional copper recovery values—even higher than those practiced in other traditional copper-producing countries (Branquinho 2014).

8.5.3 Forging Ahead Phase (Early-2000s—Mid-2010s)

8.5.3.1 Windows of Opportunity

The "super commodities cycle" of the early/mid-2000s combined increased mineral price and demand with high growth rates of large customers such as China and India. High domestic growth rates further augmented this trend. Together, they opened up windows of opportunities for growth, innovation, and internationalization. New idiosyncratic problems emerged, as leading firms faced different environmental, health, and safety challenges from new technologies and regulations, forcing them to respond with innovative solutions. Advances in 4.0 technologies and the enactment of new laws to stimulate innovation in Brazil also contributed to opening new opportunities for innovation and learning. For example, the *Good Law* created tax incentives for firms undertaking R&D activities. Also, the *Innovation Law* sought to stimulate firms to interact with universities to create cooperative laboratories, develop joint projects, incubate start-ups, and train R&D personnel. During this industry upturn, Vale's new leadership engaged the company in mega expansion projects through internationalization (e.g. acquisition of the Canadian Inco, the then world's second-biggest producer of the metal, which is used mainly in stainless steel). Votorantim expanded into China and Canada and also acquired the Peruvian mining company Milpo to create Nexa Resources.

Vale's leadership also sponsored ambitious innovation projects as a way of preparing the firm for long-term growth and transition to new technologies. In Votorantim, top leadership sponsored a strengthening of technological innovation management areas and projects. Following the end of the commodities super cycle by the mid-2010s, the global mining industry began to downsize, despite stabilization in prices, leading to delays in new investments (Ali et al. 2017). These changes were reflected in the technological learning strategies of the leading Brazilian mining firms.

8.5.3.2 Firms' Technological Learning Strategies and Technology Upgrading

Leading firms and related organizations in Brazil's mining industry responded to these windows of opportunity and leadership actions by engaging in technological activities with a higher level of complexity and new-to-the-world degree of novelty. Vale engaged in extensive internationalization and learning investments to support its engagement in world-leading innovation activities through world-class collaborative R&D and engineering. Evidence suggests deliberate actions involving elements of offensive innovation strategy at the beginning of this phase. However, within the same phase, elements of defensive strategy became prominent following the downturn of the industry after 2011.

8.5.3.2.1 DUI Learning Mechanisms

Leading firms' professionals engaged in short- and medium-term courses through interaction with different partners. For example, Vale interacted with the Federal University of Ouro Preto to implement short-term technical courses on mining–metallurgical systems. Together with Accenture, IBM, and the Catholic University at Rio de Janeiro, Vale implemented internal artificial intelligence (AI) courses at its AI Centre, as stated by the digital transformation director (Vale 2019):

> Vale's AI Centre represents another important step in our digital transformation programme to drive innovation to increase productivity […] and improve our health and safety standards, and financial performance.

The AI Centre also contributed to stimulating internal knowledge creation, sharing, and codification, as stated by the information technology innovation manager (Vale 2019):

> Vale's AI Centre encourages intense integration and collaboration between project leaders. Professionals' experiences and knowledge exchange are fundamental to increase synergy between teams and generate results on a global scale. Much of what is created for one project can be applied to another.

Vale also established a partnership with CETEM to develop simulation-based training and flotation modelling, including observation tours and specific technical training in Vale's operations (e.g., the bauxite operations in Paragominas and potassium in Taquari Vassouras). Through joint engineering and experimentation with a supplier, Vale adapted a filter from the food industry to develop a fine-grained mud filtration process in Carajás. There was technical assistance acquisition from universities to tackle complex engineering problems. For example, Votorantim interacted with the Federal University of Lavras to solve plant waste problems, as a technology manager described:

> As we interacted with the university [Lavras], they identified that our residue was an innovative product and could be used by farmers. So, what used to be a problem turned out be a new business opportunity.

With specialized suppliers, leading mining firms conducted engineering-based interactions for new mining projects. For example, Anglo American, in partnership with Geoambiente, a local SME supplier (see Table 8.2), developed a geographic system to assist in the execution and development of a mining pipeline project of the mining company, as described by Geoambiente's CEO:

> That was a joint engineering and development work on how a geographic system could help the company develop a new pipeline project.

Votorantim established a joint-engineering and consulting service interaction with Terravision, a local specialized SME (see Table 8.2), to generate cartographic bases and mappings for the development of new pipelines, as Terravision's technical director commented:

> We built the project layout for the pipeline based on a project that the companies already had. That created a basis for our own company to enter a new market with a new product. It was a win–win knowledge-based interaction.

8.5.3.2.2 STI Learning Mechanisms

By 2005, Vale engaged in studies to expand its operations in the Great Carajás through the mega project, the S11D Project, reflecting the name of the iron ore deposit: Carajás Serra Sul S11D, denoting Carajás southern mountain range iron ore body 11, block D. Carajás accounts for more than 70 percent of Vale's output. Deemed in the global mining industry as the world's largest iron ore mine project and one of the most revolutionary projects in mining history, S11D involved a USD 16-billion investment, producing 90 million tonnes of iron/year and its operations began in 2016. This project triggered a mix of innovative activities and learning mechanisms based on design, engineering, experimentation within Vale in partnership with suppliers, and in-house and collaborative R&D.

Designed to minimize environmental impacts, instead of using fixed crushers and 100 off-highway trucks, which would be needed to operate the site, the S11D system uses movable crushers and 60 km-long truckless conveyor belts that lead the product to the processing plant. 3D technology helps analyze maintenance and operation interferences. This replacement enables a 77 percent reduction in fuel consumption and dramatic reductions in waste (tires, filters, and lubricants) and GHG emissions. All operators' training was undertaken through the S11D Training Centre, which became a tool for the development of professionals. Responding to the idiosyncratic wet-season humidity of the region and innovating the use of water resource, Vale opted for dry processing of the ore and used the iron ore's own natural moisture, thus cutting water consumption by approximately 90 percent and eliminating the need for tailings dams. To design the tailored equipment and processes, Vale sought specialized suppliers, particularly Haver & Boecker Latinoamerica (HBL), a major vibrating screens supplier. Vale's project teams worked with HBL engineers to co-design a dry-screening setup that would enhance the efficiency at S11D (Jankovic 2015).

Another response to the boom-related windows of opportunity of this phase was the intensification of internationalization by Vale and Votorantim. Vale's responses, in particular, sparked several research-based learning practices. In 2006, Vale entered the nickel industry by acquiring the Canadian Inco, assuming the second position in world nickel production, behind Russian Norilsk. Through Inco's acquisition, Vale incorporated robust world-leading innovative technological capability—for example, Inco's Base Metals Technical Excellence Centre. Additionally, Vale kept Inco's partnerships with Snolab and Vale Living with the Lakes Centre research centers, through which Vale undertook basic and applied R&D activities in geological exploration technology to create world-class tools and methodologies.

In 2008, responding to technological opportunities (4.0 technologies) and mainly customer demands, Vale created the Ferrous Technological Centre (known by Portuguese acronym CTF) to study the use of iron ore and coal at the steel industry. It sought to deliver products best suited to customer needs. Vale became the world's only mining company with this type of research center. CTF hired specialized researchers in mineral characterization (e.g. Mössbauer spectroscopy), nanotechnology, and genomics.[6] Vale's activities in nanotechnology attracted new R&D partnerships with the federal universities of Minas Gerais and Ouro Preto and a Singaporean university to develop nanotubes to strengthen pellets structure, as a CTF manager described:

> As we searched for possibilities of using these new materials (carbon nanotubes) to strengthen the structure of our products, we opened new research lines.

Reflecting more research-based responses and, particularly its corporate leadership impetus, by the mid-2000s, Vale created the Vale Technological Institutes (known by Portuguese acronym ITV) involving partnerships with local and international institutions to focus, according to official documents, on the development of long-term disruptive research to generate high-impact technologies and new businesses. A manager of Vale's Mineral Development Centre (known by Portuguese acronym CDM) states:

> We have projects with various universities in UK, Toronto, Colorado, British Columbia, and Brazil. Currently, we are doing research in biometallurgy and biolixiviation of nickel ores [R&D in biotechnology]. We map out universities and their areas of reference and approach them.

In Brazil, the Ouro Preto's ITV (southeast) focused on mining studies; the Belém's ITV (north) focused on sustainability research. Vale's ITVs offered training, including for non-Vale professionals, in the application of industry 4.0-related technologies and

[6] Mössbauer spectroscopy is an analytical tool capable of identifying the chemical composition of rocks. This technology was present in NASA's robots to discover the presence of goethite, a ferrous mineral that only forms in the presence of water, on Mars.

sustainable use of natural resource in tropical regions (idiosyncratic issues). Interviews suggested that Vale sought to engage in innovations different from its core technologies as a way to guarantee long-term growth and respond to growing environmental pressures such as water use. Based on biotechnology, Vale's Mineral Development Centre developed research on the industrial use of bioleaching, a technique that uses bacteria to stimulate the extraction of copper (Vale 2015). Other initiatives involve a joint development between Vale, a local university, and 3M to develop a hollow glass microsphere that improves the blasting process and the development of alloys with higher concentration of niobium from a partnership between SME Useligas and CBMM (a leading Brazilian niobium producer).

By the late-2000s, Vale and Votorantim began collaborative R&D projects with leading international research institutions, such as the Australian Mineral Industries Research Association (AMIRA) to undertake projects such as practical 3D electromagnetic inversion for exploration, geologically constrained automatic and interactive interpretation of electromagnetic data, predictive geochemistry in areas of transported overburden, and enhanced geochemical targeting in magmatic-hydrothermal systems. One of these projects sought to improve comminution (reduction of solid materials from one average particle size to a smaller average particle size), classification, and flotation performance through modeling, simulation, and characterization of particles and their process environments, as Vale's CDM's manager described:

> These projects' outcomes include training and transfer of skills and technology to participants. They also deliver new measurement and characterisation tools that will greatly improve predictability of plant performance.

Firms participating in AMIRA's projects need to offer technological and scientific innovative capabilities to contribute substantially to advances. To strengthen their participation in the R&D projects with AMIRA, Brazilian mining firms engaged with local universities. In the case of Project P9, the Federal University of Rio de Janeiro participated in facilitating knowledge absorption and dissemination. Another example of Vale's interaction with universities for innovative R&D was the partnership with the Federal University of Rio Grande do Sul for the Fragcom project. Following a similar initiative in Australia during the 1990s (Mine to Mill project), but adapting it to Brazil's specific geological conditions, it researched the fragmentation produced by blasting rocks using explosives, and its impacts on mining and comminution operations. It also included MSc training of Vale's employees and their participation in scientific events.

Using opportunities emanated from the wave of 4.0 technologies, Vale started the Autonomous Mine project, an R&D initiative based on IoT in partnership with major suppliers (e.g., Flanders) and the Federal University of Rio Grande do Sul to develop autonomous equipment (e.g., drill rigs and self-propelled explosives trucks). Vale provided suppliers with design specifications and tests of new equipment at the Brucutu mine. Similarly, based on IoT, Votorantim started the Digital

Mining Program to undertake innovation activities in flotation processes, preparation and metering of reagents, drilling, and predictive monitoring of metallurgy and mining assets, and remote detonation. Real-time monitoring allows almost instantaneous adjustments in the amounts of reagents and inputs used in ore beneficiation and recovery, as well as optimizing mine cycles and increasing productivity (Inforchannel 2017).

Responding to environmental pressures, Votorantim interacted with the Federal University of Lavras to undertake R&D to solve plant waste problems. This interaction led to an innovative product: due to the residue composition (e.g., calcium, magnesium, manganese), it has been transformed into a fertilizer for use on agricultural properties (patent). Mining firms also engaged in R&D-based interactions with suppliers to tackle idiosyncratic environmental problems. AngloGold and Verti, a local SME supplier (see Table 8.2), established a joint-R&D for effluent treatment, cyanide, used in gold processing. Subsequently, Verti identified an opportunity to address idiosyncratic problems related to the use of dam rejects and began an internal R&D project in this area.

Following the end of the commodities super cycle by the mid-2010s and the global mining industry downturn, the leading Brazilian firms' technological learning strategies were more oriented towards sustaining their technological innovation capabilities around their core businesses. This move reflected a mix between offensive and defensive elements. Responding to pressures for cost-reduction emanating from the new industry's conditions, leading firms' strategies aimed to strength and focus on highly profitable activities, businesses, and shorter-term projects. The change in strategic orientation was reflected in specific learning efforts. For instance, Vale's ITV (Ouro Preto) moved away from long-term and disruptive impact R&D activities towards short-term R&D activities, focusing on cost-reduction alternative technologies for reducing iron ore moisture content.

8.6 Discussion

8.6.1 Discussion of Findings and Contributions to Research

Regarding our research question on how the interplay between windows of opportunity and leading firms' technological learning strategies affected technology upgrading intensity in Brazil's mining industry, thus shifting this industry into a globally leading position, we found that leading firms implemented technological learning strategies that emerged as their responses to windows of opportunity (demand, technological, institutional, and idiosyncratic problems) across the emergence, gradual catch-up, and forging-ahead phases of the technology upgrading process.

These technological learning strategies manifested in various ways from imitative and defensive to offensive, with elements overlapping over the three phases of the technology upgrading process, involving two major forms of knowledge inputs for innovation: "doing, using and interacting" (DUI) and "science, technology and innovation" (STI), which were operationalized through various learning mechanisms. These knowledge inputs were externally accessed and acquired and internally generated (and shared, integrated, and codified) through the use of various learning mechanisms (see Table 8.1). The use of these learning mechanisms by the leading firms changed qualitatively, affecting the intensity of technological upgrading across those three phases. Stated differently, as leading firms implemented *technological learning strategies*, as responses to windows of opportunity, there was a subsequent increase in innovation capability levels (or a reduction in the capability gap in relation to the international innovation frontier). This suggests that those learning strategies were effective in affecting technology upgrading.

Table 8.4 summarizes our main findings on the interplay between changing windows of opportunities and firms' technological learning strategies. Demand windows, including the industry upturn of the 2000s, played a key role in triggering capability-building efforts. Nonetheless, it should be recognized that corporate leadership was essential in responding to signals emanated from windows of opportunities and making their own strategic choices on capability-building efforts. Without corporate leadership's impetus, those technological learning strategies and the consequent technology upgrading would probably not have been materialized.

Figure 8.1 represents the progressive intensity of the technology upgrading process in Brazil's mining industry as an outcome of leading firms' technological learning strategies. Our study captured a wide range of innovation capabilities, from production to various levels of innovation capabilities such as experimentation, design, and engineering, and R&D involved in that technology-upgrading process, as an outcome of the complementary use of DUI and STI learning mechanisms. In sum, our study shows that firms' *technological learning strategies* that emerge as strategic responses to changing windows of opportunity, may vary from imitative and defensive to offensive, involving various DUI and STI learning mechanisms, whose use are qualitatively changed over time, affecting firms' technology upgrading process across its emergence, gradual catch-up, and forging ahead phases.

Thus, our study generates relevant theoretical and empirical contributions to and implications for the technology upgrading/catch-up and innovation literatures, in different ways. First, we believe that our study contributes to furthering the understanding of technology upgrading, particularly regarding its explanatory factors, from a micro-level perspective. Specifically, we unveil how *technological learning strategies* are formed and implemented to affect technology upgrading. We thus add substantial empirical insights to the framework of Radosevic et al. (2019), Lacasa et al. (2018), Lee and Malerba (2017) and Figueiredo and Cohen (2019).

Second, we adopt a comprehensive perspective on proxies of technological innovation capability and the underlying knowledge inputs, through a long-term

Table 8.4 Windows of opportunity and firms' technological learning strategies

Phases/Issues	Emergence (early 1940s—mid-1960s)	Gradual catch-up (late 1960s—late 1990s)	Forging ahead (early 2000s—mid 2010s)
Windows of opportunities	**Demand:** WW2, reconstruction of countries, and Korean War → increased iron ore demand →Intense demand by Japanese steelmakers → Opportunity for Vale to secure long-term iron ore supply to Japan. **Idiosyncratic problems:** Scarcity of high iron ore content and tailings without economically viable use → decrease in the ore quality and efficiency → increased capability-building efforts. **Technological:** Diffusion of the basic oxygen furnace technology in steelmaking process → demand for high-quality iron ore loads with more stringent chemical and granulometric specifications → efforts to improve iron ore quality. **Institutional:** The government plans to foster growth and development and import substitution policy → expansion of mining activities and increased mineral demand.	**Demand:** Australia Pilbara's upstart: increased competition → Growth of iron ore users' international network. **Idiosyncratic problems:** Forecast of Brazilian mines exhaustion and lack of knowledge on local geological potential ➞ new government and firms' leadership actions ➞ new institutional windows. **Technological:** Obsolescence of Brazilian mine infrastructure. Discovery and upstart of Carajás operations ➞ new learning and capability building efforts **Institutional:** Brazilian government support of geological research and technological development through 1st and 2nd national development plans. Government support for education/training and research in the mining industry. National Privatization Program → Vale's privatization.	**Demand:** Super commodities cycle and industry upturn→ Increased mineral demand and mineral prices and expansion of Brazilian mining industry through internationalization efforts. Industry downturn: after 2012 ➞ slowdown in learning and innovative capability efforts. **Idiosyncratic problems:** Intensification of environmental, health and safety issues → new research efforts. **Technological:** Intensification of activities based on 4.0 technology and bio and nanotechnologies → renewed learning and capability-building efforts. **Institutional:** Government policies to promote collaboration between companies and universities.
↓	↓	↓	↓

Technological learning strategies	Mostly **imitative strategy with some elements of defensive strategy**, operationalized through the use of: ➢ DUI learning mechanisms to create production capabilities. ➢ Some STI learning to accumulate basic to intermediate innovative capabilities.	The prominence of **defensive strategy, with some elements of offensive strategies,** through the use of: ➢ DUI learning mechanisms to strengthen production capabilities and engage in intermediate innovative capability accumulation. ➢ A wider variety of STI learning mechanisms to accumulate intermediate to advanced innovative capability level. R&D use still mostly in-house.	The prominence of **offensive strategy** (during industry upturn) with **elements of defensive strategy** (during industry downturn), through the use of: ➢ DUI learning mechanisms to accumulate intermediate, advanced, and even world-leading level innovative capability. ➢ STI learning mechanisms (including local and international collaborative R&D) to accumulate advanced and world-leading level.

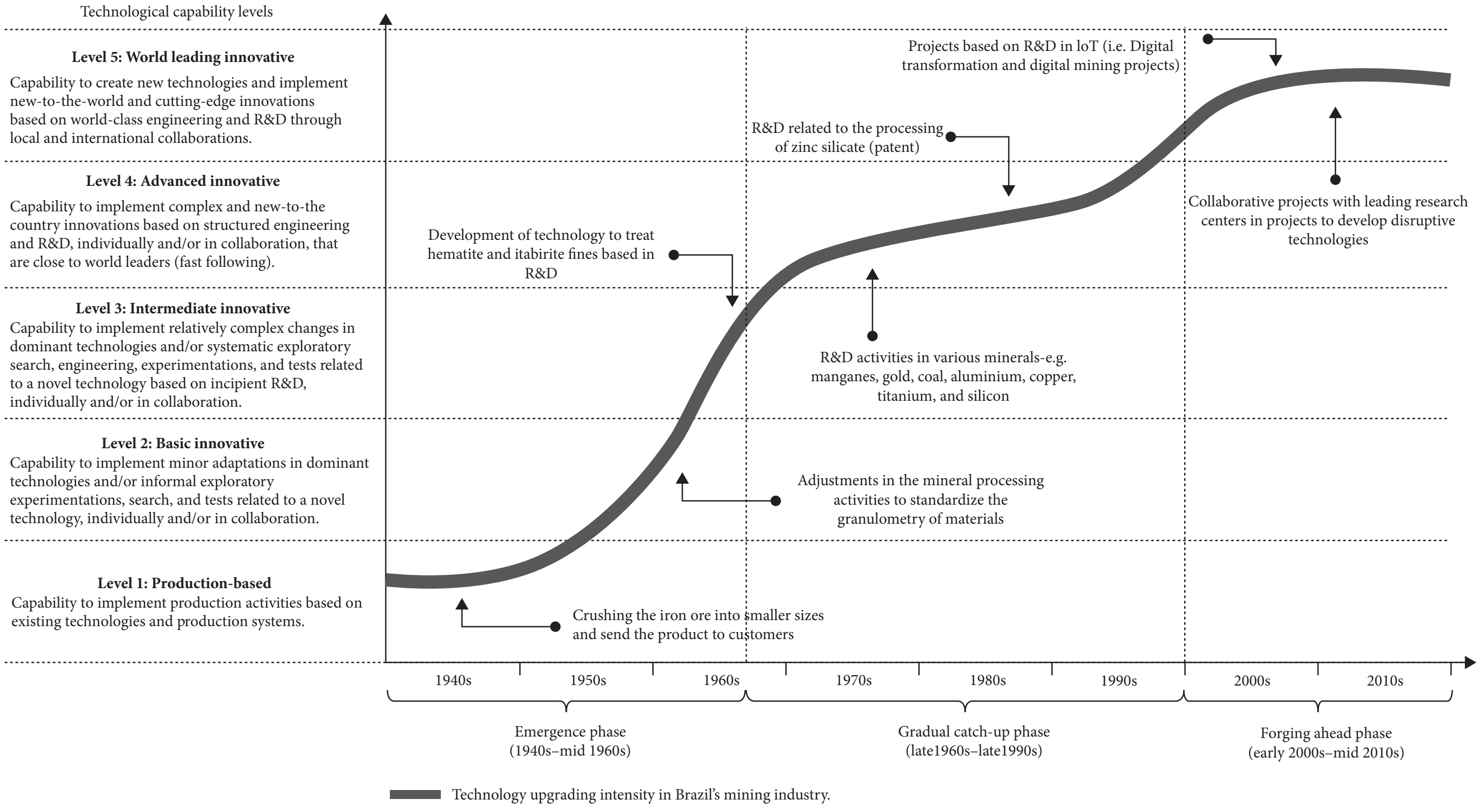

Figure 8.1 Technology upgrading intensity in Brazil's mining industry

qualitative study. By doing so, our study captures nuances and a broader spectrum of innovation capabilities and learning mechanisms involved in technology upgrading intensity. We move beyond extant studies of technological catch-up/upgrading, which tend to focus on specific proxies for technological innovation capability and learning channels (see Miao et al. 2018). We also respond to calls in the latecomer literature (Bell 2009) and innovation literature (Lundvall et al. 2008; Lundvall 2012; Martin 2016) to adopt a wider perspective on technological capabilities (e.g., non-R&D) and a complementarity between different knowledge inputs.

Third, our study adds relevant empirical insights to the stream of innovation literature focusing on knowledge forms and its implications for firms' innovative performance (Jensen et al. 2007; Lundvall et al. 2008; Lundvall 2012; Apanasovich 2016) by examining the changing complementary of DUI/STI learning modes and how they affect latecomer firms' technology upgrading/catch-up, an issue that has been mostly overlooked in this literature stream. Contradicting extant studies that examine these learning modes in natural resource-intensive industries in advanced economies (Isaksen and Karlsen 2010; Simensen 2018), we found that a complementarity between both learning modes, not only DUI, was essential for technology upgrading. Accordingly, our findings provide enhanced empirical support for Lundvall and Lorenz (2007) who argues that in both "high-tech" and "low tech" industries a combination of strong versions of DUI/STI learning modes matters for innovative performance.

Fourth, by examining technology upgrading intensity and the role of technological learning strategies, through the use of DUI/STI learning mechanisms, from a micro-level perspective, in an under-researched natural resource-intensive industry, such as mining, in a resource-rich emerging economy, we add substantial empirical insights to the understanding of technology upgrading/catch-up, beyond the commonly examined assembled products industries. Additionally, our findings contribute to questioning existing industrial classifications (OCDE, 1999), which, although not reflecting reality, still condition policy-making and related decisions. Given the importance of natural resource-intensive industries for most resource-rich developing/emerging economies, our findings suggest that technology upgrading intensity in these industries seems to be highly relevant for the economic catch-up of these economies, particularly those which are trapped at the middle-income and technology levels. Finally, our study provides an empirical methodological basis for the analysis of technology upgrading and its sources in other industries and other countries.

8.6.2 Policy Implications

We provide policymakers with evidence of levels and sources of technology upgrading in natural resource-intensive industries, which account for a considerable part of emerging resource-rich economies' GDP and exports. Policymakers in these countries should develop a broader perspective on these industries and support their technology upgrading, as they are likely to contribute to economic growth significantly. For managers, our findings suggest that despite latecomer firms' initial lack of innovation capabilities, they may engage in technological learning strategies through the use of various learning mechanisms based on DUI/STI knowledge inputs, to upgrade technologically, and achieve competitive performance in global markets.

8.6.3 Limitations and Further Research

Our study has several limitations. First, our study is based on one industry in one country. Future studies could enlarge the coverage of industries through international comparisons. Second, future studies could systematically examine broader outcomes of technology upgrading to capture operational and technical performance improvements (energy and water consumption), environmental, economic, and social impacts. Further research could deepen the study of the role of other intra-firm and intra-industry factors affecting technological learning strategies and technology upgrading in natural resource-intensive industries in resource-rich developing/emerging economies.

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9

Upgrading Non-Technological Capabilities

Evidence from Korean Firms

Jae-Yong Choung and Hye-Ran Hwang

9.1 Introduction

As the capabilities of late-industrialized countries improved, research on technological catch-up evolved along with our understanding of the learning mechanisms associated with technological capabilities (for a comprehensive review, see Dutrénit 2004; Bell 2009; Bell and Figueiredo 2012). Since the 1990s, several latecomer countries have passed the catch-up learning stage and attained leading positions in several sectors where their core competencies reside, such as memory semiconductors, display, mobile phones, shipbuilding, and automobiles, and manufacturing of hardware-based mass-produced products. In recent years, Korean firms have attained a competitive position with reference to producing complex product systems (CoPS),[1] which is distinct from mass-produced products. After rapidly catching up in the military, nuclear, and telecommunications industries, these latecomer firms allowed Korea to undertake the world's first instance of the commercialization of wireless CDMA communication services, to develop for the first time an integrated-type nuclear reactor, and to become the fourth country worldwide to develop high-speed trains and to export supersonic advanced trains and light combat aircraft, as well as large-scale nuclear reactors (KISTEP 2015)*.

However, first-tier late-industrialized countries such as Korea faced major challenges in the 2000s as they transitioned from the phase of "catching-up" with the global frontier, through technological imitation and assimilation, to a post catch-up phase involving the development of new knowledge for world-leading product and process innovations. This chapter investigates the key elements that bring

[1] In this chapter, the term for complex product systems will be used interchangeably with mega-projects. This is often called a mega-project, where large-scale investment is required, involving sums as high as US$1 billion or more.

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about building new capabilities and sheds light on the challenging areas which must be understood properly to ensure a successful transition to leadership for latecomer countries.

Based on in-depth case studies in Korea, this study demonstrates that beyond building technological capabilities, at each stage latecomers face different non-technological challenges. While non-technological capabilities, such as marketing and organizational innovations (OECD 2005) are critical in firms' innovation, little research has been conducted on the relationship between technological and non-technological capabilities.[2]

This study discusses the challenging issues of non-technological capability: the organizational innovation at the mature stage, the financial packages at the transition stage, and regulatory innovation at the fluid stage. Although this study focused on Korean cases, the exploration of challenging activities also clarifies our understanding of the transition process toward product development and market diffusion in newly emerging economies. The remainder of this chapter is organized as follows. Section 9.2 presents the literature review and conceptual framework for the analysis. Section 9.3 describes case overview and methodology and Section 9.4 presents three stylized taxonomies of innovation activities and challenges. Finally, Sections 9.5 and 9.6 present discussions and conclusions.

9.2 Capabilities: Technological and Non-Technological

9.2.1 Technological Capabilities

One important academic stream in understanding technological catch-up and industrial development comes from the capability approach. The technological capability refers to the ability to make effective use of technological knowledge (Lall 1992; Kim 1997). This approach is based on the resources in a broader sense: the technology accumulation process through learning and the accumulation of dynamic corporate (firm) capabilities. Many discussions on the latecomer firms deal with the process they employed to accumulate the knowledge needed to consume, use, apply, and modify existing technologies. These studies argued that latecomer firms must acquire three capabilities—production, investment, and innovation (Dahlman et al. 1987)—and that the technological capabilities to generate and manage technical change can be differentiated with respect to a level. This level can be basic, intermediate, or advanced, and holds either a primary or a support function (Lall 1992). Technological capabilities also consist of skills, knowledge, experience, and institutional structures and linkages (Bell and Pavitt 1993). Moreover, technological capabilities can be divided into two categories: production capability

[2] As pointed out by Bell (2009), Mothe and Nguyen-Thi(2010), Bell and Figueiredo (2012), additional attention should be focused on the learning mechanisms of non-technological(R&D) capabilities as well as on non-R&D innovation capabilities such as marketing and financial activities.

and innovation capabilities. The former is described as capability to carry on producing goods and services with given product technology, and to use and operate given forms of process technology in existing organizational configurations, while the latter is described as the capability to create new configurations of product and process technology and to implement changes and improvements to technologies already in use (Bell 2009).

As far as sequence goes most latecomer firms follow the stages of imitation to innovation (Kim 1997). More specifically, from assimilation, through adaptation, to generation (Kim 1980; Lee et al. 1988), from OEM, ODM, to OBM (Hobday 1995), from production to technological capability (Bell and Pavitt 1993), from internal to external combinative learning with functional capability (manufacturing, product development, efficiency improvement) (Mathews and Cho 1999), from "specilization and integration," and "integration and coordination", to strategic dynamic orchestration (Dutrenit 2004), from passive through reactive and strategic to creative (Hobday et al. 2002), from production to innovation capability (Bell 2009), and from basic, intermediate/incremental, and advanced, to world leading (Bell and Figueiredo 2012).

Moreover, the technological trajectories of developing and advanced countries exhibit different patterns. Utterback and Abernathy(1975) postulate that technological trajectories are made up of three stages of fluid, transition, and specific in advanced countries, while the development path of latecomer firms operates via a Reverse Product Life Cycle (hereafter RPLC, Kim 1980; 1997). The technological capabilities of such companies move from the mature (specific) to the fluid stage as they assimilate mature technologies from advanced firms and afterwards innovate with regard to their own products and technologies. In addition, the fast-follower strategy and leverage effects are also considered key factors in the technological catch-up process of latecomer firms (Mathews and Cho 2007; Mathews 2002; Wong and Mathews 2005) and recently, latecomers have been able to enter the PLC via large firms in design and R&D stages; or via networks of new, technology-based firms immediately after dominant design has been established; or via cooperation between public R&D organizations and firms in early stages of new PLCs (Choung et al. 2014). Having passed through various stages, latecomers were able to master the mass-produced products and market creation.

9.2.2 Non-Technological Capabilities

As mentioned above, past works have contributed in understanding catch-up in mass-produced products, learning mechanisms for production and organizational capabilities, and maintaining achieved industrial leadership. Indeed, to continue advancing our understanding of the problems faced by latecomers in producing capabilities for developing new knowledge, profound changes are imperative in both technological and organizational capabilities developed to imitate, absorb, and assimilate existing products and processes (Dutrenit 2004; Dantas and Bell 2009; Figueiredo 2010; Choung, Hwang, and Song 2014). Furthermore, it is difficult to create organizational capabilities in latecomer firms because of resource scarcity and lack of technological competencies. Therefore, it is important to establish whether the technological capabilities in the catch-up period (particularly on the process improvement in the scale-intensive sector) are still valid in the transitional period to innovation-intensive high-technology areas. Moreover, the accumulation of new technological capabilities has to be closely linked with the organizational change which defines the rules of the game among innovation actors. We are particularly interested in organizational capabilities (non-technological capabilities) in creating innovation as part of co-evolution between technology and organization. Its fundamental premise is that technology evolves in relation to product specialization and connects how the latecomer builds and manages organizational capabilities related to frontier products.

In recent years scholars point out that non-technological innovation may contribute significantly to a firm's performance (Damanpour 2014). Studies of innovations in organizations include generation and adoption of technological and non-technological innovations, and the understanding of innovation capabilities stems from the traditional wisdom suggesting that technological and organizational innovations are intertwined and co-evolve. Moreover, the non-technological intellectual structure has diverged into various aspects such as administrative, management, strategic, business, etc. (Černe et al. 2016) and implies there is no single coherent framework on non-technological innovation (see Table 9.1) Finally, recent reviews point out that research on the non-technological process of latecomers is relatively scarce and hardly sufficient attention is given to non-R&D components such as design, engineering, and organizational capabilities in and by industrial firms (Bell 2009; Bell and Figueiredo 2012).

The term "organization innovation" (see Alves et al. 2018 for the past and future of organizational innovation) refers to the studies of innovation in organizations, including both business and public organizations and examines what external and internal conditions influence innovation, how organizations manage the innovation process, and in what ways innovation changes organizational conduct and outcome (Damanpour 1991). The term "administrative innovation" refers to the creation of a new organization design which better supports the creation, production, and delivery of services or products (Daft 1978; Kimberly and Evanisko 1981, Damanpour and Evan 1984), but does not include innovations in, for instance, marketing or operations management (Birkinshaw et al. 2008). The conceptual differentiation of technological and non-technological innovation comes in part from the definition proposed in the third edition of the *Oslo Manual* (OECD 2005, 2018), which identifies the process and product innovation (goods or services) as "technological innovation" and marketing or organizational innovation as "non-technological innovations." Moreover, marketing innovation is defined as "the implementation of a new marketing method involving significant changes in product design or

Table 9.1 Definitions of different types of non-technological innovation along with their authors

Term	Meaning or definition	Representative authors
Administrative innovation	Technical (new products, processes or services) vs. administrative innovation (new policies of recruitment, allocation of resources, and the structuring of tasks, authority and rewards—organizational level, but content-wise related to administrative practices at lower level)	Evan (1966), Daft (1978), Kimberly and Evanisko (1981)
Organizational innovation	Individual characteristics, such as sex, age, and personal attitudes, administrative positions and roles, structural characteristics of the organization, such as size and complexity, environmental input from the community and other organizations. Later on: non-technical process and service innovations	Baldridge and Burnham (1975), Damanpour and Evan (1984), Damanpour (1991), Armbruster et al. (2008)
Management innovation	How companies organize, lead, allocate resources, plan, hire, motivate—a holistic view; what managers are and do; organizational structures (structural innovation), management techniques and marketing concepts/strategies—in line with CIS	Hamel (2006), Mol and Birkinshaw (2009)
Marketing innovation	Innovation in marketing—creating, communicating, delivering, and exchanging offerings that have value for customers, as opposed to product and process innovation	Simmonds and Smith (1968), Johne (1999)
Non-technological process innovation	Focused on how (a form of innovation, not a type)—process innovation = a set of activities to produce output	Papinniemi (1999), Krause, Gebert, and Kearney (2007), Lambertini and Mantovani (2009)
Ancillary innovation	Organization–environment boundary innovations or cross-organizational innovations	Damanpour (1987), Tether and Tajar (2008)
Open innovation	The use of purposive inflows and outflows of knowledge to accelerate internal innovation and expand the markets for external use of innovation (also technological innovation), respectively	Chesbrough (2007), Vanhaverbeke, Van de Vrande, and Chesbrough (2008)
Strategic innovation	Business process improvement; marketing, licensing, adoption/generation	Kodama (2004), Afuah (2010)
Business model innovation	Innovation in strategic choices, value network, creating value, and capturing value; innovation in the way a company does business, what is its source of competitive advantage, how it transcends traditional firm boundaries	Zott and Amit (2008), Teece (2010)
Green or eco-innovations	Innovations aimed at producing solutions with lower negative environmental impact than relevant alternatives; they may be technological or non-technological (organizational, institutional, or marketing-based)	Schiederig et al. (2012)

Continued

Table 9.1 *Continued*

Term	Meaning or definition	Representative authors
Non-technological innovation	Non-technical product and process innovation: organizational (implementation of innovative organizational concepts: structural vs. procedural; intra vs. inter- organizational; business processes or organizational structures) and marketing	OECD—Community Innovation Survey (OSLO Manual, 2005), Barañano (2003)

Source: Cerne et al. (2016).

packaging, product placement, product promotion or pricing," and organizational innovation as "the implementation of a new organizational method in business practices of the company, workplace organization or external relations." In this study, we endeavor to investigate non-technological innovation and its challenges which include marketing innovations (Baranado 2003; OECD 2005), organizational innovation, and administrative innovation (Damanpour 1987).

Although considerable research has been devoted to measuring technological innovation, rather less attention has been paid to measuring non-technological innovation. Some attempts have striven to measure the non-technological innovation: marketing innovation (Armbruster et al. 2008), link between technological and non-technological innovation (Mothe and Nguyen-Thi 2010; Geldes et al. 2017, Community Innovation Survey of OECD). However, accepted typology has yet to measure the non-technological innovation because it is considered more complicated than that of its attributes (Damanpour 2014).

Although the above studies have shown the importance of non-technological innovation in advanced countries, studies of non-technological innovation of latecomer firms need further investigation in terms of how they are built and what challenges exist. Indeed as latecomers move 1) from production to innovation capability building, 2) to upgrading the innovation system, 3) to developing more frontier products, we believe that these changes are so important that they lead us to think about developing new capabilities needed for innovation in very different ways. The presence of technological capabilities may not only correspond to the technology regime (Malerba and Orsenigo 1997; Breschi et al. 2000), but also to other capabilities required in various stages of product development (Choung et al. 2014). Such interpretation motivated us to emphasize understanding non-technological capabilities for developing the complex products in latecomer firms.

To continue to advance our understanding of the problems faced by latecomers in producing frontier products, referring to the reverse product life cycle (Kim 1997) framework can be a useful point of embarkation. In other words, in developing countries, the process takes place in the reverse direction (from a specific point to a transition to a fluid phase) (Kim 1997). The product life-cycle approach implies that strategies and identifying issues have been different with respect to the product development phases, such as the mature and early phases of technology. Similarly, products designed for stable and mature end-user markets require a process optimized for control and efficiency, while first-of-a-kind breakthrough products require a more emergent process that aims to discover whether there is any market to be served initially at the firm level (MacCormack et al. 2012). However, with regard to the product-cycle-based approach for complex products, challenges are still unclear, and certain modifications are necessary to address this issue. Therefore, we combine the elements of PLC and structural dimensions. This study considers the structural dimensions of actors and their relationships. The relationships among innovative actors are salient factors in the dynamics of innovation systems, and they play important roles in producing knowledge.

9.2.3 Exploratory Framework

The developing non-technological capabilities (organizational and marketing, OECD (2005)) in particular organizational capabilities such as administration and management, and marketing capabilities such as marketing, sales, and after-sales support, OECD (2018) of firms lead to a change in the intra-firm and inter-firm activities. Given that we are particularly interested in identifying the key issues of phase per se of the product life cycle, this study proposes an expansion of PLC theory by positing the structural elements of the inter-firm, intra-firm, and public research institutes.

Intra-firm innovation activities for non-technological capabilities: In the innovation systems approach, as mentioned above, actors play important roles in economic and innovation processes. Moreover, one actor among all actors in the categories of producers, users, intermediaries, and universities plays the most important role in a particular firm. By integrating the functions within the organization, in this case design, production, and marketing, a firm creates new knowledge and secures new market opportunities. Therefore, analyzing the competence-building (learning) process, referring to various costly and deliberate processes by which additional technical skills and knowledge are acquired by individuals and by the organization (Bell 1984; Bell and Figueiredo 2012), is critical but should not be limited to the technological side only. In addition, after mastering the technological capabilities, it is necessary to build marketing capabilities to guarantee successful access to export markets and to build organizational capabilities via new structural innovation and procedural innovation (for example, see Teece et al. 1997). From our perspective, non-technological (marketing and organizational) capabilities differ such that different challenges can emerge during innovation activities.

Inter-firm innovation activities for non-technological capabilities: In the system of innovation approach, connections and interactions among actors during the production of new knowledge are crucial. Moreover, interactions among different actors may be market and non-market related, and actors may be from other firms, universities, regulatory agencies, and/or public research institutes during the processes of product development and market creation. As Mazzoleni and Nelson (2007) and Bell and Figueiredo (2012) have argued the role that universities and public research institutes and interaction will play is important. Positive interactions, regardless of whether they occur with a firm, may secure various elements of technologies through relationships with other actors, making a significant difference in the area of technological competitiveness. Despite the fact that the degree of interaction may differentiate firms' competence-building activities, strong interaction may exacerbate product development and market diffusion. That is to say, the formation of strong interactions within the network exhibits a reluctance to change/exit and become locked into their relationships (Woolthuis et al. 2005; Negro et al. 2012). From this standpoint, interaction among actors is critical for product and market development but is often a source of failure and challenging issues with regard to CoPS development (Hobday and Rush 1999).

Stage of the product cycle: Substantial literature has been investigated in the mass-produced products for advanced countries (Utterback and Abernathy 1975; Abernathy and Utterback 1978) and in latecomer countries (Kim 1997; Choung 2014), while less attention has been paid to latecomer countries due to high entry barriers (Davies 1997, Hobday 1998). This chapter elaborates the key challenges and characteristics of innovation process from a PLC. In doing so it proposes a framework for analyzing the phase of innovation in the evolution of complex products as well as the key challenges.

According to Davies (1997), there are three types of innovation (architectural, components, systemic) for complex products within PLC and birth and early development of a CoPS is powerfully influenced by regulators, system suppliers, standard-making bodies, and large users. Similarly if latecomer firms enter the industry in the fluid phase and produce global-level products based on their original technology, it can be conjectured that countries would follow similar process. Entering the fluid phase of the economy is challenging for latecomer firms due to market and technological uncertainties. To deal with this concern, latecomer firms actively participate in international standardization processes or provide pioneering global commercialization services or products to demonstrate their technological capabilities and subsequently win the market (Choung et al. 2011). In particular, during the diffusion process of fluid-stage technology, the achievement of system stability through extensive tests has become a major issue, similar to that in advanced countries. In addition, innovative actors in the fluid stage must create new game rules for standardization and operation in the global environment. In this regard, a policy regime effective during periods of imitative learning may turn out to be rigid during the standardization, technology development, and commercialization processes of fluid-stage technology in latecomer countries. Hence, new policies will be required to overcome these obstacles.

The second evolutionary path begins with the firm's entry immediately after the establishment of a dominant design. It is typically followed by the production of various applications through architectural innovations. Architectural innovations are achieved by the application of new combinations of the installed components or a new interface among the components within the systems (Henderson and Clark 1990). Hence, proliferation can be guaranteed when various specialized companies exist. In addition, proliferation can be attained by the system vendors and suppliers of the components, materials, and equipment through collaborative learning between the user and supplier firms. Establishing relationships between local and global system vendors is therefore an important goal for latecomers. Institutions, both public and private, must provide support for technology-intensive firms and the underlying venture ecosystem while also stimulating the inter-firm learning network.

One evolutionary path is initiated during the mature technology stage, from which point a firm moves on to develop frontier products in the reverse direction from the original PLC mainly through a technology-deepening process. This path is nearly identical to that suggested by the RPLC. Technology deepening is the most frequently mentioned evolutionary pattern of latecomer firms, in which technological capabilities incrementally accumulate in traditional manufacturing. However, for complex products, to achieve deepening of the innovation processes, the learning effect is critical in the manufacturing or construction of complex products. Furthermore, as latecomer firms compete with leading companies in the manufacturing of frontier products, the integration of design and manufacturing and access to the manufacturability of improved product designs are important sources of innovation. Public-sector institutions that support the coordination of collective learning (to reduce imitative learning) and technology diffusion become relevant.

Finally, this chapter's unit of analysis is to delineate the causal mechanism that explains latecomer challenges via interactions among the many actors involved. Moreover, it attempts to broaden the scope of firm strategies aimed at the dynamics of actor interactions at the firm level. There are good reasons to focus on organizational-level performance, as firms operate within the environment of their national economy and, in a similar vein, this chapter can draw management implications for the actors that are involved (see Table 9.2). Moreover, as Hobday (1998) mentions, CoPS market characteristics are institutionalized, politicized, regulated, and bureaucratically administered, not contested or only partially contested. It implies that CoPS market transaction and deals are sometimes confined to political proposition rather than rational business and technological proposition. However

Table 9.2 Research framework

Non- technological innovation activities		**Product Life-Cycle Phase**		
		Fluid Phase	**Transitional Phase**	**Specific Phase**
	Firm's activities Inter-firm relationships	Challenging factors(a)	Challenging factors (b)	Challenging factors (c)

Modified from Choung et al. (2014).

this chapter puts more emphasis on the process issue of CoPS development and diffusion than how suppliers and users are responding to the risk, regulation, and management of the transformation and innovation, putting aside the political influence on business deals.

9.3 Case Overview and Methodology

These cases have the traits of complex product systems and frontier capital goods. Moreover, these products individually have varying characteristics in terms of technology innovations. The APR1400 design was developed and exported based on improvements by an advanced economy's technology, while SMART nuclear reactors are product systems that Korea indigenously developed for the first time and attempted to commercialize. The KTX train system was constructed with technology imported from France and was launched in 2004. Korea was recognized as the world's fifth country to provide a high-speed rail service (KISTEP 2015).

9.3.1 Nuclear Reactor (SMART, System Integrated Modular Advanced Reactor)

First, the SMART project was conducted between 1997 and 2002 as a national R&D project to develop small- and medium-sized nuclear reactors by the Korea Atomic Energy Research Institute (hereafter KAERI). Once the basic design was developed, the next phase (2002–6) involved acquiring approvals and certifications to build reactors of this smaller scale (SMART-P models). In 2005, the Science and Technology Policy Institute (STEPI) conducted a feasibility study on the SMART market and found that Korea could create an overseas market by exporting small-scale nuclear reactors (STEPI 2005). This was partly due to small-scale reactors being considered more cost effective to construct as opposed to large-scale commercial reactors. In response to these changes and to create a window of opportunity in the global nuclear industry, the Ministry of Science and Technology (hereafter MOST)[3] announced the initiation of the SMART-P verification project. However, the SMART project, which has been underway for fifteen years, has experienced unexpected difficulties in constructing the SMART-P pilot plant as well as formulating export strategies.

[3] Over the past 15 years, the names of the ministries have changed under different administrations, as follows: 1) with the mission to coordinate the nation's industries: the Ministry of Trade, Industry and Energy (MOTIE, 2013~present); the Ministry of Knowledge Economy (MKE, 2008~13); and the Ministry of Commerce, Industry and Energy (MOCIE, 1998–2008); 2) with the mission to coordinate the nation's science and technology: the Ministry of Science and ICT (MSIT, 2017-present); the Ministry of Science, ICT and Future Planning (MSIP, 2013–17); the Ministry of Education, Science and Technology (MEST, 2008–13); and the Ministry of Science and Technology (MOST, 1998–2008).

9.3.2 Nuclear Power Plant (NPP) Construction (APR1400)

By internalizing and optimizing global nuclear power plant (hereafter NPP) technologies from leading countries through its national G-7 project in the 1990–2000s, Korea finally developed its indigenous NPP design, the APR1400. With the APR1400 design, Korea has achieved a 30 percent cost reduction and a 40 percent capacity scale-up from 1000 to 1400 MW, as well as a 40 percent reduction of the total construction period from ninety to fifty-four months. In 2009, a consortium led by the Korea Electric Power Corporation (hereafter KEPCO) won a contract of $20 billion to design and construct four APR-1400s at the Barakah site in the UAE, with the first reactor scheduled to start supplying electricity in 2017. However, after the winning the contract in the UAE, Korea failed to win further nuclear power plant orders in the US, China, India, Finland, Vietnam, Lithuania, Romania, Bangladesh, Jordan, Turkey, and Bulgaria as main contractors (Kyunghyang 2015).

9.3.3 High-Speed Train (KTX: *Korea Train eXpress*)

When the saturation of railroad capacity[4] was projected in the 1970s, several proposals were made to address this issue, including expressway expansion/construction and railroad route additions. Among these alternatives, the construction of an express train system[5] was concluded as the most efficient proposal, with the government focusing on the Korean Express Train System Project commencing in the 1980s. In May of 1989, the government decided to build the Korea-Busan Express Train System. With the entire route finalized in June of 1990, the ground-breaking ceremony for the system was held at the planned site of the Cheonan-Asan Station in June of 1992. The project was eventually completed in 2004, significantly exceeding the original schedule of six years in 1996. Further, the cost incurred was 20 trillion Korean won, which was nearly four times the initial budget.

9.3.4 Research Methods

This study is an exploratory study to understand challenging key issues arising during the development of complex product systems in latecomer countries. In

[4] The reasons cited for project initiation were serious traffic congestion along the Seoul-Busan axis as the center of transportation and logistics, weakening industrial competitiveness due to mounting logistical costs, and the urgent need for new transportation facilities along the Seoul-Busan axis. The expected effects of the project were revolutionary improvements in transportation capabilities, enhanced industrial competitiveness through the transfer of cutting-edge technologies, energy savings and environmental conservation, and balanced regional development (KHSRCA 1992).

[5] An express train system is defined as a railway system designated by the Minister of Transportation, where trains run across key sections at speeds exceeding 200 kilometers per hour. In addition, the system is divided into the wheel-on-rail and magnetic levitation types (KHSRCA 1992).

order to explore the problems encountered in this area, this chapter uses qualitative research methods in the form of case studies. Based on the advantages of case studies (Eisenhardt 1989: Yin 2003), the study focused on three complex product development projects as well as market creation, and conducted an in-depth examination of the various actors involved (such as developers, regulators, and policymakers). This chapter derives from an empirical study based on four years of (2014–17) fieldwork and a series of in-depth interviews for the case studies were conducted at the firms involved (KEPCO, KHN, KORAIL, KR (Korea Rail Network Authorities), Rotem) or at the public research institutes and universities (KINS, KAERI, KAIST, KRRI) that are mainly responsible for each of the products referred to above. A structured questionnaire was used for the in-depth interviews with regulators, product development managers, regulation managers, CTOs, and directors of each participating organization (interviews with 25 participants). In particular, they were asked to address the following issues: (1) regulator issues: the development of regulatory policies, the process of regulation framework development, the development of regulation guides, interaction between the regulator and developer, and the process of operational and standard design approval, (2) product developer issues: the process of product development, the process of construction, and the process of overseas market creation. In addition, interviewees were asked to supply supporting documents where possible, and the interviewer used White Papers, product review reports, and minutes published by governmental and individual institutions.

9.4 Case Studies

9.4.1 Fluid Phase: SMART-P

9.4.1.1 KAERI's Regulatory Response for SMART-P

To verify the technology of SMART reactors, the government has approved what has been termed the SMART Pilot Plant (SMART-P: Heat output 65MWt) program, which is reduced from the original size by one fifth. As the first of these activities, KAERI conducted a preliminary study of the operation of the Integrated Reactor Technology Development Research Group (hereafter IRTDRG), including an evaluation of the SMART 330MWt design and the utilization of the SMART-P basic design (KAERI 2002).

Subsequently, IRTDRG aims to design and build an integrated reactor (SMART-P) by 2008. In doing so, in the first phase of development the group has undertaken the tasks of 1) reactor system design, 2) nuclear fuel technology development, 3) reactor design, desalination plant construction and plant design, 4) integrated reactor control technology development, and 5) regulatory development (KISTEP 2002).

Given that SMART-P is an integral-type reactor which employs passive safety systems, it is expected that existing regulatory requirements may not be met (Interview 2014). In addition, because the scale of the model is reduced, KAERI made a determined effort to conduct a preliminary safety review of SMART-P. The purpose of these activities is to define the requirements for licensing and licensing standards for SMART-P, to prepare a preliminary safety analysis report, and to enable the provision of a formal SMART-P license. A preliminary safety review commissioned by KAERI to KINS noted that during the SMART-P study (KINS 2005), demonstrating the suitability and safety of the design through an empirical test may be necessary. Accordingly, it is necessary for KAERI to provide the content of the planned test and the method by which to conduct it (e.g., lab test, shop test, and an on-site test).

In the second phase, in June of 2005, KAERI filed a SMART-P application with the Ministry of Science and Technology for a construction/operation permit, during which time the examination process and technical problems were emphasized. There were seventeen issues, including an inadequate design for in-service inspections, insufficient verification data, insufficient verifications of performance standards, insufficient analyses of accident codes and nuclear design codes, and a lack of a control system by the evaluation committee (Jo 2012).

In December of 2005, there was a request call for a hosting organization for a SMART-P verification demonstration to outline the contents of the standard design and to undertake the development and production of nuclear fuel and equipment, as well as construction and demonstration activities related to research (MOST 2005). However, when the hosting organization could not be selected during the three-month announcement period, the government decided to terminate the commercialization project of SMART-P (Interview 2014). Thus, SMART-P commercialization efforts proved to be a failure.

9.4.1.2 Inter-Firm Relationships: Regulatory Agency

It can be challenging to separate product developer and regulatory development agencies during the fluid phase of product development. The regulatory body has also recognized the necessity of developing a regulatory framework, as it proposes new concepts for both the design and the fuel. The importance of regulation is equally evident in regulatory agencies, and KINS pointed out safety issues related to the SMART model before IRTDRG was established (Interview 2016). Subsequently, KINS stipulated the following items to be developed as the licensing criteria for SMART: (1) proving the safety of designs or materials which differ from those of existing reactors, (2) coping with beyond-design-basis accidents, (3) rulemaking with regard to the safety of the reactor safeguard vessel, (4) ensuring the integrity of steam generator tubes, and (5) classifying equipment based on their degree of safety significance (Kim et al. 2001).

Since 2002, IRTDRG has worked to analyze the KINS perspective on the previous model of SMART and has carried out regulation-related research. Specifically, with reference to institutional aspects, the following major issues have been addressed: 1) the issue of laws and regulations which pertain to nuclear reactors, 2) a guideline for the licensing and permit system, and 3) the use of new fuels (KINS 2004a). In other words, the Korean Nuclear Energy Act provides safeguards and licensing procedures for power generation reactors, research reactors and educational reactors, but there are no regulations for small-output nuclear reactors such as the SMART-P type (Interview 2017). Therefore, a new classification as research reactors should be formulated through regulatory research, with requirements identical to those of document submission and identical technical standards identical as well with regard to the reactors used for power generation. Moreover, permission is needed for the separation into the two stages of the construction and operation from the Nuclear Safety and Security Commission (KINS 2004b). In addition, SMART-P is designed to use metal fuel, and technical standards for the metal fuel used in SMART-P have not been developed. It has remained difficult to design related equipment as well. Another issue is that the LB-LOCA (large-break loss-of-coolant accident) performance evaluation, which is applied to the standard setting of existing nuclear fuel, cannot be applied to SMART-P because the permissible standard for the fuel used in PWRs (pressurized water reactor) is not ideal for use as in the design concept of SMART-P (KINS 2003). KINS also commissioned a study to draft new regulatory policies for SMART-P in 2004. Some of the recommendations include: 1) providing more timely and effective regulations for new reactors, 2) providing timely regulatory requirements for new reactors, and 3) providing timely and independent evaluations of the safety characteristics of new reactor designs. It was also recommended that operators should maintain contact with regulatory agencies from the early stages of the design to provide preliminary safety assessments and design information (KINS 2004b). Thus, before the filing of the construction/operation permit application for SMART-P to KAERI, legal and procedural issues recognized by regulatory agencies must be resolved. As noted above, as new innovative technologies and products emerge, regulators in turn must put more pressure on the provision of new regulatory guidelines.

Given the rudimentary empirical analysis of the regulatory development process, it appears that both developers and regulatory agencies have made an effort to set up a regulatory framework as well as to conduct preliminary exercises to acquire a construction and operation license. Nevertheless, many readers can point out gaps in the capabilities of developers. However, emphasized here is that problems can arise from the existing regulatory regime and organizational arrangement, exacerbating the failure of SMART-P commercialization efforts. First, updated reactor verifications can be achieved with the proper timing with reference to regulatory guidelines and policies. Empirical evidence has suggested that most guidelines, such as regulatory standards for metal fuel usage and guidelines for verification methods for safety measures are associated with a time lag. Therefore, KAERI SMART-P developers were required to design reactors with uncertain regulatory standards, thus inserting risk during the review process. Second, problems which arise from established routines and organizational arrangements must be understood. In general, KINS is not an independent regulatory agency but is subordinate to the NSSC, which is responsible for carrying out duties commissioned by the Commission which is supervised by the Commission.[6] Therefore, the structure of KINS is such that only the responsibility of a regulatory body is assigned, but without much responsibility (Interview 2016). Regulatory agencies around the world have what are termed technical support organizations (TSOs)[7] which, as the name implies, provide technical support (NRC 2007). Korea has both a regulatory support function and a technical support function. Third, commercialization failures can also be observed in situations where existing industry and business structures are focused generally on large reactors. KEPCO is responsible for most nuclear business in Korea, and the organization relies on a business market largely driven by large-scale nuclear reactor demand; thus, they are less interested in innovative and small- and medium-size reactors, especially considering that large-scale reactors are sensitive to economic outcomes. Korea's nuclear business ecosystem is composed of a significant number of nuclear reactors which operate at 1000 MW or higher. In other words, the transition to a small- and medium-sized reactor business ecosystem in Korea has been neither automatic nor easy given the operational and economic efficiency of the existing nuclear reactors. Finally, in general, upon demands from nuclear power plant operators, the regulator must set the appropriate regulatory standards early. In such cases, design directions are easily established by designers because the direction and criteria are clear. However, legislation pertaining to the construction and operation of SMART-P reactors is directly related to the number of reactors in question. If the number is small, regulatory demand is not needed, and it can be considered that both time and effort would have no value. Thus, a mismatch can arise between the regulatory setup and the level of developer demand. For this reason, an important part of the process of the world's first instance of reactor commercialization depends on the provision of various types of regulatory guidelines in a timely manner within a new policy framework and with organizational reform.

9.4.2 Transition Phase: APR 1400

9.4.2.1 Process for Project Financing by KEPCO

In 2008, the UAE requested bids for the turnkey construction of nuclear power plants in the 4000-5000 MW range, and in March of 2009, Korea, France (Areva),

[6] According to the organizational identity of KINS, it is a regulatory expert organization which supports the Nuclear Safety and Security Commission (NSSC), which is a consolidated regulatory authority governing all matters related to safety, security and safeguards for nuclear facilities, materials and activities, including nuclear safety regulations, environmental radiation monitoring, emergency preparedness and response, and education and training at INSS (International Nuclear Safety School), www.kins.re.kr/, accessed 21 January 2021.

[7] Technical and scientific support organizations (TSOs) consist of experts who deliver technical and scientific services to national nuclear regulatory authorities and to the nuclear industry and who may advise governments and assist them in achieving the highest possible levels of safety and security in the nuclear, waste management, radiation protection areas (www.iaea.org). For example The NRC continues to take advantage of the wide range of expertise and capabilities in national laboratories such as the Argonne, Brookhaven, Idaho, Los Alamos, Livermore, Oak Ridge, Pacific Northwest, and Sandia National Laboratories (NRC 2007).

Table 9.3 Nuclear construction cost comparison

	EPC Cost ($/KW)	Source
APR1400 (KEPCO)	2,300	MKE
EPR (Areva)	3,500	EDF
ABWR (GE-Hitachi)	3,000	Platts
AP1000 (WEC)	3,000–3,500	Platts
VVER (ASE)	3,050	WNA

Source: MKE (2009).

and Japan submitted proposals. In May of 2009, South Korea, France, and Japan passed the pre-qualification assessment, and the three countries submitted further tenders. In December of 2009, Korea (KEPCO consortium[8]) won the bid to build nuclear power plants in the UAE (see Table 9.3). The cost was to be US$18.6 billion and financing was pursued according to typical project financing methods (MKE 2009).

KEPCO's project financing package contained investment, direct loan, and external debt guarantees for the special purpose of the vehicle as well as preferred loans for domestic suppliers (a consortium of financial institutions). The plan was to raise money to repay lenders from the revenue generated by the UAE nuclear project itself. More specifically, both the UAE side of the UAE Nuclear Power Corporation (ENEC) along with the KEPCO consortium of Korea would participate in an SPV (special-purpose vehicle), a special-purpose company established specifically for these types of projects. The SPV would finance the construction of the nuclear power plants using an equity method and a loan scheme (see Figure 9.1). To this end, the Export-Import Bank of Korea would participate in equity investments on behalf of the KEPCO-consortium-owned SPV, would be involved in procuring external funding loans for the SPV, and would lead the way to major domestic and overseas financial institutional investors. Initially, the original plan was to procure funding of US$10 billion from the Export-Import Bank of Korea (Kexim), US$2 billion from the Export-Import Bank of the US (US Exim), US$6 billion in funding from the government of Abu Dhabi, and US$2 billion from other commercial banks. Moreover, as part of the deal, in 2010 the Korean government submitted an investment Letter Of Intent (LOI) to the UAE, stating that the Export-Import Bank would support financing of $10 billion, equivalent to 50 percent of the total business outlay (KEXIM 2013).

In general, export credit agencies (ECAs) often help fund the export of reactors, with government schemes such as loan guarantees. However during the project financing process, several issues emerged. First, the $10 billion scale of the loan to

[8] The consortium was led by KEPCO and composed of KEPCO (Korea Electric Power Corporation), KOPEC (architecture engineering), KPS (maintenance), KNF (nuclear fuel), Doosan Heavy Industries & Construction, Hyundai Engineering and Construction, Samsung C & T, and Westinghouse, and Toshiba.

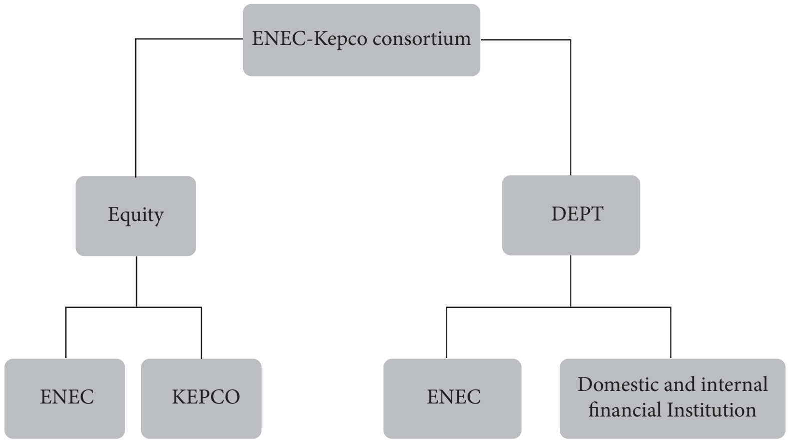

Figure 9.1 Financing structure of UAE nuclear power plant construction

UAE by the Export-Import Bank was not only the largest ever for a single direct loan out of all loans overseas in the last ten years, but it was also not possible to institutionalize it in the beginning (Interview 2014). According to the Export-Import Bank Act and Decree, it must limit the self-capital credit line for the same entity to 40 percent. If the Export-Import Bank loan of $10 billion to the UAE implied that it supported more than 2.5 times the capital stock of the Export-Import Bank, the loan would be denied (Interview, 2015). As a means of solving this problem, there was a movement to abolish the credit limit by the government, but this was opposed by the National Assembly, though later they provided an exemption in the form of a special credit limit, allowing the provision of loans without the previous credit facility limit of $10 billion by the Export-Import Bank (MOSF 2010).

Second, because the construction of nuclear power plants is complex and highly capital-intensive and with high upfront capital costs, which are difficult to finance, KEPCO requires careful structuring and comprehensive finance planning. Above all, risk allocation, finding the right equity partner, and stake holder management were challenges related to financing the NPP in the UAE (KIM, 2016). Indeed, every project stakeholder plays an important role in the accomplishment of the project, but complex product systems with high value, important technology, and engineering-intensive capital goods are more relevant with regard to stakeholder relationships. Soon after the winning the deal, KEPCO started on the project financing package, but there was a delay in financing the project that continued for seven years. Over the course of project financing, it was decided that KEXIM would provide US$3.1 billion rather than US$10 billion, with the rest coming from the Abu Dhabi government (KEXIM 2016). Moreover, KEPCO has amended the range of the target return rate, and the arbitrage settlement details (see Table 9.4).

The successful negotiation of project financing issues is critical to current and future NPP exports by KEPCO and to its credibility as an internationally recognized entity with a strong track record in construction. However, during the years of negotiation

Table 9.4 Roadmap and negotiation items

2011	KEPCO presumes an IRR (internal rate of return) of 16%
2012	UAE defers contract approval (DCA)
2013	UAE requests reducing the KEXIM credit loan
2014	UAE 1) added a clause on compensation for deferment during the construction process, 2) DCA
2015	UAE requests the lowering of the IRR to 10%
2016	KEPCO board of directors holding company approval and signing of the final contract

Source: Authors' compilation based on National Assembly data (2017).

with the UAE, items were changed dramatically with regard to detailed stakeholder relationships pertaining to the building of the nuclear power plant. Perhaps the most significant testimony of this during the negotiations was the creation of additional clauses. The KEPCO board of directors in 2012 had reached a consensus to go through arbitration involving a third party in London. The article on KEPCO's sovereign immunity was also removed in the 2016 deal, in contrast to the 2012 agreement by the KEPCO board, while also claiming that the target rate of return from the investment was lowered from the initial 16.0 percent to 10.5 percent (National Assembly 2017).

9.4.2.2 Inter-Firm Relationships: Horizontal Interaction

During the catch-up period, the nuclear power plant construction ecosystem was formed on a continuous and repetitive large scale, aiming at cost efficiency. For example, eight nuclear plants in the 1980s, seven nuclear plants in the 1990s, eight nuclear plants in the 2000s and nine nuclear plants during the current decade were completed and entered into commercial operation (KHNP 2017).

Moreover, the construction and operation processes of nuclear power plants were managed by KEPCO, which is a public company. More specifically, KEPCO owned six nuclear and thermal generation companies in the following sectors: power generation (Korea Hydro & Nuclear Power; KHNP), design (ENC), maintenance (KPS), and nuclear fuel supply (NEF). KHNP, which was set up in 1978, operates a nuclear power plant as a base-load power plant and a hydro power plant as a peak-load power plant. It supplies approximately 32.1 percent of the nation's electric power and is the world's fifth largest nuclear power generation company. KEPCO E&C was founded with the objective of securing independent technologies to design and build nuclear and thermal power plants. KEPCO NEF is Korea's only nuclear fuel design and production company, and it focuses on localizing nuclear fuel and gaining technological independence. KEPCO NEF produces and supplies nuclear fuel for light- and heavy-water reactors. It supplies nuclear fuel to the UAE's nuclear power plant and exports related equipment. KEPCO KPS is a plant service provider that undertakes the maintenance of power facilities (nuclear, thermal, and hydro), power transmission/transformation facilities, and industrial facilities (KEPCO 2017).

In addition, large *chaebol* construction companies, such as Samsung, LG, and Hyundai, participate in the construction stage. Doosan Heavy Industries &

Construction supplies existing reactors and the APR1400 reactor model, a third-generation and the Korean standard nuclear power model. Thus, Korea's nuclear power generation industry is led by the KHNP (Korea Hydro and Nuclear Power Company), managing most of the functions of construction, fuel, generation, and maintenance, in close interaction with companies in collaboration with KEPCO. This horizontally segmented business structure is effective in the domestic market, as companies related to fuel procurement, construction, and maintenance are able to achieve effective cooperation (Interview 2016). However, governance in this structure leads to ineffective decision-making, as it is segmented in terms of design, manufacturing, and maintenance functions. With regard to exporting nuclear plants, it is difficult to gain a competitive edge, as the structure of Korea's nuclear industry has de-segregated functions for production, maintenance, and repair compared to competitors that incorporate integrated features with greater efficiency (Interview 2017). For example, cooperation among companies in the construction, design, and fuel sectors is essential during the project-bidding process, but individual companies must pursue their own profits and thus cannot offer lower prices. Therefore, in order to export domestic nuclear plants to overseas markets, it is essential to improve or change the industry structure to be amenable to overseas market development. With regard to the vendor structures of developed countries, with the exception of Westinghouse, most are integrated within a single company, including the overall design, system design, equipment, BOP (balance of plant), fuel, and maintenance process. As indicated in Table 9.5, Korea is divided into a vertical structure with ENC for design; Doosan Heavy Industries & Construction for design, reactor manufacture, and BOP; NEF for fuel; and KPS for maintenance. Additionally, it functions at a lower level, as it is generally only responsible for the specifications required by KHNP, who is in charge of the EPC (engineering and procurement) function. Such a structure is considered very effective for the domestic market but is unable to flexibly respond to the demands of foreign markets.

9.4.3 Specific Phase: KTX

9.4.3.1 KHSRCA's KTX Construction Process

In 1983, the Ministry of Transport entered into a contract with the joint venture of Louis Berger International Inc., Kampsax International, Hyundai Engineering, and KRIHS (Korea Research Institute for Human Settlements) to conduct a feasibility study focusing on a high-speed railway (MT 1983). They concluded that the route (Seoul-Busan) was economically feasible and proposed system engineering design criteria. Subsequently, between 1989 and 91, the Korea High-Speed Rail Construction Authorities (KHSRCA)[9] signed a contract with KOTI (Korea Transport Institute) to conduct a preliminary engineering study of the Seoul and

[9] In 2003 KHSRCA merged with Korea Rail Network Authority (KRNA).

Table 9.5 Comparison of foreign vendor functions and Korea

	Total design	sys. Design	equipt. design	equipment	BOP Balance of Plant	Fuel	Maintenance
Westinghouse (USA)		√	√	√		√	√
AREVA NP (FRANCE)	√	√	√	√	√	√	√
GE/Toshiba Hitachi	√	√	√	√	√	√	√
Korea	ENC	ENC	Doosan	Doosan	Doosan	NEF	KPS

Source: KEEI(2009).

Busan high-speed railway (KHSRCA 1991). Such activities included a traffic-demand study and a cost-benefit analysis, the preparation of the RFP (request for proposal), and basic planning and design. The engineering team commenced alignment design studies based on economic system engineering and the system comprised technological aspects (performance evaluation, determination of the need for facilities, an estimation of the project cost, maintenance details, and the demand for transport), and the basic design (route, structure, track, station, signal/communication, power supply, rolling stock, and railway management). In terms of RFP for rolling stock selection, the engineering team provided the two options of a core system or a total system and recommended the total system. The total system includes rolling stock, civil engineering, electronics, and control components, while the partial technologies were the rolling stock and the ATC (automatic train control) system. Moreover, the preliminary engineering report suggested that for a high-speed railway system consisting of the roadbed and rolling stock, the total system method designs and provides both components together, whereas the core system designs them separately. The core system has a simpler procedure as separate orders are possible, but problems can arise due to a lack of interconnectivity. On the other hand, the total system allows for an interface between the roadbed and rolling stock, as the rolling stock manufacturer participates in roadbed, communication, and track issues.

According to a public hearing related to the high-speed train construction investigation in 1997 organized by the National Assembly (National Assembly 1997), it was reported that two issues emerged in the preliminary engineering study. There had been some conflict on the issue of engineering design philosophy between systems engineering, which aims to maximize profit by integrating sub-systems, and straight-line tracks. The subcontractors sought an economical design for route allocation, whereas KHSRCA preferred to construct a straight line even if it involved viaducts and tunnels (MacDonald 1997). In addition, because KHSRCA has adopted core system, interface problems could be expected among sub-technology systems and coordination problems were likely to arise between the rolling stock and line aspects (Cha 1997).[10]

In the early phase of construction, KHSRCA selected the core system, stating that Korea was capable of designing the roadbed and civil engineering works even if the rolling stock was procured from overseas manufacturers.[11] More specifically, domestic technology would be used for civil engineering, tracks, and construction, and

[10] It is important to bear in mind that a series of issues such as a commercial planning strategy, fast learning, and a lack of understanding of high-speed train systems abounded from the beginning (Interview 2014).

[11] When establishing construction plans for the Gyeongbu High-speed Railway, KHSRCA (1992) stated that Korea had extensive experience in civil engineering, construction, and railroads, including large-scale construction projects in Saudi Arabia and other countries, construction of a waterway in Libya, and the building of the Gyeongbu Expressway. KHSRCA was confident that domestic technology would be capable of handling the project, and it established construction standards after consulting with the Korean Society of Civil Engineers and other experts (KPMG 2003).

overseas technology for the rolling stock, train control system, electric car line, and train radio system, with the eventual goal of localization.

After the core system approach was undertaken, individual components were developed separately and modifications were made in modules; thus, the project required integration from a systems perspective (Interview 2014). The task of selecting the vehicle type began by sending RFPs to the three countries of Japan, France, and Germany, in 1991, and on 14 June 1994, about two months after the announcement of the negotiation results, the contract for the introduction of vehicles and the core system was concluded (MLTM 2012). Despite the delay in ordering the rolling stock, a blueprint was delivered in 1991, and construction of the pilot line commenced in 1992. Two years later, the decision on rolling stock led to changes in the design. There were fundamental differences between the high-speed railways being constructed and the existing ones. Tracks of the existing railways were constructed by workers, but high-speed railway tracks were produced by machines. To ensure comfort and to minimize noise/vibration during the movements of the rolling stock, the materials used for track construction must be able to withstand shock and vibration, thus requiring high levels of precision and uniformity (KR 2005). More specifically, general railways usually involve separate orders, though turn-key is also an option. Turn-key orders are placed for high-speed railways by grouping rolling stock, maintenance facilities, railways, and signals. This is done because rolling stock operations are linked to the above-named facilities, and a liability can be imposed if problems occur.[12]

The pilot route construction began even before the rolling stock was finalized and while only 8 percent of all sites were obtained. For this reason, design changes became inevitable once the rolling stock was chosen. The track to run the railroad rolling stock and the roadbed supporting it were installed on the same ground (i.e., a vertical foundation) to convey the rolling stock loads; they are closely correlated as changes in the track structure cause the roadbed to be altered altogether. Considering the high correlation and difficulties in dividing accountabilities, it is widely recognized that the two should be constructed under an integrated contract. When these general practices are not fulfilled, design changes occur frequently to ensure better alignment. In the case of the Seoul-Busan Express Train System, roadbed and track construction were commissioned separately without examining the correlation and/or responsibilities for potential defects.[13]

[12] Construction conditions to be added (e.g., roadbed, railroad ties, and railways) compared to rolling stock in general are as follows: (a) technology to construct a reinforced roadbed and low-vibration, low-noise, and high-smoothness rails; (b) technology to produce and construct continuous welded rails and high-strength concretes; (c) installation of cant facilities (i.e., difference in the railway height on curves) suiting the railcar speed; (d) technology to design adequate transition curves considering the railcar length and speed; (e) tunnel design technology to reduce micro-pressure waves (i.e., pressure generated by pressure change) in tunnels; (f) technology to design low-noise and low-vibration bridges; (g) technology to install high-strength concrete long-span bridges; and (h) technology to build soundproof and seismic facilities for residents near railways (Interview 2014).

[13] According to cost-management guidelines by the MOST, roadbeds and tracks, in principle, should be designed in an integrated manner (MOST 2006). This implies that the Gyeongbu High-Speed Railway construction process was conducted in a non-integrative manner.

The adoption of the core system led to limitations in the interface (i.e., interrelation) and delays during the environmental impact assessment by the client. KHSRCA embarked on railroad construction when the train type was yet to be finalized. Dividing the Seoul-Busan route into seven sections, it requested five large companies to undertake an environmental impact assessment. During this process, the French TGV method (300 kilometers/hour) was applied to three sections, and the Japanese Shinkansen method (160 kilometers/hour) to the remaining four. Consequently, noise and soundproofing forecasts differed depending on the section (BAI 1996).[14]

One of the reasons for the various design changes may have been that external factors led to the reversal of decisions during the integration process to realize a systematic approach. It was believed that poor basic design as part of the construction philosophy[15] (i.e., the route, structure, track, platform, signal/communication, power supply, rolling stock, and railroad operation), the selection of rolling stock as the core system, and the disintegration of the roadbed led to coordination in numerous areas. Such coordination should be understood as a procedure to ensure operational stability at the hourly speed of 300 kilometers, and a means to correct the mistakes stemming from conventional practices.

Design changes were made in most areas after the train type was finalized, focusing on bridges, tunnels, earthworks, and seismic designs. The technical stability of the roadbed design and its technological alignment with the rolling stock, in particular, were examined by SYSTRA. In 1996 and 1997, the safety assessment was commissioned to Wiss, Janney, Elstner Associates Inc. (WJE). The target of the safety assessment was the pilot line, whose construction began in 1992, and one area linking Seoul and Cheonan, with its focus on tunnels, bridges, earthworks, and culverts. The results showed that 39 out of 1,012 areas—especially bridges—required reconstruction (KR 2005). The Board of Audit and Inspection also identified the scope of necessary improvement in budgetary aspects, demanding (a) a review of the dynamic behaviors of previously designed bridge structures following finalization of the train type, (b) a review of previously designed roadbed structures and interfaces following finalization of the train type, and (c) redesigns of bridges to be consistent with the changed design criteria following finalization of the train type (BAI 1999).

[14] This led to conflicts between the ministries, with the Ministry of Construction and Transportation sticking to the French standard and the Ministry of Environment the Japanese one. Consequently, noise criteria were not developed until seven years after construction, and the issue was eventually pointed out by the Board of Audit and Inspection (BAI 1999). This example can be understood as resulting from different practices pursued by government agencies in the past, indicating poor coordination between ministries with regard to systems.

[15] Frequent design changes were made during the construction of the express train system, believed to have occurred because the basic geological environment assessment and basic design were poorly done before the detailed design. For the Seoul-Busan Express Train System Construction Project, the authorities spent a meager seven billion Korean won in this regard, including 5.8 billion Korean won for the geological environment assessment, and 1.2 billion Korean won for the basic design (Hankyoreh 1997).

9.4.3.2 Inter-Firm Relationships: Vertical Disintegration

At the time the high-speed railway was being completed, KHSRCA raised the need for separation from the existing railway, and this was why the high-speed railway could overcome the operational inefficiency of the existing system and the railway operation deficit (KPMG 2003). In particular, it was possible to utilize the accumulated skills and professional manpower from the construction process to promote the differentiation and efficiency of the operation of the high-speed railway. At the same time, the Ministry of Construction and Transportation announced the "Railway Industry Structural Reform" in 2003. The government planned a vertical designation policy under the following rationale: 1) to offset the cumulative operating deficit of existing railroads and to separate debt from additional high-speed rail construction activities, 2) to strengthen expertise and operational efficiency through the disintegration (also known as vertical disintegration) of operations (top) and facilities (bottom) roles, and 3) clarification of responsibilities in the event of an accident (MOCT 2003). More specifically, railway facilities such as public facilities continue to be owned and invested in by the state at the SOC level (e.g., roads, airports, harbors, and railway operations), while commercial issues and activities such as customer attraction and ticket sales will be managed effectively by establishing public companies.[16] Subsequently, the Korea Rail Network Authority (KRNA) was established in 2004 and the Korea Railroad Corporation (KRC) came into being in 2005. In particular, KRNA is responsible for the construction and facility management of the existing general railway and the high-speed railway, and KRC is responsible for railway and vehicle operations.

In fact, the railway industry, closely related to railways, roadbeds, stations, rolling stock and services, has been broken into the construction, operation, maintenance, and control sectors. First, as a result of this structural reform, both KRC and KRNA were expected to show improved financial performance; however, there were increases in costs and adjustments in construction and operation processes. The liabilities of the KRC increased greatly from 8 trillion won to 14 trillion won in 2005, which was the time of its launch. Moreover, KRNA's liabilities increased from 5 trillion won to 17 trillion won at the time of its launch in 2004 (Kyunghyang Biz 2013). As such, improving the deficit through railway reform will be limited and promises to be a challenging issue. This approach also led to ineffective strategies for both KRC and KRNA, where financial improvements are important. On the one hand, KRNA is motivated to expand its business with the utilization of public funding so as to improve its financial management. On the other hand, it is the KRC which operates the many non-profitable routes that were built (Interview 2016). Secondly, as KRC and KRNA became separated, it meant that operator assets and facility assets had to be separately managed, with Station's Sphere Influence Development also

[16] The government pointed out that several problems may arise when the integration is carried out. Because the operator has to conduct sales, transportation, history management, and maintenance of the vehicles while in ownership and during the construction and maintenance of the facility, it is difficult to balance public interest and a business mindset (MOCT 2003).

promoted separately. However, KRC and KRNA are not clear on the scope of development of specific station areas; hence, there is some overlap of the business scopes and disagreement about project proponents (Interview 2016). Accordingly, at the initial stage of the reform of the railway structure, it proceeded in the opposite direction from the goal of reinforcing the expertise of facilities and operations and sharing roles. Finally, there were many technical obstacles preventing the introduction of new technology owing to the difficulty of mutual business coordination between KRNA and KRC due to the vertical disintegration process (Interview 2017). For example, with regard to the railway transporter, an orbital facility for moving the train self-volume from one track to another track, it was installed without sufficient consultations with the railroad operator (KRC), and a total of 956 technological obstacles and disruptions of operation occurred between 2010 and 2013 (Park 2013). In conclusion, the inter-firm relationships between operation and construction indicate that there was no system for monitoring and difficulties in mutual cooperation. It is important to note that a railway is an integrated system in which infrastructure entities such as the railway, signals, and electricity are closely connected with operation parts such as vehicles, stations, and systems management; moreover, the interface between construction and operation is important. In addition, by separating the railway corporation and railway facilities, the train operational safety is lowered, and disintegration is likely to weaken the competitiveness of the products exported by the industry in the near future.

9.5 Discussion: Non-Technological Innovation in Latecomers

Recent literature within the context of organizational innovation highlighted the importance of non-technological innovation. We examined the characteristics of non-technological innovation of frontier products that are developed by the latecomer. Using three case studies, this includes organizational innovation (organizing the product and product development) as well as marketing innovation that are discussed in the non-technological innovation literature. In the case studies presented earlier, we identified different patterns of challenges in building non-technological innovation during each phase of the product life cycle. Despite the fact that this study is exploratory and limited to Korean cases, the findings are consistent with those of previous research which showed that latecomers experience similar issues (McKendrick 1992; Goldstein 2002; Han et al. 2009; Mulugeta and Kitaw 2016) rather than idiosyncratic issues; in other words, latecomers tend to experience insufficient non-technological innovation (i.e., project, product, and financial aspects).

In order to understand organizational and marketing innovation, we compared three different cases and identified key characteristics of non-technological innovation in each product's life cycle (See Table 9.6). *1) Fluid phase:* Developers face new challenges with regard to how latecomers commercialize new and original

Table 9.6 Latecomers' challenges in non-technological capabilities

Innovation activities		Product Life cycle Phase		
		Fluid Phase	**Transitional Phase**	**Specific Phase**
	Firm's activities	-Perception of regulation by developers -Capability of creating new regulations and technical service by regulatory agency	Project financing capability	Organizational capabilities
	Inter-firm activities	Joint regulatory development between developer and regulators	Transition to global business oriented structure	Inter—organizational set-up

technology. First, to create demand for small- and medium-sized nuclear reactors and for related exports, it is necessary to acquire SDA from the pertinent regulatory agency and to complete the stage of test plant construction. Both regulatory agencies and nuclear design organizations have experienced difficulties and dilemmas during the process of acquiring and issuing SDA effectively. Given that such technology was new to the world, the agency failed to provide a new regulatory standard and design agencies relied on old regulation standards, leading to a failure to prove innovativeness overall. Second, the construction of SMART nuclear reactors remains a slow process. The reason for sluggishness in the construction of small-scale reactors in Korea is the existence of a large-scale nuclear reactor ecosystem that comprises a significant number of 1000 MW and higher nuclear reactors. In other words, the transition to a small- and medium-sized reactor business ecosystem in Korea is neither automatic nor easy, given the operational and economic efficiency of nuclear reactors. Third, for the regulatory organization to perform relatively routinized tasks such as approvals or the issuing of licenses, new research activities and providing new regulatory guidance may be limited due to exiting routines. Therefore, building an inter-firm relationship to create new regulatory guidelines with product developers and regulators is more problematic. *2) Transitional phase:* During the transition phase, building financial capabilities is indispensable for market creation by product developers. As latecomers, both KEPCO and the credit loan organization (KEXIM) had difficulties in not only organizing but also complying with the regulatory regime. Admittedly, business operations between domestic and overseas markets require different capabilities and the formation of inter-firm relationships. With regard to exporting complex products to overseas markets, the required task was more complex, reflecting the two issues of re-orientation of the business structure such that it will be favorable to exporting the product, and acquiring non-technological capabilities such as skills with project financing. First, in this case, the established horizontal ecosystem in the domestic market served as an obstacle preventing efficient nuclear plant construction. That is to say, overseas competitors were participating in an international competition under the integrated vendor structure, while Korea was extending the domestically routinized horizontal vendor structure for international competition. Second, despite the fact that Korea won a contract to design and construct four APR-1400 reactors at the Barakah site in the UAE, the project financing process was not as smooth as was hoped. KEPCO faced delays at the global level of project financing as well as in obtaining a loan from the Export-Import bank of Korea. *3) Specific phase*: Evidence suggests that Korean firms failed to conform to the technological regime of the complex product, leading to negative consequences in terms of time and the budget. First, in a preliminary engineering study, the user ignored systems engineering methods by requesting RFP rolling stock selection before traffic alignment studies had been completed and by requesting straight-line alignment instead of systems engineering alignment. Second, the adoption of the less integrative system approach during the process of constructing the high-speed rail network caused schedule delays and increased costs. For instance, lengthy modifications of the design occurred due to the adoption of the core system strategy. Moreover, placing separate orders instead of turnkey orders for rail construction (i.e., roadbed and tract separation) exacerbated the coordination problems. Possibly the most fundamental issues concerned harmonization between operators (KRC) and network builders (KRNA), two entities which often operate under the same organization in most countries. Current inter-firm relationships are preoccupied with business expansion *pro se quisque* on the Station's Sphere Influence Development. Therefore, latecomers would have difficulties or face challenging issues with regard to achieving operational efficiency between the old and new railway system management styles.

9.6 Conclusion and Implications

From the 2000s, Korea has faced major challenges as it makes the transition from (a) the phase of economic development characterized as "catching up" with the global technological frontier, involving technological "imitation," to (b) the phase of continuing development based on the development of new knowledge for globally leading (post catch-up) product and process innovations. Selected case studies identified the number of experience-related challenges in the area of product development ranging from the specific to the fluid phases of the product lifecycle; such problems have been hampering effective product development and market (domestic and overseas) diffusion, thus offering certain implications, that is, that key actors play important roles in each phase but the required capabilities are different.

Although this study is exploratory and the possibility of generalization is limited, there are at least three implications for those devising business strategies. First, as firms and organizations make the transition from the catching-up phase of reaching the technological frontier, involving technological imitation based on the accumulation of new knowledge for globally leading products, to the process of innovation, the co-evolution of technology as well as regulatory development is essential.

Moreover, in the fluid phase, such firms are involved in the development of new-to-the-world technology while also creating new rules of the game. From a developer's viewpoint, data accumulation and system reliability are critical issues which can be conducive to global regulatory standards. In the transitional phase, the firm's capability-building efforts should be focused not on only technological capabilities but also on non-technological capabilities (project financing), which are important, while acquiring appropriate knowledge (systems engineering knowledge) and skills (system integration) for complex products, as both can be critical in this specific stage.

Secondly, key actors and the inter-firm relationships among them typically differ in each phase. In the fluid phase, key actors are technology developers and regulatory agencies. To acquire approval for new and innovative designs in the early stage, neither authorities nor developers have a picture of a new regulatory framework. If regulatory agencies do not establish new regulatory standards and provide guidance, developers may face difficulties with regard to the acceptance of innovative designs. Therefore, developers must have close relationships with regulatory agencies for new product approval and to boost user involvement for effective product diffusion from the early stage of product development. In the transitional phase, just after the setting of the dominant design, user–component supplier relationships in the cooperative product development phase and the setting up of the ecosystem are more important. As identified in the case studies, established distinct and efficient ecosystems become ineffective business ecosystems. Therefore, it is essential to realign the business ecosystem so that it may be conducive to international competition. Furthermore, it is likely that the most fundamental issues affecting firms as they attempt to achieve success in both international and domestic markets depend upon whether the firm can develop complicated project stakeholder relationships and a related interface. In the specific phase, the ability to build a business ecosystem and the ability to manage the capabilities of component supplier networks are indispensable elements and a necessary condition for successful product development. At the same time, existing routines often hinder the shaping of new routines.

There are numerous possible science, technology, and innovation policy implications that help to build or upgrade non-technological capabilities which have been under-emphasized. Traditional wisdom suggests the need for co-evolution between technology and organization (non-technological) for better performance at the organizational or national level. At the same time government policies were implemented in the area of technological capabilities while non-technological issues were not reflected during the catch-up period. As latecomers enhance capabilities in innovation and challenge global leadership, new forms of non-technological innovation are required. Hence policy measures could be focusing on two aspects: 1) Concentration of science and technology policy on balancing and upgrading the non- technological and technological innovation. In other words, uncertainties in technology and market development that have not been experienced during the catch-up period, such as commercialization of original technology, intellectual property rights, international standards setting, and initial market creation, are increased. The issues of setting standards or securing initial markets are not matters of individual firms, but are closely related to institutional assets in the country's innovation system. In building non-technological capabilities during the transition period, it will be important to recognize that new institutional factors are needed, such as organizational innovation for searching for new technology, establishing new regulations and standards, upgrading intellectual property rights, strengthening project financing capability (e.g., export credit and trade insurance agency), and testing/certification to create markets. 2) Focus of firms on enhancing non-technological innovation. As described in the case studies, a series of key challenges or difficulties have been identified. In frontier products where a high level of technological know-how, and organizational innovation (e.g., new inter- and intra-firm relationships) are expected, policy measures to strengthen and upgrade non-technological innovation activities could include the followings. Policies are needed to support firm-based human resource training facilities to balance technological and non-technological knowledge. This might include technology management training for engineers (e.g., regulatory innovation, IPR strategy, and technology marketing). Such accumulated human resources at the firm level might contribute to achieving non-technological innovations.

While the findings of this study extend our understanding of the non-technological innovation using case studies, less emphasis is placed on the sufficient depth or breadth with regard to challenging issues at the firm level. These areas would be fruitful for researchers who study the upgrading of firms and frontier products in the context of latecomers or rapidly developing economies. Insights from such experiences can lead to the following research topics in the future. 1) N*on-technological innovation capability-building processes*, such as those related to financial/marketing capabilities. Investigating the aforementioned issues would be meaningful to the frontier product and process development efforts of latecomers and would shed light on the market diffusion process. 2) *Common measurement/indicators of latecomers' non-technological capability-building*. Development of measurement or indicators of non-technological innovation still lags behind compared to those of technological innovation. An interesting task for future research may also be to investigate the common indicators for building/upgrading non-technological innovation capabilities. 3) *Comparison of non-technological innovation between advanced and latecomer economies*. In-depth comparative analysis of non-technological innovation may provide deeper understanding of whether two economies have similar theoretical foundations.

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PART III

EMERGING PARADIGM ON TECHNOLOGY CAPABILITY UPGRADING

10
Catching Up or Developing Differently?
Techno-Institutional Learning with a Sustainable Planet in Mind

Tilman Altenburg

10.1 Introduction

We are living in a world with enormous gaps in terms of economic wealth and human development. In 2019, per capita income of US citizens was sixty-one times higher than per capita income in Least Developed Countries.[1] While neoclassical economic theory suggests that capital and knowledge should flow into lagging regions and thereby close the income gaps, this has only happened in some (mainly Asian) countries, whereas per-capita income in most other developing countries has been stagnating relative to the US over the last few decades, and some have even fallen further behind (Verspagen and Kaltenberg 2015). Economic convergence between rich and poor countries is thus possible, proven by successful latecomers such as South Korea and China, but by no means a standard outcome of competition in the globalized economy.

This observation has given rise to a rich body of research on the determinants and dynamics of catching-up (Kim 1997; Mathews 2006; Lee 2013; Lee and Malerba 2016). Catching-up is defined as the process by which a latecomer country reduces the gap either in income (economic catch-up) or in technological capabilities (technological catch-up) vis-à-vis a leading economy (Odagiri et al. 2010, p. 2).[2] This research has shown that it makes a big difference *when* countries (or firms) integrate into the global division of labor. Latecomers enter global competition at a point in time when others have already developed capabilities, networks, economies of scale in production, brand reputation, and many other things that give them an enormous competitive advantage. Being a latecomer thus implies manifold disadvantages. Yet, as Gerschenkron (1962) reminded us, there is also an "advantage of backwardness" in

[1] In current US$. Own calculations based on https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations, accessed 21 January 2021.
[2] Technological catch-up is mostly associated with decreasing income gaps, yet economic catch-up may be driven by other factors, such as resource rents.

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that latecomers can build on knowledge and technology developed by the incumbents without having to go through costly processes of trial and error to develop them on their own. The research has also contributed to a better understanding of stages of the catching-up process. In a stylized way, latecomer countries start by borrowing technology through foreign direct investment or licensing agreements; then gradually create the capabilities to use these technologies efficiently and adapt them to local conditions; and finally build up capabilities for indigenous innovation (Kim 1980 and 1997, Lee and Lim 2001; Lee 2013).

What is important in our context: This notion of catching-up starts from appropriating long-established technologies and institutional role models from the economically dominant countries. Technologies acquired through foreign direct investment or technology licensing, and institutions in the widest sense—from rules and regulations to organizational patterns—are shaped after international role models. Proven technologies and institutions are thus imitated—and of course sometimes slightly adapted to local conditions—with a time lag. This time lag may be exacerbated by the fact that foreign investors often do not provide the latest technology to avoid high capital outlays and investment risks as well as any leakage of their core competencies (Chudnovsky and Lopez 1999, p. 6). Even if we acknowledge that a few successful latecomers have been able to deviate from the trodden paths and continue in new directions on the basis of indigenous innovation (Lee and Lim 2001; Lee and Malerba 2016), this has only happened at later stages. The essence remains: The *early* stages have always been path-dependent on long-established technologies and emulation of the institutions in which they are embedded.

This is highly problematic against the background of looming global environmental catastrophes stemming from the use of unsustainable technologies and institutions. Global warming is the most immediate threat to life on earth, and it essentially stems from technologies and economic practices based on burning stocks of fossil energy. Similarly, other environmental pressures—such as the loss of biodiversity, deforestation, contamination of soils, freshwater scarcity, and air pollution—reflect unsustainable technologies and institutions. In the dominant world economy, the natural environment is treated as external to the economy, and GDP growth is therefore closely coupled with resource consumption and environmental pollution (Jackson 2016).

There is now increasing agreement in academia, including leading institutions of global governance such as the OECD, the World Bank, the International Monetary Fund, the United Nations Development Programme and the World Economic Forum, about the need to "green" the world economy. This agreement is also gradually percolating into concrete budget allocations, as is the case of the European Union's European Green Deal. Moreover, environmental analyses show that this "green techno-economic paradigm shift" (Perez 2016) needs to be radical, encompass all economic sectors, and happen fast. With regard to climate change, the IPCC warned in a 2018 report that only a dozen years remain to undertake radical mitigation action if global warming is to be kept under 1.5C above preindustrial levels, which the organization deems to be the critical threshold levels at which catastrophic consequences can still be avoided (IPCC 2018). This is exactly where environmental requirements clash with the stylized catching-up model that *starts* with borrowing technology from the early industrialized countries and emulating business models and institutional arrangements. Going through stages of "duplicative imitation" and "creative imitation" (Kim 1997) before their own technologies can be developed implies, firstly, that latecomers invest in a set of high-carbon technologies whose negative externalities have triggered the current global environmental crisis and that need to be phased out in the next few years; and second, that they may develop the wrong set of capabilities that, given the path-dependent character of institutions, may make a green transition even more difficult in the future.

Against this background, this chapter at discusses what the green paradigm change implies for latecomer development. To what extent can and should latecomer economies and firms still benefit from technological and institutional experiences elsewhere and to what extent and in which aspects do they need to pursue radically different strategies? The challenge of closing the gaps between rich and poor countries and improving the latter's techno-institutional performance remains as pressing as ever. Yet, it is also clear that the "advanced" economies' countries can no longer be taken as role models for a sustainable route to prosperity. In fact, the notions of "advanced" and "backward" need to be fundamentally reconsidered. How then, should latecomer countries design their economic development strategies? How can they deal with the "dual challenge" (Altenburg and Rodrik 2017) of catching up and creating wealth in an unbalanced world economy while at the same time managing a radical techno-economic paradigm change towards environmental sustainability?

The chapter has five sections. Section 10.2 brings out why the transformation is urgent and without alternatives, how radically it will affect production and consumption patterns in essentially all economic sectors in all countries, and why it has to happen very quickly. It shows that resource efficiency must increase at least as fast as economic output to ensure what has been called "absolute decoupling." Section 10.3 discusses what we already know about the contours of an environmentally sustainable "green economy" that also offers sufficiently attractive socio-economic perspectives to be politically implementable—and whether such an economy would be compatible with the predominant mode of capitalist societal organization. Section 10.4 revisits the concept of catching-up in some of its ramifications, emphasizing the fact that it generally starts from imitating established techno-economic patterns. Section 10.5 then discusses to what extent the notion of catching-up is still useful in a situation where a radical departure from environmentally unsustainable patterns is inescapable. The concluding Section 10.6 draws policy lessons combining insights from catching up and green transformation research.

10.2 Planet under Threat—and the Need for Absolute Decoupling

Economic development pathways cannot continue following the established trajectories of the past. Since the Industrial Revolution, the world economy has expanded at the expense of the natural environment. Natural resources have being depleted by using them beyond their capacity to regenerate, including freshwater reserves and soils; anthropogenic atmospheric warming is causing irreversible degradation of ecosystems at a global scale; the loss of biodiversity is unprecedented in human history; a wide range of persistent pollutants have accumulated in the biosphere, with dire consequences ranging from premature deaths due to urban air pollution to the mass mortality of bees and other insects, which prevents pollination and jeopardizes agricultural productivity; the fixation of atmospheric nitrogen is polluting soils and aquatic ecosystems; micro plastics are accumulating in ocean webs with unpredictable long-term consequences; and the same holds for ocean acidification (e.g., UN Environment 2019; IPCC 2014, Steffen et al. 2015). Research on "planetary boundaries" (Rockström et al., 2009) identified nine so-called "planetary life support systems" which are essential for human life on earth and pointed to threshold levels of environmental degradation beyond which non-linear, abrupt processes may kick in that change planetary-scale systems with unforeseeable and potentially irreversible consequences for human survival. In several life support systems, the respective boundaries of a "safe operating space for humanity" (ibid.) have already been, or are about to be, crossed.

To avoid such dire consequences, major changes are needed in the way economies are currently organized. Let us consider the issue of global warming to illustrate how deep the transformation of economic development pathways will need to be. Under the auspices of the United Nations' Intergovernmental Panel on Climate Change (IPCC) detailed scenarios have been developed to show how emissions need to be phased out in order to stay on the environmentally safe side. They suggest that if 1.5°C of global warming above pre-industrial levels is to be avoided, global net anthropogenic CO_2 emissions would have to decline by about 45 percent from 2010 levels by 2030 and reach net zero around 2050. As not all emissions are avoidable, net zero implies the need for innovative solutions that remove CO_2 from the atmosphere in order to compensate remaining emissions. To stay below 2°C of warming—a less ambitious scenario that would imply some irreversible environmental damage, for example to coral reefs—emissions would need to decline by about 25 percent by 2030 and be reduced to net zero by 2070 (IPCC 2018). Even this scenario presupposes a radical and speedy departure from an economic system that has been (and so far still is) based on burning coal, oil, and gas to literally "fuel" the world economy, from manufacturing industry to agriculture and transport. Carbon phase-out will affect all sectors of all economies and involve radical departures from technological pathways as well as incentive systems, and all this needs to be achieved within an ambitious time frame of three to five decades. Bear in mind that global warming is only one of the various earth system processes that are currently out of control. Additional regulatory changes are needed to bring techno-economic and institutional systems in line with all other planetary boundaries.

The core challenge for the transformation towards an environmentally sustainable economy is to achieve human well-being and undertake the economic activities needed for that purpose without depleting natural resources and impacting negatively on the natural environment. This is captured by the concept of "decoupling."

	Relative	Absolute
... from resource consumption	X	x
... from environmental impact	X	x

Figure 10.1 Four dimensions of economic decoupling

For our purposes here, four types of decoupling matter (Figure 10.1). To be sustainable, economic activities need to be performed (a) using fewer physical resources and (b) without deteriorating the natural environment; both can be either relative (per unit of economic activity, e.g., GDP) or absolute (UN Environment 2019).

To ensure staying within bio-physical ecosystem boundaries, resource efficiency must increase at least as fast as economic output. This is absolute decoupling. Relative decoupling, that is, improvements that are overcompensated by demand growth, is not enough. Growing demand has in fact often more than offset the resource-saving and pollution-reducing effects of new technologies. Greening et al. (2000) show this for energy efficiency gains. Resource-saving technological innovations have two side-effects: They lower the price of the respective resource which in turn increases demand; and they increase profits, thereby purchasing power and consumption, resulting in a rebound effect (Petschow et al. 2018).

Absolute decoupling is thus the goal—and it has to be achieved in a global economy that is still characterized by substantial deficits in terms of human well-being (UNDP 2019). Let us again refer to global warming to illustrate how challenging this is. Table 10.1 shows the annual rates at which greenhouse gas (GHG) emissions, respectively GHG intensities—that is, the ratio of GHG emissions per unit of GDP—need to be reduced every year from 2013 to 2050 to achieve the targets agreed at the Climate Summit in Paris in 2015. The table shows three scenarios presented by Rogelj et al. (2015). It reveals that GHG emissions would have to be reduced (from 48 Gt CO2e in 2013) to a range of 4-19 Gt CO2e/year if we want to stay below 1.5 °C global warming and 9-26 Gt CO2e/year to stay below 2 °C. If we only take the median scenarios, emissions' intensity would have to decrease by 5.0 percent every year over a period of four decades to stay below 2°C global warming and even 6.2 percent if 1.5°C is to be achieved. This contrasts with actual reductions of GHF intensity of 1 percent per year (Petschow et al. 2018, 18).

10.3 Is Absolute Decoupling Compatible with Capitalism?

The big question then is: Can gradual reforms of capitalist market economies, such as the introduction of certain price-based mechanisms for the valuation of

Table 10.1 Required GHG emissions and GHG intensity reductions for achieving climate targets

Climate targets	Global GHG emissions in 2050, Gt CO2e/year		Annual change of GHG emissions 2013–2050 needed to reach targets	Annual reduction of GHG intensity (assuming 0.7 percent population & 2 percent GDP growth/year)
1.5 °C	min.	4	−6.5 per cent	−9.2 per cent
	median	13	−3.5 per cent	**−6.2 per cent**
	max.	19	−2.5 per cent	−5.2 per cent
2.0 °C	min.	9	−4.4 per cent	−7.1 per cent
	median	20	−2.3 per cent	**−5.0 per cent**
	max.	26	−1.6 per cent	−4.3 per cent

Source: Rogelj (2015), adapted from Petschow et al. (2018).

environmental goods and targeted support for green technologies achieve decoupling of such an order of magnitude? Or are more fundamental reforms necessary that challenge the fundamentals of capitalist market economies? Some scholars argue that the required efficiency gains are virtually impossible within a growth-oriented capitalist system. Almost half a century ago, Georgescu-Roegen (1971) and Daly (1974) already argued that economic systems which by their very nature depend on an ever increasing input of natural resources will, at some stage, invariably overstep the limits of the earth's carrying capacity. Until quite recently, however, those warnings had hardly any impact on economic mainstream thinking and policymaking. Yet, this seems to be changing now. Environmental deterioration has reached such levels that the threat to human survival is now glaring and the need to internalize environmental costs in order to stay within what Rockström et al. (2009) call "a safe operating space for humanity" is widely recognized among academics and governments. This has also given rise to a new generation of social scientists searching for the ingredients of a non-capitalist economic order that would allow for achieving social welfare without depleting scarce resources and impacting irreversibly on the environment. Scholars of "degrowth" (e.g., D'Alisa et al. 2014) posit that environmental sustainability can only be achieved with a reduced material footprint of the global economy and a general shifts towards values such as sharing, sufficiency, care, solidarity, and autonomy that are largely incompatible with capitalist institutions. In the discipline of economics, Jackson (2016) points to an inextricable tension between an economic system that presupposes permanent growth to remain viable and the finite carrying capacity of environmental systems, arguing that the possibility to decouple in absolute terms is a "myth."

In the following, I argue that conceptually, the big gap between actual efficiency gains and those required for absolute decoupling does not imply that it is impossible to meet the latter within a capitalist market economy. This said, far-reaching techno-economic, institutional and behavioral changes would be needed that require an active state that enforces strict internalization of environmental externalities, stimulated and coordinates investments accordingly, and ensures societal support for the change. Following Hall and Soskice's (2001) distinction of varieties of capitalism, this clearly calls for coordinated (rather than liberal) versions of market economies. Yet, regardless of the type of institutional governance, the main problem remains unsolved: it is currently not foreseeable if and how consumers' (and voters') readiness to change lifestyles accordingly and the political elites' willingness to enact the necessary reforms against powerful vested interests can be achieved.

The most important argument why the *current* failure to decouple tells us little about *potential* decoupling is that many environmental goods are currently not priced; and when they are, the market prices do not reflect the true social cost of the environmental damage caused. For carbon emissions, for example, many economies do not price them at all, and where price-based mechanisms have been introduced, generous exceptions and very low caps resulted in underpricing. According to Gaspar et al. (2019), about fifty countries have a carbon-pricing scheme in some form, but the global average carbon price is as low as US$2 per ton. The European Emissions Trading Scheme, probably the most famous example of a cap-and-trade system, currently prices the ton at 25€ (end July 2020),[3] yet the IMF estimates that this price should rise to 75 US$/t by 2030 to curb carbon emissions to the level necessary for keeping global warming below 2 degrees (Gaspar et al 2019). Low carbon prices result in underinvestment in technologies that would reduce emissions, such as in solar energy, electric vehicles, and energy-efficient buildings. Yet, capitalist market economies are learning systems and able to solve many problems building on a Schumpeterian dynamic of market entry of firms with new ideas, competition that weeds inefficient companies out and forces all remaining companies to continuously improve, thereby rewarding creativity, entrepreneurial spirit and innovation. If prices were set to reflect the full social cost of pollution, innovation could be expected to be much faster.

Many technological solutions for environmental pressures are already, or will soon be, ready for deployment. Deployment is often only held back because the hidden social costs of the polluting incumbent technologies are not reflected in their prices. This is the case for a wide range of renewable energy technologies; energy efficiency technologies for buildings; electric, gas, and hybrid vehicle technologies; smart grids, and sustainable farming technologies. Moreover, incumbent technologies often benefit from economies of scale that the emerging clean alternatives do not yet have. As the examples of solar photovoltaic modules, offshore wind turbines, solar thermal electricity, ocean energy (Tsiropoulos et al. 2018) and lithium car batteries (Bloomberg NEF 2019) show, production at scale and technological learning lead to an enormous cost digression once these technologies start competing with the dominant design technologies and being rolled out globally. The so-called "Swanson's Law" suggests that the price of solar photovoltaic modules decreases

[3] https://ember-climate.org/carbon-price-viewer/, accessed 22 January 2021.

20 percent for every doubling of cumulative shipped volume.[4] Similarly, between 2010 and 2018 the cost of lithium car batteries dropped from 1,160 to 176 US$[5] (Bloomberg NEF 2019). In addition, a number of promising green technologies are under development, including safe and efficient large-scale captured carbon storage technologies, biofuels sourced from waste or from algae, waste-based biomass gasification, floating wind turbines, printable organic solar cells, and artificial photosynthesis, many of which could have major decoupling effects. Internationally orchestrated and well-funded technology missions could substantially compress the time needed for commercial deployment (Mazzucato 2015).

Furthermore, economic growth can be driven by intangible and less resource-intensive goods and services. Economies can continue to grow with less resource consumption and environmental impact if consumption patterns shift from resource-intensive material goods and services, such as automobiles and air travel, to resource-light organic food, product sharing, or cultural services (Hepburn and Bowen 2013; Petschow et al. 2018). To what extent this will happen is closely related to the previous aspects of environmental pricing and technological choice. Higher air fares for example are likely to shift demand towards more resource-efficient modes of transport or video conferencing that renders physical travel unnecessary, and taxing meat may shift dietary habits to more resource-light food products. Yet, consumer behavior is also dependent on cultural values and lifestyle trends that are difficult to anticipate. Some consumer trends indeed suggest a shift away from the traditional patterns of consumerism with their inherently increasing environmental footprint. These include, for example, new preferences for sharing instead of owning assets (Hamari, Sjöklint and Ukkonen 2015) and for vegan food (Chai et al. 2019). Likewise, a growing number of "energy prosumers" adopt new renewable energy technologies in their households to become producer-consumers and depend less on traditional energy utilities (Parag and Sovacool 2016).

Last but not least, growth can be measured in different ways that capture human well-being and aspirations better than GDP in absolute or per capita terms (Jakob and Edenhofer 2014). New approaches to green accounting try to ensure that the value of the damage and depletion of natural assets is included in national accounts (World Bank 2012). Moreover, many contributions to human well-being are not mediated via monetary exchanges, including community services, sharing and barter deals (D'Alisa et al. 2014). Including those in welfare accounting makes the link between economic performance and environmental impacts even more indirect. Societies can in principle increase their standard of well-being with a shrinking GDP and vice versa.

Summing up: Against looming threats to human life on earth, fundamental changes are needed in the way growth-oriented capitalist economies are organized

[4] https://en.wikipedia.org/wiki/Swansonper cent27s_law#cite_note-SPWRTech-2/, accessed 22 January 2021.

[5] Per volume-weighted average lithium-ion pack, in real 2018 US$.

(see also: Jacobs and Mazzucato 2016). So far, there is no agreement on what a green world economy should look like: one that delivers the productivity gains that allow everyone to live a decent life without overstepping our planet's ecological carrying capacity.[6] Yet, the contours are gradually becoming clearer. Economic performance needs to be decoupled from resource consumption and environmental impact. It must shift from a throughput economy (Boulding 1966) that extracts large quantities of raw materials and transforms them into waste towards a closed-loop system that minimizes the use of new resources as well as waste and pollution by consuming less, reusing, repairing, and recycling resources (Ellen MacArthur Foundation 2013). It must be carbon-neutral, starting with the transformation from a carbon-based energy system to one using renewable sources, and then electrifying end-uses such as transport, cooling, and heating once the energy mix is decarbonized. It must change land-use systems to preserve ecosystems and not exploit any resource beyond its regenerative capacity.

Current progress in this regard is far from sufficient. What is more, not a single national economy has achieved a high level of human development without exceeding what the Global Footprint Network calls the biocapacity of the area available to its population. Put differently: There is no role model for sustainable development at a national scale. On the other hand, the pathway to a sustainable economy does not lead through entirely uncharted territory. The required policy package is essentially known. It requires a mix of regulations and market-based instruments to ensure non-natural capital stocks are not overexploited. Extensive literature is available on the pros and cons of a variety of environmental policies (IPCC 2014; Hepburn et al. 2018) and how they can be packaged (Kern et al. 2019). Similarly, a wide range of the necessary technologies and business models have already been developed and tested and are ready to be scaled up once the right incentives are in place. Others that are still under experimentation could be brought to commercial viability with the support of targeted technology missions.

In essence, it's a matter of will rather than techno-economic feasibility. The main obstacles are political and behavioral. What is needed are three complementary changes: First, a new consensus is needed on the societal goals to which economic systems should contribute. This is reflected in the SDG agenda and the work of international commissions trying to find generally acceptable measures of people's well-being and societies' progress that would replace GDP growth as the still prevailing proxy for economic success; second, more ambitious policy frameworks guided by science to adapt incentive systems to the limitations of Rockström et al.'s (2009) planetary life support systems; and third, changes in lifestyle that involve increasing consumption of immaterial welfare-enhancing services and resource-light products and decreasing the consumption of goods and services with a huge environmental footprint.

[6] For some approximations, see UNEP 2011; Jacobs 2013; Jackson 2016; and Raworth 2017.

If and how a mutually reinforcing dynamic of sustainability-oriented policies and sustainable lifestyles can be set in motion remains unclear. It requires overcoming strong vested interests in established unsustainable industries, and also lifestyles change tend to happen slowly. Environmental deterioration can be expected to accelerate the willingness to change, but when that driver of change kicks in, planetary life-support systems may already be damaged irreversibly.

The above analysis calls for a reconceptualization of the notion of catching-up, which is about reducing the gap between rich and poor countries in GDP per capita and/or technological capabilities. As we have seen, the appropriateness of GDP per capita as a proxy of social welfare is now more disputed than ever, and technologies that enabled the growth episodes of the past are largely associated with carbon combustion as well as with a linear raw materials-to-waste rather than a closed-loop logic of production—technologies that have brought our planet to the brink of disaster.

10.4 The Catching-Up Debate Revisited

This chapter started out showing the enormous income differentials between rich and poor countries. Neoclassical economic theory suggests that such differences should gradually disappear. Incomes of rich and poor nations should converge, because returns to capital are diminishing faster in the former; hence, investments should flow into poor countries. The latter would then be able to attain high rates of productivity growth because they can bring in the best technologies and emulate the best institutions from abroad, rather than having to develop them using their own resources.

In reality, unfortunately, such convergence is the exception rather than the norm. Analyzing GDP per capita trends for virtually all countries in the world for the period 1950–2008, Verspagen and Kaltenberg (2015) show that the gap between the richest quintile of countries and the rest grew between 1950 and the mid-1990s; only after that period, per-capita incomes started to converge, as countries in the mid-income range grew faster than rich countries. Korea, Taiwan, and the People's Republic of China stand out for their steep upward trend.[7] Yet, even in this period, the lowest-income quintile of countries fell further behind all other countries (Verspagen and Kaltenberg 2015).

If we understand catching-up in terms of *technological* rather that *income* gaps, the prospects for convergence look even bleaker. Using patenting as an (admittedly imperfect) proxy for technological capabilities, we see an impressive emergence of China as the new global leader in patenting development and a slightly rising share in the global patent market for a handful of emerging economies, but for most

[7] And Oman, which is a unique case due to its enormous oil rents in combination with a small population.

developing countries, their share in global patenting stagnates at a negligible level, especially when non-resident applications are excluded (WIPO 2019).

These findings suggest that catching-up has a number of preconditions. Abramovitz (1986) was among the first researchers to point out that endogenous capabilities to attract, absorb, and improve technologies are indispensable for exploiting the opportunities of international knowledge transfer. These "social capabilities," as he calls them, largely explain whether countries catch up or fall behind.

To unpack these capabilities, scholars in innovation research and evolutionary economics have analyzed what has enabled successful catching-up, focusing on the way technologies were acquired, fully mastered, and further improved, and what kind of capabilities had to be built to achieve such graduation. Some researchers put individual firms at the center, whereas others emphasized capabilities in the firms' environment, ranging from the supporting institutions to the ability to maintain macroeconomic and political stability (Bell and Pavitt 1992; Fagerberg et al. 2010; Altenburg and Lütkenhorst 2015). Malerba (2002) stressed that very different combinations of capabilities are required depending on specificities of economic sectors, thereby triggering a huge body of research on sectoral innovation systems. These differences in focus notwithstanding, catching-up research is consistently showing the following three patterns:

First, latecomer countries and firms only exceptionally acquire their technological capabilities through systematic research and development efforts aimed at developing new products and processes (Mathews 2001). At early stages at least, foreign direct investment (FDI), technology licensing and trade are the main conduits for technological upgrading. This is closely related to the emergence of global value chains in which products are made by order from, and according to the specifications of, global lead firms. Consequently, learning from global buyers (Schmitz and Knorringa 1999) has become a crucial element for technological learning. This has important implications for latecomer strategies. It implies that "implementation capabilities" (Lee et al., Chapter 4, this volume) and "technology diffusion management" (Mathews 2001) are much more relevant than autonomous indigenous capabilities to innovate, for example through firms' own research. What is primarily needed then is strategic attraction of FDI that is particularly promising to pull the domestic economy, the ability to negotiate licensing agreements to the benefit of indigenous learning, and proactive technology transfer measures as well as nurturing local suppliers and productive interdependencies between foreign and national firms. Indigenous innovation or design capabilities for developing own, new-to-the-world products only become important at quite advanced stages of the catching-up process (see Chapters 5, 14, and 8 by Lee; Gao; and Figueiredo and Piana in this book).

Second, the transition "from imitation to innovation" (Kim 1997) evolves through distinct stages with increasing sophistication of capabilities. While recognizing that researchers have drawn slightly different boundaries between the stages and use different terminologies (see for example, Katz 1971; Kim 1980; 1997), they coincide on the essential direction. At the risk of simplifying, we can summarize the various descriptions of stages in the following three-stage-process:

1. Technology acquisition/pre-catching-up: The task here is to select the most appropriate foreign technology for any specific purpose, to buy, install, and use it effectively in the local conditions. Basic technical training is crucial at this stage. The technologies imported or licensed are typically mature, because this is when they can be transferred easily and operated on the basis of largely codified knowledge. Also, technology owners are keen to keep tight control of their technological core competencies, hence they prefer employing older technologies in their operations abroad or licensing agreements—those that are no longer creating innovation rents and thereby involve fewer risks of technology users copying the design.
2. Technological mastery/catching-up: At this stage, latecomer countries and firms deepen their know-how, starting to imitate and reverse engineer-imported technology, diffusing it, and adapting it to various contexts. Process innovations play a relatively larger role here than original R&D.
3. Innovation/post-catching-up: Indigenous research activities and design capabilities (Lee Chapter 5, this volume) now become more important. Latecomers develop new products and processes, diversifying away from the imported technologies. Firms may "enter a different industry, governed by a different technology regime and market environment" (Choung 2016, p. 3), and technological trajectories start to diverge. Technological capabilities are now developed, not only for using mature technologies, but also to cope with the fluid stage of the product lifecycle. As Lee (2016) states, "[A] latecomer's sustained catch-up is not possible by simply following the path of the forerunners but by creating a new path or 'leapfrogging.'' Thus, "firms and countries often diverge from the practices of pioneering firms and countries that serve as industry models" (Lee and Malerba 2016). Case studies of such transitions from catching-up to leapfrogging ahead are provided by Lee and Malerba (ibid.) and Yap and Rasiah (2017).

Lee and Lim (2001) observe that latecomers may in some cases skip a stage. Yet essentially, indigenous innovation and path-creation is always preceded by imitation, as firms and countries start borrowing and using proven technologies before they learn to improve them, and design capabilities are preceded by implementation capabilities (Lee et al., Chapter 4, this volume).

Third, research on catching-up highlights the importance of strategic and proactive industrial and innovation policy. The path from buying and using foreign technology to mastering it fully and developing new technologies is thorny. By no means all latecomer countries manage to advance through the various stages, and while many countries make progress in terms of mastering imported technologies fairly well and advancing from low to middle-income status, only very few manage to reach the innovation/post-catching-up phase that would enable them to join the exclusive club of high-income countries. The World Bank (2013) shows that of 101 countries that were in the middle-income bracket in 1960, only thirteen (mostly European and East Asian countries) had reached high-income status by 2008. Getting stuck thus seems to be the norm rather than an exception. This phenomenon has been referred to as the "middle-income trap" (Aiyar, S. et al. 2013; Eichengreen et al. 2013, Vivarelli 2016).

The bottleneck lies in the difficulty of building the required techno-institutional capabilities, which obviously become much more sophisticated as countries move from importing and applying imported technology and business models to inventing things that are new to the world. Technologically leading nations have accumulated assets—from diversified webs of highly specialized firms to locally embedded multinational corporations and from well-trained workforces to large R&D budgets. Competing with them for leadership in knowledge products requires a lot. Research by Lee and Malerba (2016) point to the existence of specific windows of opportunities, such as a technological paradigm change or a shift in demand patterns, that facilitate catching-up with, or even leapfrogging ahead of, technological leaders. Whether national societal actor groups are able to identify such windows and devise the right country-specific strategy to exploit them makes the big difference between catching up and falling behind. The inherent strategic choices are far from trivial. Difficult trade-offs need to be navigated, for example between protecting firms vs. exposing them to international competition, and between unrestricted vs. regulated entry of foreign firms. Moreover, the right timing and sequencing is often as important as the choice of policy instruments.

While the catching-up literature emphasizes the role of technological and institutional capabilities, and the ability of national political and business leaders to anticipate and strategically exploit windows of opportunities, the political science literature reminds us of the importance of interest groups and power relations. Political and economic elites may be more or less able to make wise strategic choices, but more importantly, they may not be interested in techno-institutional reforms and even deliberately block them. Chang (1993) highlighted the difference between ability and willingness in his seminal books on the political economy of industrial policy. Economic history is full of examples where incumbent elites blocked economic modernization, from feudal landlords opposing agricultural reforms to rent-seeking oligarchs blocking industrial diversification in oil-exporting countries and fossil-fuel-based industries undermining the low-carbon transformation. Research into the political economy of structural transformation takes existing elites' vested interests as a starting point to explain why some countries manage economic structural transformation better than others and why it is so difficult to enact reforms that may negatively affect some factions of the incumbent elites (Khan 2018; North et al. 2009; Whitfield and Buur 2014). Altenburg and Lütkenhorst (2015) therefore argue that catching up depends on *political* as much as on techno-institutional capabilities. The former includes the ability to create and withdraw protection and the related economic rents in a way that ensures the maximum competitive efforts of firms, while keeping political capture by interest groups to a minimum and maintaining political stability.

10.5 Does the Notion of "Catching-Up" Become Meaningless in a Green Transformation?

We have raised the fundamental dilemma in the introduction: current patterns of economic development are jeopardizing the continuation of human life on earth. With regard to some of Rockström's "planetary life support systems," radical shifts of resource-consumption patterns need to be initiated immediately. This raises serious doubts about the functionality of the three-stage model of catching-up. As we have seen, at the beginning of the catching-up process, lagging countries are almost exclusively reliant on foreign technologies. They are "historical imitator countries" (Furman and Hayes 2004) whose emphasis is on learning to operate imported technology and maybe undertaking some marginal improvements to adapt them to local conditions, but who do not invest (much) in new capabilities on the basis of R&D and systematic experimentation. Moreover, imported technologies are typically at the maturity stages of their product lifecycle. This is, firstly, because it makes them easier to handle, and secondly because foreign investors often hesitate to employ cutting-edge technology abroad when this involves risks of their most innovative designs leaking to competitors. Lagging countries thus tend to receive technologies that have been developed years ago when the fossil-fuel economy was in full swing and environmental standards were lower. Going through the normal transition from imitation to innovation may therefore delay the adoption of sustainable alternatives, which is particularly problematic when a looming environmental crisis require a fast turnaround, as is the case of decarbonization.

What is more, replicating development pathways implies a major risk of becoming locked into outdated technologies. Such lock-in results from techno-institutional path dependency: Once a certain technology becomes dominant and benefits from increasing returns to scale and network effects, it tends to hinder the deployment of alternative technologies, even when those have a superior performance. This is because other industries depend on the existing standards, institutions are shaped according to the dominant industries' needs, and consumers develop preferences and habits that are difficult to change (for the case of carbon lock-in: Unruh 2000). If in such circumstances global environmental standards become stricter and governments step up their efforts to decarbonize, countries that still depend on outdated unsustainable technologies may have to write-off enormous investments. Such "asset stranding" is now increasingly recognized as a major systemic risk (Carbon Tracker Initiative 2013). It affects oil- gas-, and coal-producing corporations and countries as well as carbon-intensive industries, from steel, aluminum, cement, and plastics manufacturing to greenhouse horticulture (van der Ploeg and Rezai 2020).

Furthermore, the catching-up paradigm uses per capita income gaps as its yardstick. As such unidimensional indicators are increasingly under attack, the concept of catching-up should be realigned with more comprehensive and human-centered definitions of welfare.

Still, these observations do not render the catching-up concept irrelevant for the green transformation. Many lessons from catching-up research still hold even when a green paradigm change and the need to accelerate the transformation limit the scope for going through the normal stages described above. Especially the following four insights remain highly relevant:

First, the catching-up literature explicitly recognizes that know-how and technologies do not flow frictionless between firms and countries, and economic convergence is an exception rather than the rule. Fostering technological learning, creating and strategically exploiting linkages with foreign investors, and investing in specific institutional capabilities are essential. Strategy is needed to set targets for technological learning, assess technologies, and market potentials, attract investments strategically with a focus on firms that fit the national strategy, nudge them to adopt local suppliers, and share knowledge and increase the absorptive capacity of local firms (Altenburg 2000; Mathews 2006). Strategy becomes even more relevant when environmental pressure forces governments and societies at large to both accelerate structural transformation and deviate from the trodden paths of early industrializing countries.

Second, latecomer countries can reap "advantages of backwardness" using enabling green technologies at low cost. They can, for example, benefit from advancements in renewable-energy technologies which enable them to electrify rural households at low costs and in some cases produce cheap energy, exploit favorable solar irradiation, good wind and water resources to produce cheap energy, co-locate energy-intensive industries and/or export electricity or hydrogen. While the pioneering countries made huge investments in developing the respective technologies, latecomers can now use them at very low costs. In 1976, at the beginning of the photovoltaic product lifecycle, the cost of photovoltaic modules was 79.30 US$ per Watt. Forty-two years later, in 2018, technological progress and economies of scale had brought the cost down by 99.6 percent to 0.30 US$/W (both in 2018 USD; Wang and Barnett 2019). In green technologies, as in any other field of technology, latecomer countries thus need to make strategic choices: They can adopt green technologies at an early stage which is associated with considerable costs and risks, but provides opportunities to exploit early mover advantages, at least relative to other latecomer economies; or they can wait and import and deploy mature green technologies at low cost, piggybacking on others who take over the initial development costs (Pegels and Altenburg 2020).

Third, many capabilities and assets are generic. Hence, certain capabilities acquired in "brown" industries are still useful even when industries shift towards greener alternatives. These include capabilities related to project management, banking, technology assessment, quality management, marketing, logistics and many others. Table 10.2 exemplifies this for two sectoral transformations, distinguishing

Table 10.2 Enduring, stranded and newly required capabilities: The example of two "brown-to-green" transformations

Technological change	Capabilities			Assets		
	A Enduring	**B Stranding**	**C Newly required**	**A Enduring**	**B Stranding**	**C Newly required**
Coal-fired to solar power plants	Energy system planning, project development, distributed control systems	Capabilities required for coal mining, specific power plant layout	Thin film manufacturing, solar irradiation measurement, smart grid design	Part of grids, back-up power facilities, energy research centers	Power plants, steam turbines, generators	Clean room facilities, converter manufacturing, photovoltaic and solar-thermal power plants
Combustion engine to electric vehicle	Tiered just-in-time supplier systems, automotive R&D, many auto parts, marketing/branding	Manufacturing capabilities for combustion engines, power trains and parts	Lithium batteries, new light materials, thermo management	Manufacturing plants, 80 percent of supply chains	fuel filling stations, engine factories	Lithium-battery factories, electric engine factories, charging infrastructure

Source: author.

between capabilities and assets that remain valuable (enduring), those that are likely to become devalued (stranding) and those that are newly required.

Fourth, the catching-up literature has always insisted in the strategic long-term perspective of leapfrogging ahead (see Lee, 2016 and several chapters in this volume). New opportunities for leapfrogging arise as the green techno-economic paradigm shift devalues some of the competitive assets historically accumulated by early movers. China's competitive success in electric vehicles (after decades of disappointing performance in the manufacturing of conventional vehicles) is a prime example of leapfrogging aided by the green paradigm change (Altenburg et al. 2017); yet, so far such examples are few and far between.

In sum, latecomer countries need to deviate substantially from established development models that have proven to be environmentally unsustainable. Thus, the historical path of catching-up based on borrowing the previous generation of technologies and learning to master them step by step is incompatible with the urgent need to abandon those technologies, especially fossil-fuel technologies. Still, the catching-up literature still holds a number of important lessons with regard to strategic policymaking, and it still makes sense to exploit the opportunities of borrowing foreign know-how if it this is done selectively.

10.6 Policy Lessons: Combining Insights from Catching-Up and Green Transformation Research

What, then, are the implications for policymakers? The following, five important implications are sketched out requiring latecomer countries to realign their policy frameworks for catching up when also pursuing a green transformation.

First, policymakers need to invest in consensus-building about the right transformational strategies. Citizens have very different, and often conflicting, views on the appropriate balance between the pursuit of material prosperity and a life in harmony with nature. Thus, a societal discourse is needed to reconceptualize welfare. At the same time it is uncertain what kind of changes in lifestyle are necessary for staying within a safe operating space for humanity, to what extent these imply personal sacrifices, and how far citizens are willing to take the interest of future generations into account. All this requires societal dialogue accompanied by experimentation and learning. Decisions also need to be taken with regard to which pro-environmental reforms are to be prioritized and which policy instruments are the most efficient to achieve the respective objectives.

In the same vein, firms with a green business model are likely to be in favor of pro-environmental policies, whereas others will see their competitive advantage and profit margins erode with more stringent environmental regulations. In most cases, a green transformation will require some subsidies for firms and workers to adapt and some compensation and grace periods for losers. Such measures are essential to garner political support for green reforms. Taking the introduction of carbon prices as an example, Klenert et al. (2018) provide a detailed discussion of how green policies can be designed to gain public acceptability. They suggest ways to use the revenues collected from carbon pricing in ways that create new constituencies with economic incentives to support the respective policy—for example paying out the revenues as per-capita dividends. In the German environmental tax reform of the 1990s, revenue recycling was used to reduce the nonwage labor cost, thereby saving employers and employees money and creating an incentive for employment creation. Pegels and Altenburg (2020) underline the importance of political legitimation and societal support for the success of any reform as deep as the green transformation, and provide a series of economic arguments in favor of adopting green policies earlier than one's competitors in the global economy.[8]

Second, environmental policies need to be strategically co-designed with industrial and innovation policies. The challenge is to combine the necessary environmental measures with the pursuit of competitive advantages and additional and better employment (Altenburg and Rodrik 2017). Typically, however, both types of policies are designed in institutional silos, driven by separate ministries, each embedded in, and gaining legitimacy from, specific constituencies with diverging interests. Environmental ministries typically call for more stringent regulations, which are opposed by ministries of trade and industry that emphasize the cost of compliance and how they might undermine industrial competitiveness.

Potential trade-offs between environmental and economic objectives need to be assessed carefully. The Porter hypothesis (Porter and van der Linde 1995) suggests that stricter environmental regulations are not just a financial burden on firms; instead, they may trigger innovation that makes production processes and products more efficient. Such efficiency gains may overcompensate the cost of compliance with the new environmental standards and strengthen firms' competitiveness. Pioneers of environmental innovation may reap early-mover advantages if other jurisdictions apply similar regulations with a time lag. The Porter hypothesis has been tested extensively (see e.g., Ambec 2017). Evidence is mixed. Most reviews confirm that stringent regulations encourage innovation, but with regard to competitiveness, both positive and negative effects have been shown, depending on industry characteristics and other specific conditions.

We have argued elsewhere that existing analyses may underestimate the positive effects of more stringent environmental policies on competitiveness (Pegels and Altenburg 2020), mainly because of dynamic knowledge spillovers. Regulations that force utilities to buy renewable energy, for example, may not only trigger innovation in technologies for renewable energy generation, but also induce second-round innovations in subsequent innovations as a market for energy storage technologies, smart grids, and electric vehicles emerges following the decarbonization of the

[8] The respective Special Issue of the journal *World Development* explores the relationship between environmental policies and economic opportunities for latecomer countries (Altenburg and Pegels, eds. 2020).

energy system. This is what a techno-economic paradigm shift is about. Early movers in renewable energy generation may thus reap innovation rents in many related industries, and countries delaying the change may fall back in a whole range of newly emerging industries. Aghion et al. (2016) confirm such path dependency, showing that countries depending on "dirty" industry technologies continue innovating in these industries, whereas early movers in clean technologies diversify their innovations in related industries. Similarly, Mealy and Teytelboym (2018) find that countries with more ambitious environmental regulations export a larger number and more sophisticated green products competitively.

Most likely, only a few countries with deep financial pockets and sophisticated institutions will be able to reap rents from "new-to-the-world" innovations. Two arguments, however, speak in favor of latecomer countries also being able to reap early-mover advantages:

- Many green technologies are new to everyone because they have been under-researched as long as there were no stringent environmental regulations to make them commercially attractive. This applies for smart grids, carbon capture, and storage, and bioenergy from algae or straw, for example. Hence, markets are not yet taken by incumbents and technologies not yet protected by patents.[9]
- Even low-income countries can improve their competitive position relative to others with similar factor endowments. Suppliers to global value chains, for example, can enhance their competitiveness through improved environmental performance;[10] similarly, exporters of agricultural produce can innovate, adapting farming methods to climate change to ensure optimal crop yields (Schleussner et al. 2016). Such measures do not depend on resource-rich innovation systems, and they can sometimes draw on international open-source pools of knowledge, such as the CGIAR network of agricultural research centers for the case of climate-adapted yields.

Third, investments in technology foresight should be stepped up. The green transformation requires technological choices. Following our argument that we are at the beginning of a global green techno-economic paradigm change and natural capital will be priced to a much larger extent, the broad direction of change is not difficult to predict: Power generation will shift to renewables, energy storage technologies need to be developed, end-uses such as transport, heating, and cooling will be based on electricity, more products will have environmental labels, demand for energy-saving materials, second-generation bioenergy and meat substitutes will increase,

[9] Lee (2017) shows this for specializing in sectors with short cycle times; the same arguments hold for technologies that are new to everyone because they depend on rising stringency levels of environmental policy.

[10] For example, using eco-labelling or ISO 14000ff certification as a value-creating vertical differentiation strategy (Ambec 2017).

production will move from linear raw material-to-waste to closed cycles, carbon capture and storage technologies will be needed, and so on.

Within this broad corridor, however, choosing the best technology is far from trivial. Typically, several technological options are available, especially at times of major industrial discontinuities, such as the green techno-economic paradigm shift. Anderson and Tushman (1990) coined the term "era of ferment" to describe a phase of intense technical variation and competition before one technology typically gains the upper hand and becomes the industry standard. Each technical alternative involves up-front costs to be developed. In market economies it is mainly private enterprises that take risks and search for the best-fitting technologies and business models, and competition that weeds out the less efficient ones. Yet, there are market failures[11] driving a wedge between what is sensible for firms and what is socially optimal. Hence, there is a case for public-sector support in terms of subsidizing technologies, skills development, and specific infrastructure. In an era of technical discontinuities and enhanced uncertainty, the public sector in latecomer countries cannot support all potential alternatives and thus needs to select promising options. Technology foresight, in close collaboration with the most competent firms, is therefore crucial to make reasonable bets.

Fourth, governments should also consider opportunities emanating from social innovations. Social innovations are new social practices that aim to meet societal needs in better ways than existing solutions. Such innovations may give rise to new business models without requiring sophisticated technologies, which makes them particularly interesting for latecomers. Considering the need to curb consumption of environmentally harmful products the green transformation requires innovations on the demand side. As an example, sharing arrangements and collaborative consumption initiatives (Hamari et al. 2015; Albinsson and Perera 2012) help to make better use of existing stocks of goods and services and thereby reduce material and energy consumption. Social innovations can take place at different scales. Some operate at small scale and are typically embedded in local communities and often not-for-profit, whereas others are fully commercial and operate at a large scale. Food-sharing networks, repair cafés where skills are shared, and community gardening are examples of the first type. Car, bike, and scooter sharing and sub-letting living space are more often driven by commercial interests and sometimes have large corporations of the platform economy behind them. Open data and the increasing usage of mobile phones and social media allows for formation of new enterprises with relatively low technological entry barriers. Likewise, enterprises with artistic and cultural content may create welfare with a very small material footprint. "Living labs" have emerged as a new way of exploring, practicing, and evaluating social innovations in real-life use cases. Their main purpose is a better understanding of current and future user needs through co-creation of innovative solutions with real users (Leminen et al. 2012) Examples range from letting test persons live in a sustainably constructed

[11] Stemming from the fact that firms cannot appropriate the full benefits of their R&D outlays as well as from environmental externalities.

house to experimenting with mobility options in a city or trying to change whole sub-districts of a city from a more systemic perspective (Voytenko et al. 2016).

Fifth, the global dimension of the green transformation needs to be considered. The earth's shared natural resources can be understood as global commons requiring a new architecture of international governance. The United Nations Framework Convention on Climate Change, the Conventions on Biological Diversity, or the Montreal Protocol on Substances that Deplete the Ozone Layer exemplify the growing role of global environmental governance. Most of these emerging institutions recognize a differential treatment of early industrialized and latecomer countries, as the former have in most cases created more environmental damage than the latter. Based on this principle, an increasing number of institutions are supporting latecomers' access to green technologies and providing financial support. This includes the Clean Development Mechanism, the Technology Mechanism under the United Nations Framework Convention on Climate Change, and the Global Environmental Facility, among others. While the incentives and resources these new institutions provide are clearly not commensurate with the requirements of a global green transformation, they do provide opportunities latecomers can exploit to catch up in environmental technologies.

In sum, catching-up research consistently shows that closing the gap between early industrializers and latecomers is a challenging task. Considerable strategic capabilities are required to move up the technological and income ladder, and not many countries have been able to do so and maintain the momentum over longer periods of time. In a world economy that gradually shifts towards greener technologies and institutions, even more advanced capabilities are needed, because latecomers are likely to run into major environmental problems if they imitate the technologies of a carbon-based industrial era. Strategic capabilities are needed to decide what can be imitated and where it is necessary to explore new pathways. At the same time, the green techno-economic paradigm shift opens up windows of opportunity for some latecomers to leapfrog ahead of established industrial leaders.

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11
Leapfrogging on Steroids
China's Green Growth Strategies

John A. Mathews

11.1 Introduction

World dynamics have witnessed major upheavals in the past two centuries. There was first the Industrial Revolution, in which European powers led by Britain discovered how fossil fuels could displace organic sources of energy with steam and thereby lift previous iron-clad Malthusian limits to growth. This was a momentous breakthrough, ushering in the era of coal, steam, and iron. Then there was the Great Divergence, as erstwhile global leaders like China and India were displaced by the upstart Western powers, from Europe and then the US, powered by the fossil fuels and technological leaps of the Industrial Revolution. This process created the modern world, and enriched around a billion fortunate people in the West—but left the Rest in relative poverty. Now the world is in the grip of a Great Convergence, as China and other giant industrializing powers are starting to catch up, diffusing the benefits of industrialization to the Rest—to the billions who had missed out on the first industrial revolution and had been sidelined by the Great Divergence. This Great Convergence can be expected to be the dominant process of the twenty-first century, as China moves to leapfrog ahead of the current dominant powers, with India expected to be next, and then Brazil, and other large countries in Central Asia, Latin America, and Africa.[1]

These are the three great processes that have created and are creating the world of the twenty-first century, and which define the limits of social scientific scholarship that seeks to understand these processes and their drivers. The process of convergence has been clarified by scholars like Gerschenkron, and Abramovitz, with notions like catch-up and varying rates of convergence/divergence ("forging ahead and falling behind").[2] In the second half of the twentieth century the world witnessed the rise of new industrial nations in East Asia—first Japan, and then Korea, followed by Taiwan and even Singapore. These NIEs from Northeast Asia broke the mold in that they were the first non-Western powers to achieve industrial breakthrough, and

[1] This threefold framework is well attested in the literature. On the Great Divergence, see Pomeranz (2000). On China's catch-up, see "China's Great Convergence and beyond" (Storesletten and Zilibotti (2014).

[2] See the fundamental contributions from Alexander Gerschenkron (1962) and Moses Abramovitz (1986).

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in the process they built a new model of the developmental state which has been the focus of concentrated scholarship and argument ever since.[3] But on one point there has been no argument at all—all the debates over development, convergence, and catch-up have assumed that the original breakthrough with fossil fuels would be continued, and that the first requirement for any country that wished to join the club of industrialized countries would be to secure reliable supplies of fossil fuels. That has certainly been the pattern that fits the case of the twenty-first-century industrializing giants like China and India, and which underpins the debates over industrialization and development.

That was then. Now as giant industrializing countries like China and India claim their place in the sun, and do so at a colossal scale never before attempted, so they run into the unexpected limits of the fossil-fueled pathway to wealth and power. As first mover in this group, China is demonstrating how these limits work. The more coal it burns in factories and power stations, the more oil it burns on roads, the worse the particulate smog created in its cities. And without its own major coal, oil, or gas resources, the more the traditional industrialization pathway enforces dependence on fossil fuel imports—which means dependence on countries that are geopolitical hotspots. As latecomer to the world of oil, China has had to build relations with "new" exporters like Venezuela, Ecuador, Angola, and South Sudan, each of which presents geopolitical complications that threaten China's energy security.

The argument advanced here is that it is *geopolitical limits* that constrain the capacity of late industrializers like China and India to pursue conventional pathways involving fossil fuels for energy and resources plundered in a linear flow. They confront a completely new context where green growth strategies make sense, not so much for moral or ethical reasons (to meet the challenge of fighting climate change) but for reasons of economic survival, to provide energy security and resource security. My purpose in this chapter is to demonstrate the plausibility of this argument, examining both the green shift in countries like China and India, and the evidence that supports their pursuit of this novel trajectory. I agree with Burlamaqui and Kattel (2016) that it is not just catch-up that is the strategy being pursued by these emergent giants, but leapfrogging—and on a scale never before witnessed. The forging of a green economy out of the ashes of the black, fossil-fueled economy, is really a case of "leapfrogging on steroids."[4]

11.2 Development as Leapfrogging: Beyond Catch-Up

Economic and industrial catch-up has been the subject of intense scholarly endeavor ever since Japan achieved the first breakthrough by a non-western country, followed

[3] For a recent exposition of the East Asian success, and the strategies of industrial upgrading employed by developmental states, see Storm and Naastepad (2005).

[4] By this phrase is meant a leapfrogging strategy that incorporates elements of stage-skipping and which is attempted at a greater scale than in previous experiences.

by other East Asian industrial success stories. All these cases have brought attention to the role of state agencies interacting with private firms in facilitating technological learning and the acquisition of dynamic technological capabilities. Technological catch-up has been the focus, with cases like semiconductors, PCs and other ICT sectors, automotive, steel, and petrochemical all being subject to study. Then as the East Asian countries consolidated their position, and thrived in some sectors like flat panel displays (FPDs) and digital switches while trailing in others like automobiles or PCs, the differences between learning as a catch-up process and learning as a leapfrogging strategy came to the fore, with studies in Korea, Taiwan, and Singapore again emphasizing these various strategies and their contingencies.[5]

Now in the twenty-first century it is the turn of newly emerging industrial giants, led by China but also involving India and others eventually like Brazil. These emerging giants look set to take over all the acquired learning and strategies perfected by the prior firms and agencies in the Northeast Asian NIEs, and doing so at enormous scale. Some Chinese firms are already becoming world-dominant competitors in many of the commoditizing sectors.[6] In an important article in *SMR*, Willy Shih discusses how Chinese firms have learnt not only to catch up with market leaders but leapfrog to the lead in one sector after another as they drive commoditization in the ITC industries.[7]

There is an element in the story of catch-up in these emerging industrial giants that makes them *sui generis*, and which demands a revised approach to the question of leapfrog strategy as it comes to be practiced in China, India, and other countries. It is the question of *green growth*, which derives from the issue of *scale*, and its implications for energy needed to drive the emerging manufacturing systems, and the demands for energy security and resource security created by the vast manufacturing systems that are being built.

The earlier industrializers in Europe, the US, and Japan all developed their manufacturing industries at what appeared to be large scale at the time, but in retrospect are really small and medium in scale when compared with what is being accomplished by China (and to some extent) by India. The demands for basic resources and fossil fuels to drive their manufacturing engines were very large by the standards of pre-industrial activities—but never to the scale of running up against real limits

[5] The literature on leapfrogging as a development strategy can be traced to Perez and Soete (1988) and Hikino and Amsden (1994), the latter scholars pointing to the experience of the nineteenth century where leading American and German firms were able not just to catch up with the then leaders but leapfrog ahead of them. In more recent scholarship on the NIEs, Lee and Lim (2001) use the examples of six industries in Korea to discuss successful cases of "stage-skipping" or leapfrogging strategies, particularly in the ICT and CDMA industries. Lee (2013) provides a synoptic account. Early efforts to apply these insights to China can be found in the work of Wu and Zhang (2010) where three case studies of Chinese firms pursuing "stage-skipping" strategies are discussed.

[6] The literature on China's "catch-up and forging ahead" strategies, with a focus on technological leapfrogging (e.g., through development of homegrown standards) is now abundant. For prominent contributions, see Breznitz and Murphree (2013); Ernst (2015); Gao (2014, 2019); Fu and Zhang (2011); Shan and Jolly (2011); Sigurdson (2004); Wu and Zhang (2010).

[7] Shih (2018).

to growth, despite the scare unleashed by the computer simulations of the *Limits to Growth* report published in the 1970s by the Club of Rome.[8] Physical limits to growth have not in fact been encountered by Western industrialized countries—even the limits associated with the notion of "peak oil" as well argued by scholars such as Deffeyes in the 2000s.[9] But geopolitical limits to growth, in the form of increasing political and economic tensions associated with rising levels of extraction of oil, gas and coal, plus iron ores, bauxite, copper and other minerals and rare earths, have very much come to the fore. And nowhere is this in clearer focus than in China, which would be facing crippling geopolitical tensions if it were to continue with a "business as usual" industrial trajectory—one based on fossil fuels for energy and linear extraction models (= global plundering) for resources.[10]

To state the argument in its clearest terms: at the scale at which they are industrializing, China and to some extent India would have to tilt global geopolitics in order to ensure their supplies of fossil fuels and resources. They would not be able to rely on supplies from contested parts of the world in the way that earlier industrializers were able to enjoy. It is in this sense that we may say that the giant industrializers of the twenty-first century are *sui generis*—and call for fresh strategies to cope with the geopolitical limits they are encountering insofar as they continue to follow fossil-fueled strategies.

Consider China's rising oil imports, which because of its latecomer status need to be sourced from "new" suppliers like South Sudan and Angola. No sooner did China become a major importer of oil from South Sudan than a civil war broke out in that country—severely disrupting China's oil supplies. This is an example of a geopolitical limit—a civil war or revolution breaks out and disrupts supplies. Or there is a geoeconomic limit when prices rise rapidly—as oil prices threaten to do at any stage, particularly as oil suppliers seek to drill at deeper and deeper sea levels and thus encounter rising levels of risk and cost, which are reflected in wild swings in the price of oil (or gas) supplied.

There is a way around such geopolitical and geoeconomic limits to fossil fuel supplies for an industrializing giant like China. It involves a strategy switch to rely more and more on domestic energy supplies—and the best means of ensuring that supplies remain domestic in origin is to manufacture them, under domestic government control. Now it happens that all renewable sources of energy—particularly those from water, wind, and sun—are based on manufacturing. Consider hydro-turbines, wind turbines and solar PV cells as devices needed to generate electric power from water, wind, and sun—all renewable. Likewise in the case of batteries for energy storage. China since the early twenty-first century has made it one of its top strategic priorities to become a domestic champion in building these manufacturing

[8] See the *Limits to Growth* report (Meadows et al. 1972).

[9] Deffeyes (2005).

[10] As the OECD puts it in its latest *Perspectives on Global Development 2019*, this does indeed call for "rethinking development strategies" (OECD 2019). Kim and Thurbon (2015) suggest how this is being done in Northeast Asia generally through greening of development strategies, in their concept of 'developmental environmentalism'.

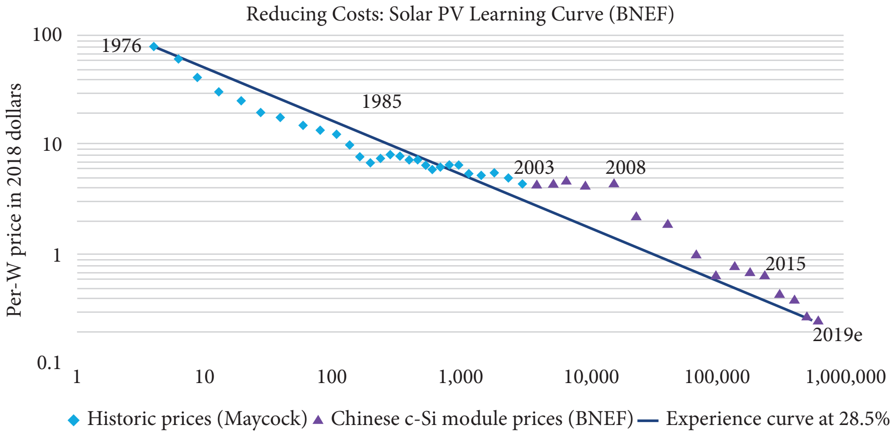

Figure 11.1 Falling costs for key manufactured energy systems
Source: BNEF.

industries—in an entirely pragmatic way to use these industries as the bases for export industries as well as domestic supply.[11] China has to import oil—but it can export hydro- and wind-turbines, solar PV cells, and batteries. Thus, a source of energy insecurity can be turned to a thriving export industry and reliable source of energy devices based on renewable sources—at steadily reducing costs. For it is a fact that all manufacturing operations are associated with learning (or experience) curves, which generate steadily reducing costs. Consider Figure 11.1, which displays falling costs for solar PV cells (where costs fall by 24.3 percent for every doubling of production) and lithium-ion batteries (where costs fall by 21.6 percent for every doubling of production).[12]

It hardly needs to be pointed out that traditional supplies of fossil fuels do not enjoy such diminishing costs—even when utilizing advanced technology, as in hydraulic fracture, or in deep-water offshore drilling. These cases are characterized by what economists call diminishing returns, typified by rising costs. The manufacture of energy via reliance on renewables, by contrast, operates with increasing returns, characterized by falling costs.

A similar story can be told in the case of resources, or commodities, needed in manufacturing operations. For IT products, for example, there is a growing demand in China for printed circuit boards (PCBs) that are the core of electronic devices such as cell phones, laptop computers and their components like displays. The key resource needed for such PCBs is copper—which is traditionally sourced from geopolitically sensitive areas like central Africa, where civil wars have ravaged countries like the Democratic Republic of the Congo. Instead of relying for supplies on such

[11] China has been using its renewable energy industries as a vehicle of technological catch-up and upgrading, in the patterns described by Lee (2013) or Lacasa et al. (2019).
[12] See Kavlak et al. (2018) for a recent study of the causes of cost reduction in PV modules, disaggregating the technological effects from market expansion effects.

geopolitical hotspots, with all their implications for resource insecurity, China is instead pursuing a quite different strategy of "urban mining" which is based on recycling of electronic products to extract their valuable components and subjecting them to chemical treatment to produce new supplies.

Urban mining in China is an example of the circular economy in action, using e-waste as "raw material," as an alternative to the familiar linear economy that extracts materials from nature at one end and dumps wastes back into nature at the other end. Hao Tan and I used the case of the Suzhou Industrial park in China in our article in *Nature* ("Circular Economy: Lessons from China") where we cited advantages derived by Chinese IT producers based in Suzhou who were no longer dependent on imports of virgin copper from geopolitical hotspots like the DRC in Africa and instead could rely on domestic manufacturing based producers of copper, utilizing urban mining. With my Chinese colleagues Prof. Jinhui Li and Dr Xianlai Zeng I demonstrated that copper produced in China from urban mining was lower in cost than copper produced by traditional mining, as shown in Figure 11.2. This is a turning point which promises a path to resources security for China.[13]

In this way China has discovered strategies for dealing with energy insecurity and resource insecurity, in the form of Green Growth strategies.[14] At the *scale of industrialization* being attempted by China, in fact, there is really no alternative than to switch to an energy trajectory based on renewables, and a resource trajectory based

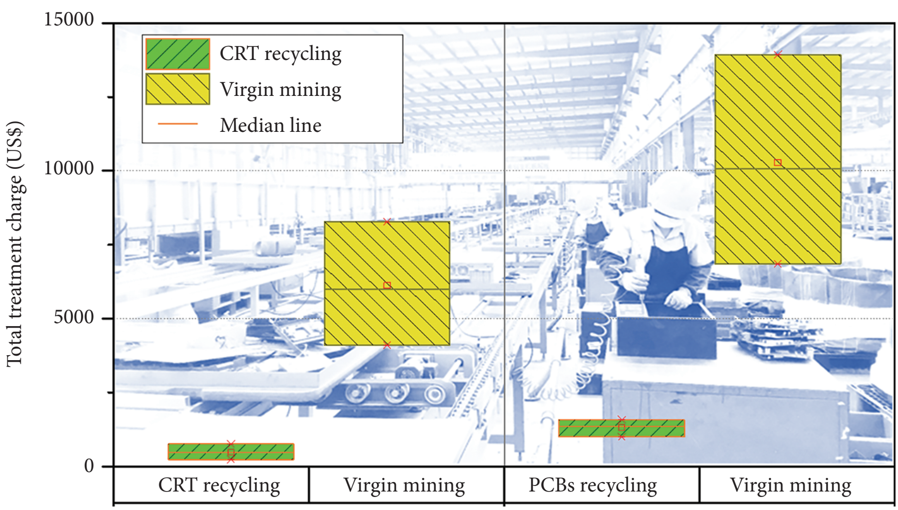

Figure 11.2 China: costs of copper from virgin mining vs recycling from discarded CRTs
Source: Zeng, Mathews, and Li, *Environmental Science and Technology.*

[13] Figure 11.2 shows that recycling of TV sets (Cathode Ray Tube (CRT) recycling) and Printed Circuit Boards (PCBs) recycling both incurred costs lower than those found in virgin mining of the elements involved (such as copper).

[14] For elaboration on this point, see my chapters on green growth and China, at Mathews (2019a, 2019b, and 2019c).

on urban mining (circular economy), because both kinds of strategies are based on manufacturing with associated cost reduction due to the learning curve. This situation needs to be contrasted with the ever-rising or fluctuating prices associated with virgin drilling (for oil or gas) and mining (for copper and other valuable metals). It is the scale of industrialization in China that drives the choices being made—but it is certainly a convenient truth that by opting for renewables over fossil fuels, and for recycled resources over virgin mined resources, China is also reducing carbon emissions and resource throughput. This is the power of the green growth strategy being pursued by China.

Effectively this strategy calls for newly industrializing countries like China and India to leapfrog to new industrial activities, deploying new technologies, and scaling them in advance of firms in the developed world. Outstanding examples include electric power grid modernization in China, where the transmission and distribution system has been scaled up through utilization of Ultra High Voltage (UHV) technology (as discussed below), in advance of grid modernization in advanced countries. Or take the case of Permanent Magnet Direct Drive (PMDD) technology in wind turbines, where Goldwind in China has taken an innovation developed in Europe and scaled it up in advance of any wind turbine producer.

China has now been pursuing this strategy since early in the twenty-first century. The more it swings to renewable energies, and to recycled materials, with their falling costs, the more it drives down costs of renewables and recycled materials worldwide, making it more likely that other industrializing countries will follow China's lead. Thus the swing towards green energy and green resources strategies promises to be a circular and cumulative process, that gathers strength as it unfolds. This is a powerful reason for expecting the process to continue, until industrializing countries throughout the world are swinging towards the green economy. There are grounds for optimism here.

We must consider, however briefly, the evidence that China is actually greening its energy system—in the face of all the evidence usually advanced that China is the biggest burner of coal on the planet and the biggest contributor to carbon emissions.[15]

11.3 Is China Greening its Energy System Faster than Expanding its Black (Coal-Fired) System?

Whereas previous studies of China's use of fossil fuels examined specific sectors such as electric power or transport, Huang and I (2018) looked at changes in China's consumption of fossil fuels encompassing the entire economy—including power generation, industrial use (e.g., in steel or cement production), transport, and domestic

[15] For my earlier contributions to these questions, going back over the past decade, see Mathews (2011, 2012, 2013, 2015, 2016, 2017a, 2017b, 2018, 2019a, 2019b, 2019c, 2020a, 2020b), as well as joint contributions including Mathews, Hu, and Tan (2018); Mathews and Huang (2018); Mathews and Reinert (2014); Mathews and Tan (2014, 2015, 2016) and Zeng, Mathews, and Li (2018).

use. We constructed a picture of China's entire fossil fuel usage and then plotted the changes in use for each year, from 2001 to 2017. One way of doing this is to use a common measure of fossil fuels in terms of coal-equivalent, or alternatively in terms of oil-equivalent. But we performed the calculations using as measure electric power generation equivalent, or terawatt-hours (TWh). This enabled us to compare the changes in fossil-fuel usage each year with the electric power generated from green sources—water, wind, and sun—for the same year. Up until 2011 the increase in fossil fuel consumption each year exceeded the level of green electric power generated (with the exception of the year 2008, under the impact of the global financial crisis), meaning that China's black energy system was getting blacker. But our data revealed that in each year for the past six years, from 2012 to 2017, the green power generated in China each year exceeded the change in fossil fuel consumption for that year. This means that, in a precise sense, China's greening has in the past six years outpaced its blackening—whereby greening we refer to generation of green electric power (from WWS sources) and by blackening we refer to increases in fossil fuel consumption across the entire economy. This is a greening trend that can only be interpreted as continuing—and leading within a very few years to an energy economy that would be greener than blacker. These results are demonstrated in Fig. 11.3.

What Figure 11.3 demonstrates is that China's green power generation is relentlessly rising, doubling every six years or so, and increasing exponentially at an average rate of 20 percent per year. Up until 2011 the yearly increase in fossil fuel burning exceeded the green power generation each year, fluctuating according to global economic conditions, with a steep dip in 2009 following the global financial crisis. But green power generation each year after 2012 has consistently exceeded the yearly increase in fossil fuel consumption. The point to make here is that this is a definitive demonstration that encompasses the entire Chinese energy system which has until recently been totally dominated by the burning of fossil fuels.

This green shift in China encompasses leapfrogging strategies pursued at the level of technologies and industries. It is not just a technology that China is adopting via a stage-skipping strategy that is conventionally known as leapfrogging. It is not just a technology but an industry and in some cases an entire industrial complex that is being invented and promoted.[16] Insofar as China is moving beyond already established industries and technology in its pursuit of green economy initiatives, it is pursuing what can only be described as a strategy of "leapfrogging on steroids." Two cases must suffice to illustrate the trend—China's grid-upgrading with UHV technology, and the rapid introduction of high-speed rail (HSR) inter-city transport.

[16] As Burlamaqui and Kattel (2016) put it provocatively: "[D]evelopment strategies should not be visions and plans regarding how to catch up with regional and/or global benchmark countries, but rather should focus on how to surpass them" (2016: 271). They build on Amsden and Hikino (1994) in making the idea of leapfrogging central to their analysis of development: "Leapfrogging is an intrinsic feature of success in Schumpeterian competition. It happened with American and German enterprises in the nineteen century, but also with Toyota, Fanuc, Nokia and Acer in the twentieth and is happening with Google, Apple, Samsung and Huawei in the twenty-first" (1994: 272).

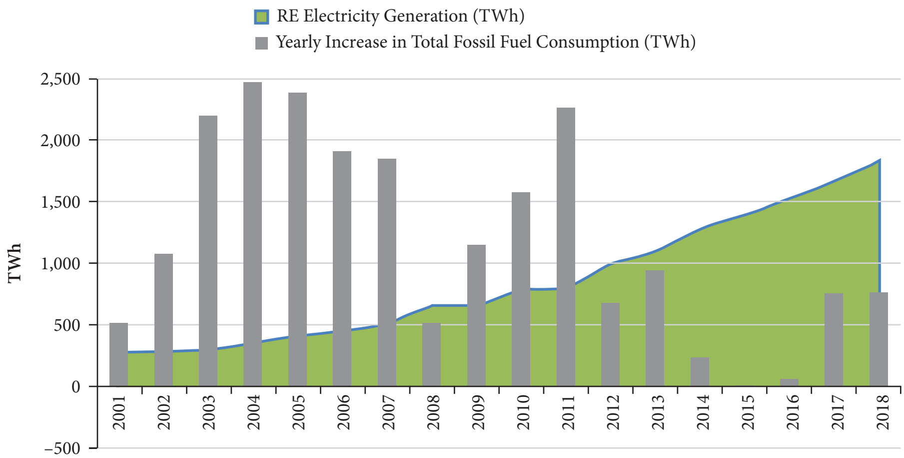

Figure 11.3 China's change in fossil fuel consumption each year vs WWS electricity generation in the same year, 2001–19
Source: Author.

11.4 Leapfrogging Cases in China

11.4.1 Ultra High Voltage (UHV) Power Grid

China has come from behind in the development of a twenty-first-century power grid, but in the past decade it has leapfrogged to the world lead in installing the next level of Ultra High Voltage (UHV) grid infrastructure, both UHVAC and particularly UHVDC. These two Transmission and Distribution (T&D) technologies, which can be utilized for carrying vast supplies of electric power over very long distances, enable the Chinese grid to run on steadily increasing levels of renewable power. The major strategic goal in building the UHV power grid was to leapfrog beyond transporting coal thousands of km from the coast to inland power stations, and transporting the power instead from inland solar and wind farms to coastal industrial regions.

China's UHV grid technology has been developed and implemented through the state entrepreneurial drive of the State Grid Corporation of China, under the leadership of *Liu Zhenya*, CEO from 2004 to 2016. The State Grid Corporation of China (SGCC) is now the world's largest grid operator (and second largest company in the world, after Walmart).[17] As a state entrepreneur it has invested more than $1 trillion in the UHV grid, and in the process has surged beyond even advanced regions in the US, EU, and Japan, in building home-grown equipment value chains. China has thus leapfrogged to world leadership in installing Ultra High Voltage (UHV) grid

[17] See the book-length study of the state entrepreneurial strategies pursued by SGCC in UHV, *Sinews of Power* (Xu 2017).

technology. While the technology was first utilized by Swiss-Swedish power company ABB and German giant Siemens, it is China that has adopted and adapted the technology and now built a twenty-first century grid with its own indigenous technology.

State Grid switched on its first UHVAC power line in 2009 (operating at million-plus volts) and its first 800 kV DC line in 2010. By the end of 2017 no fewer than 21 UHV power lines had been completed, with four further lines under construction. Even with a slow-down in construction (needed partly to allow transformer and equipment manufacture to keep up) this still places China and State grid well in advance of other countries and companies in operating UHV transmission systems.[18]

In January 2019 State Grid announced completion of the world's largest UHV-DC power line across China, stretching 3,293 km from Changji to Guquan (from Gansu province in the northeast, through Ningxia, Shaanxi, and Henan provinces to terminate in Anhui province in the city of Xuancheng). The RMB 40.7 billion (US$5.9 billion) project was approved in December 2015 and construction started immediately, with the line coming into service in January 2019. The new line can transmit power at 12 GW (equivalent to 24 large 500 MW power stations), and operates at a voltage of 1.1 million volts (1,100 kV). It can shift 66 billion kWh (66 TWh) of electricity from the remote northwest to China's eastern seaboard each year, reducing coal use by 30.24 million tonnes. This new line, which was opened for full commercial operation in 2018, is sending 50 percent more power 1000 km further than any line built.[19] The scale of the UHV grid plan embarked on by China is shown in Figure 11.4.

This nation-building effort by China promises to give the country pole position in setting standards for UHV grids over the course of the next several decades—as outlined by former SGCC chair and president, Liu Zhenya, in an address to the Harvard Law Society in April 2018.

11.4.2 High-Speed Rail (HSR) Inter-City Transport System

A counterpoint to China's development of a national integrated high-capacity electric power grid is its parallel development of a national high-speed rail grid, providing a twenty-first century inter-city transport system. From a situation where there were almost zero tracks in 2000 China had created the largest system in the world within a decade, utilizing a combination of leapfrogging and indigenous innovation.

[18] The slowdowns are documented in the article by Edmund Downie, "Sparks Fly over Ultra-High Voltage Power Lines," *China Dialogue*, 1 February 2018, at: https://chinadialogue.net/article/show/single/en/10376-Sparks-fly-over-ultra-high-voltage-power-lines/, accessed 23 January 2021.

[19] Temple *MIT Review*, 8 November 2018: https://www.technologyreview.com/s/612390/chinas-giant-transmission-grid-could-be-the-key-to-cutting-climate-emissions/, accessed 23 January 2021; See also *Bloomberg News*, 2 January 2019, "World's Biggest Ultra-High Voltage Line Powers up across China," at https://www.bloomberg.com/news/articles/2019-01-02/world-s-biggest-ultra-high-voltage-line-powers-up-across-china/, accessed 23 January 2021.

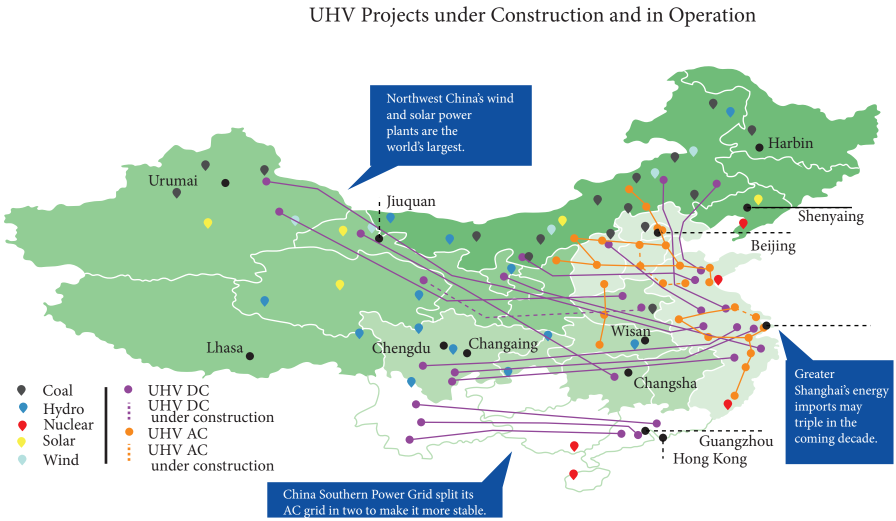

Figure 11.4 China's UHV transmission grid
Source: Author (adapted from IEEE).

China now operates more than 25,000 km of HSR tracks.[20] The country has emerged as acknowledged world leader in building high-speed rail, and it is now actively internationalizing this aspect of its infrastructure development.[21] And as in the case of grid modernization with UHV, driven by State Grid Corporation, so there is now a single, very large state-owned corporation driving the HSR process, in the form of CRRC, formed in 2015 from the merger of previous rail and rolling stock giants CNR and CSR.

China had been ramping up the speed and capacity of its inter-city rail network through the 1990s and 2000s, but it was not until the *Mid- to Long-Term Railway Development Plan* (MLT:RDP) was approved by the State Council in 2004 that a separate fast rail grid was envisaged, with new lines and tracks not shared with freight rail.[22] By the end of 2014, China had built 16,000 km of high-speed rail, which forms the largest HSR network in the world. The network is underpinned by "4 vertical + 4 horizontal lines" as its main frame. Details of the main HSR lines are outlined in Figure 11.5.

[20] See the recent review in the *Financial Times*, "China's high speed rail and fears of fast track to debt," by Tom Mitchell and Xinning Liu, 14 August 2018, https://www.ft.com/content/ca28f58a-955d-11e8-b747-fb1e803ee64e/, accessed 24 January 2021.

[21] A book-length account of China's HSR program, with an emphasis on leapfrogging strategy, is provided by Chen and Haynes (2015), with an update emphasizing the technology transfer activities (adoption, assimilation, adaptation) provided in Chen and Hayes (2016). Zhe Sun (2015) provides an account of the HSR program as an instance of state entrepreneurship in China. The account provided here draws on Mathews and Tan (2015), Section 4.3.

[22] The enormous appetite for coal created by the surge in energy production in the early 2000s contributed to this shift to high-speed passenger dedicated lines, to free up the existing rail system for freight transport, largely of coal but also of steel and other raw materials.

Figure 11.5 China's high-speed rail infrastructure plans
Source: Author (adapted from Bloomberg).

Total investment envisaged for completion of the Plan by 2020 is RMB 2 trillion (US$ 240 billion), or an average of $24 billion per year from 2010 to 2020. These impressive sums were exceeded by spending in 2008 and 2009, under the influence of the Stimulus Package, when investment rose to $49.4 billion in 2008 and $88 billion in 2009.

The China HSR upgrading package embodies a characteristic latecomer strategy for technology leverage. China's HS trainsets (locomotives plus rolling stock) draw on existing technologies, including: China Rail H1—based on Canadian Bombardier *Regina;* CRH2—based on Japanese E Series 1000 Shinkansen; CRH3—based on German Siemens *Velaro;* and CRH5—based on Alstom *Pendolino* ETR600. Furthermore, the HSR tracks have been laid along dedicated lines, separated from existing tracks with their curvatures, bends, gradients, and traffic, on a concrete bed designed by a German engineering firm but implemented in China on a scale far larger than anywhere else. This is another example of the latecomer strategy deriving advantages from not having to cope with technological inertia from earlier systems.

Now that China has emerged, within just a single decade, as the largest builder and operator of HSR systems in the world, it has been looking to export its production technology as a major export business. For example, Turkey's first HSR line, operating over the 530 km between Istanbul and Ankara, represents China's first major export of its HSR technology. By 2014 Chinese railway transportation equipment companies had exported to over thirty countries, and achieved international sales with a total value of US$ 4.4 billion in 2014 alone.[23] Now these efforts

[23] See reports in *China Daily*, such as: http://www.chinadaily.com.cn/business/2015-02/05/content_19495862_3.htm/, accessed 24 January 2021.

constitute a principal platform in China's Belt and Road Initiative, the internationalization strategy adopted by the highest levels of China's leadership.

Thus the high-speed rail project as a whole is distinctively Chinese, like its counterpart in the grid modernization program. It draws from existing technology models (doubtless with China avoiding IPR disputes through holding out the promise of gaining contracts for building trains as part of China's high-speed rail plans). It is useful to note that the China State Council decided to go ahead with conventional technology for high-speed rail in 2006, after discussing the possibility of leapfrogging with German MagLev technology—but abandoned this option when German companies refused to transfer technology nor to enter a JV with a Chinese company. The sole MagLev line in China remains the highly prominent line that takes passengers from the new Shanghai-Pudong airport to the Shanghai city center.

11.5 Greening as Leapfrogging on Steroids: Concluding Remarks

Let me summarize the argument advanced in this chapter, moving through five points.

1. There is a worldwide greening under way, as countries and industries shift from traditional dependence on fossil fuels and linear resource paths to renewable energies and circular resource paths as preferred alternatives. There is abundant evidence that this is a process well underway in China, and diffusing worldwide.[24] Contrary to the usual view that drives Western commentary, and proceedings at UN conferences, it is not so much concern over climate change that is the key or principal driver, as the quest to overcome geopolitical limits to growth. Yes, climate change is real and of massive concern—but countries like China that are in the midst of a major industrialization push (Great Convergence) are faced with immediate issues of environmental spoliation and rising levels of insecurity in their resources and fossil fuels consumption. China, in particular, is running up against the geopolitical limits to growth—and it is forced to find an alternative pathway to prosperity.

2. What drives the dynamics of this global green shift is not so much the moral and ethical choices that firms, governments, and entrepreneurs need to make but the technoeconomic dynamics of cost reductions and the capture of increasing returns in new, green industries. These green industries (such as renewables replacing fossil fuels or circulating resources replacing linear industrial processes) enable countries to evade the geopolitical limits that confront those who maintain a fossil fueled "business as usual" pathway. The greening processes are propagating largely through price reductions based on cost reductions that are in turn based on the fact that the

[24] Mainstream reports are now starting to appear in support of this assertion; see for example Amy Myers Jaffe in *Foreign Affairs* (Jaffe 2018). On the global trends, see for example the UN/BNEF report "Global trends in renewable energy investment 2018" at https://www.greengrowthknowledge.org/resource/global-trends-renewable-energy-investment-report-2018/, accessed 24 January 2021.

green economy is driven by manufacturing activities coordinated through state entrepreneurial initiative. And manufacturing activities have accompanying learning curves that drive down costs. Again it is emerging industrial giants which are capable of building new manufacturing industries rapidly that are in the lead in this transition.

3. Contrary to the view that expects transitions to new technologies and new organizational forms to originate in the advanced world, in the case of the green transition it is industrializing countries that are leapfrogging to the lead.[25] They have less inertia from the fossil fuel past—or less carbon lock-in than in advanced countries. Examples include China with its UHV power grid or high-speed rail (HSR) inter-city transport system; or China with gearless wind turbines, suitable for offshore operation; or China with new Electric Vehicle (EV) charging networks. These are cases where the emerging technology is developed in advanced laboratories but scaled up by firms in the industrializing world, as the firms leapfrog to the lead guided by judicious state entrepreneurial initiatives.

4. There is a Schumpeterian body of scholarship on the supersession of one technoeconomic regime by another. The current greening of the planet adds potentially another important episode to this body of scholarship.[26] But the fact that it is driven by business dynamics, and originates largely from giant industrializing countries—precisely the countries facing geopolitical limits as they industrialize—that lends distinctive characteristics to this current transition. Echoing Gerschenkron, we can expect this transition to provide a greater role for the state, in the form of state agencies and state-owned firms, working in conjunction with their private-sector counterparts.[27]

5. Given that all these features of the current greening are grounded in economic and technological dynamics that are all well understood in terms of entrepreneurial state initiatives (as Schumpeterian dynamics) we can expect these greening processes to continue, and propagate. Indeed they could become the dominant tendencies of the twenty-first century. Consistent with the Schumpeterian tradition, we should not expect this transition to be entirely market-driven (as assumed in proposals involving carbon taxes or cap and trade schemes involving emissions allowances) but instead we should expect state agencies and SOEs to play a significant role in guiding and shaping the transition. It is states that can stand up to the power of fossil fuel incumbents and drive through changes to economies'

[25] See studies of the process of technological upgrading of industrializing countries. Lacasa et al. (2019) find, for example, that the BRICS countries are pursuing different pathways, with the evidence of patenting indicating that China is on the point of joining the advanced group of countries in terms of both frontier innovations and in terms of "behind the frontier" innovation.

[26] See, for example, the recent work of Carlota Perez (2019), whose work with Soete helped to clarify earlier leapfrogging experiences (Perez and Soete 1988).

[27] For contributions in this spirit, see for example Ebner (2009) on a Schumpeterian analysis of the entrepreneurial state, and Pegels et al. (2018) for the role of the state in fostering greening activities. Burlamaqui and Kattel (2019) gather several contributions in the spirit that combines entrepreneurial and finance perspectives in a Schumpeterian setting.

operating conditions, through creative destruction. The argument of this chapter is that national strategies to enhance resource security and energy security, as driven by states and SOEs, will in fact provide the needed entrepreneurial impetus for the changes that are needed. The Great Convergence that China is leading may yet turn out to be the unexpected setting in which global greening and the green growth economic strategies that drive it are helping to shape the world of the twenty-first century.

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12
Innovation for Inclusive Structural Change

Tommaso Ciarli, Maria Savona, and Jodie Thorpe

12.1 Introduction

There has been a rising interest in understanding how innovation can be steered to ensure more inclusion, condensed in the recent heightened regard to *inclusive innovation policies*, particularly within the context of the Sustainable Development Goals (SDGs) (Akhtar et al. 2018; Kaplinsky 2018).[1]

The creation or adoption of new goods, services, and processes can be *destructive*, in the Schumpeterian tradition (Schumpeter 1934). The outcomes of innovation entail the creation of new activities, the obsolescence of existing ones, and the need for new skills, leaving others to become redundant. New winners and losers are visible, as some segments of society benefit from their needs being satisfied, while others remain excluded. Also, when innovation is cumulative (Schumpeter 1942), it may increase concentration at the expenses of smaller players (Autor et al. 2017), and often has consequences in terms of unequal income distribution (Aghion et al. 2015; Lee 2011). Depending on who gains and who loses, innovation may therefore have inclusive or exclusionary outcomes.

At the same time, innovation may lead to more or less structural change at the national level, typically by increasing productivity across sectors, or increasing the share of employment in highly productive sectors. Structural change, in its own right, may also be exclusionary if, for instance, large parts of the population do not have the skills to be employed in highly productive sectors, and remain un- or under-employed. If structural change and inclusion tend to be negatively associated in the short term, we might observe either innovation pathways of higher inclusion but lower structural change, or of more disruptive change that results in exclusionary outcomes.

The identification of the conditions under which innovation leads to both structural change and inclusion that reinforce each other in a virtuous circle of inclusive

[1] See, for instance, the UK Research Council's Global Challenges Research Fund (https://www.ukri.org/our-work/collaborating-internationally/global-challenges-research-fund/) and work by the OECD (OECD 2015; Paunov 2013; Planes-Satorra and Paunov 2017) among others.

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structural change (ISC), in the short and the long run, is of high relevance for analysis and policy. Currently, an analytical framework to unpack these conditions is not as developed as it could be, as the different bodies of literature on inclusion, innovation, and structural change have never been suitably bridged.

Our aim here is to propose the foundations of such analytical framework, that unpacks the theoretical blocks behind innovation, structural change, and inclusion, and supports testable hypotheses to understand *how innovation leads to inclusive or exclusionary structural change in low- and medium-income countries*.[2]

The framework has two main objectives: first, we provide a conceptual model to illustrate how the dynamics of innovation (INN), structural change (SC), and inclusion (INC) are interrelated, and identify regularities behind pathways that combine different innovation, structural change, and inclusion outcomes; second, we propose a research agenda to test the conditions leading to inclusive structural change. This agenda should better nourish industrial and development policy at large.

We first briefly map how innovation affects inclusion and structural change (Section 12.2). We then fully articulate the analytical framework and discuss possible pathways of innovation that might lead to different degrees of inclusive structural change. Here we unpack the potential virtuous or vicious dynamics between innovation (INN), structural change (SC), and inclusion (INC) based on the interactions between actors, processes, and outcomes (Section 12.3). Third, we sketch how the framework supports the narrowing of some key gaps in the literature (Section 12.4), and how to incorporate policy lessons from the existing literature to highlight what would be needed to tackle various trade-offs and challenges (Section 12.5). We argue the case for policies to be framed under an overarching concern to achieve *inclusive structural change*. In Section 12.6 we summarize the key themes of this complex topic, and propose a research agenda to direct innovation toward inclusive structural change. Our contribution aims to respond to the recently increasing demand coming from international institutions, inter-departmental research funds, NGOs, and national ministries, for better knowledge to shape a more effective innovation policy for inclusive development, to meet the Sustainable Development Goals (SDGs) in LMICs.

12. 2 Innovation, Structural Changes and Inclusion: A First Glance

Innovation induces structural change in economies and societies, and plays an important role in (economic) development (Cimoli and Dosi 1995; Cimoli and

[2] The framework builds upon the large literature on the *determinants of innovation*. Therefore, our focus is not on *how innovation occurs*, but rather on *the aftermath of innovation*.

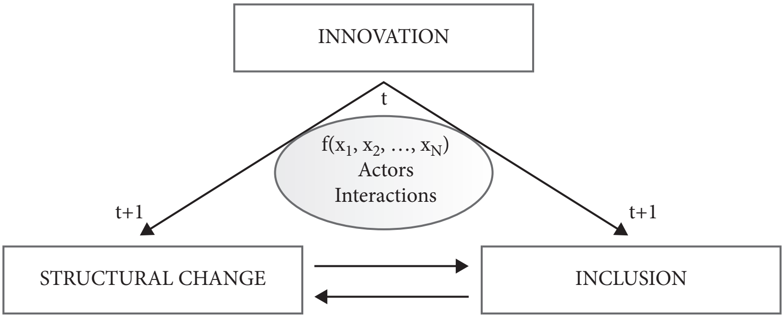


Figure 12.1 The main variables and relationships
Source: Authors.

Porcile 2009; 2011; Hidalgo et al. 2007; Syrquin 1988; Verspagen 2004). As illustrated in Figure 12.1, both innovation and structural change might have inclusive or exclusionary outcomes. On the one hand, economic growth and structural change tend to reduce poverty (Ravallion and Chen 2003), but the extent to which they do so depends on how income gains are distributed (Bourguignon 2003). On the other hand, innovation might increase productivity and growth, but is often disruptive (Schumpeter 1934), and may have distributional consequences (Aghion et al. 2019; Lee 2011; OECD 2015).

The extent to which innovation leads to more or less structural change and inclusion depends on several conditions (some of which can be measured), and the actors that enact and diffuse innovations, and how these actors interact. In Figure 12.1 the x_i represent the *conditions*. These are capabilities, characteristics of the technology such as capital intensity and scale, sectors, final demand, geographical characteristics, and institutions. Beyond these conditions, the *actors* that are responsible for carrying out, transfering and adopting different forms of innovation, and the way in which they interact, may also significantly influence the impact of innovation on structural change and inclusion. Actors do so not in a vacuum, but within a context affected by the *conditions* above (x_N).

The literature envisages one of the two outcomes of innovation, as we discuss below: higher inclusion at the cost of lower structural change and potential for economic growth, or more disruptive changes that result in exclusionary outcomes. What are the conditions, actors, and interactions under which innovation leads to both structural change and inclusion, and these reinforce each other in a virtuous circle? For instance, by including more actors in the innovation process (Aghion et al. 2017; Bell et al. 2016), through greater access to technological capabilities, a country's opportunities to innovate may increase.

We still have a limited understanding of which technological (and non-technological) innovations, lead to learning, technological upgrading, and to structural change (Cirera and Maloney 2017). Also, the concept of inclusive innovation is still loose and the understanding of how it can be achieved is limited (Chataway et al. 2014; Cozzens and Sutz 2014). There is limited evidence on which actors are included or excluded from innovation and development, and even less is known about the reverse dynamics, that is how inclusion and inequality influence successive phases of innovation and structural change.

The literature behind the blocks in Figure 12.1 has rarely been bridged to feed an integrated framework. However, this is necessary to identify the conditions x_n that are relevant to explaining the effect of innovation on inclusion, structural change, and both (inclusive structural change), and to disentangle their effects on observable virtuous or vicious outcomes (the arrows in either direction). This chapter is a first step toward synthesizing the literature under a unifying framework.

12.3 Inclusive Structural Change: The Analytical Framework

We develop an analytical framework to understand how a number of conditions, actors, and interactions affect: (i) the diffusion of a given innovation in the economy; (ii) outcomes measuring structural change and inclusion; and (iii) their trade-off. The different outcomes are the results of different dynamic pathways. We envisage pathways that might lead mainly to exclusionary structural changes, mainly to inclusive outcomes yet with little structural change, or to inclusive structural change. We first define these elements before summarizing the relation between innovation, structural change, and inclusion as devised in our framework.

12.3.1 Building Blocks: Definitions and System Dynamics

Innovation is defined as:

> a new or improved product or process (or combination thereof) that differs significantly from the unit's previous products or processes and that has been made available to potential users (product) or brought into use by the unit (process) (OECD/Eurostat 2018, p. 20).[3]

The innovation can be new to the world, the market, or the producer. In our framework we do not assume that an innovation needs to be new to the world (highly radical), but to the local market and users (low degree of radicality or incremental). For simplicity, we *initially*[4] assume that innovation occurs exogenously

[3] A major definitional difference introduced in the latest version of the *Oslo Manual* is that innovation might occur in units other than business firms, including households or informal activities. This amendment *might* affect measurement of innovation most especially in LMICs, although we do not enter into this in more depth here. We do, however, include this in the research agenda on measurement.

[4] We relax this assumption when we look at the dynamic version of the framework.

(e.g. through technology transfer). How innovation diffuses and generates structural change and/or inclusion depends on a number of conditions, actors and interactions, as shown Figure 12.1.

Conditions characterize how the innovation is absorbed into an economy (e.g., sources, channels, characteristics of the adopters, technology), and its adoption and diffusion (e.g., demand, geography, and capital intensity). The *actors* are individuals and organizations that are involved in any stage of the innovation process or in its diffusion/adoption. The *interactions* are the relations among the different actors, and may be market-related, social, and/or political.

We describe the flow from innovation to diffusion and then to its outcomes in terms of structural change and inclusion as *pathways*, using the concept of pathways as defined by Leach et al. (2007, p. 18), that is as "the particular directions in which interacting social, technological and environmental systems co-evolve over time." Such a definition also embeds the circularity discussed below—changes in the outcomes (structural change and inclusion) at time t influence innovation at time $t+1$. For the sake of readability, henceforth we refer to innovation as INN.

We define *structural change* as a shift of production toward assets based on higher knowledge and skilled labor, of organization toward more efficient structures, of exports toward knowledge-intensive goods and services with high elasticities of demand, and of consumption toward more *luxury* goods and services. These first order processes are accompanied by a number of outputs and outcomes. At the organization level these outputs and outcomes may include increased technological capabilities and technological upgrading; upgrading in Global Value Chains (GVCs); and increases in the organization's average size and productivity, associated with more complex division of labor, and new occupational tasks and categories. At the meso level, technology is internalized, necessity entrepreneurship is replaced by opportunity entrepreneurship, informality reduces as a result of entrepreneurial opportunities, and activities agglomerate spatially. Institutions also evolve, become more complex, establish regulations on the labor markets, the environment, and technology (e.g., IPR), and the innovation system evolves. For readability, henceforth we refer to structural change as SC.

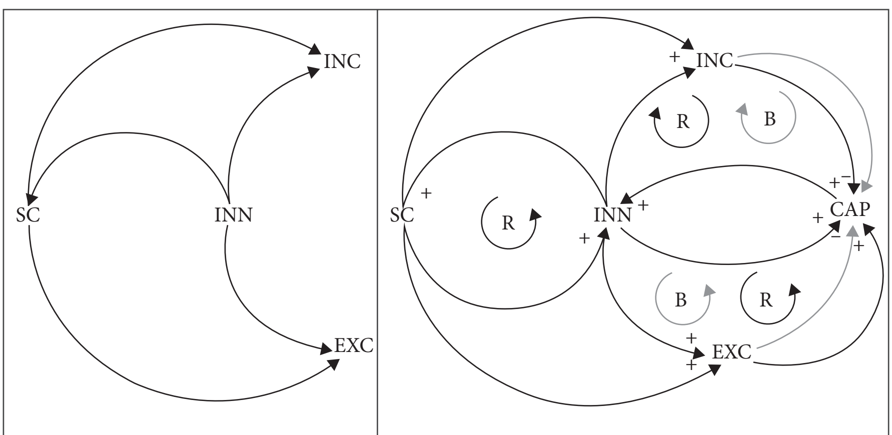
Our definition of *inclusion* encompasses elements of relative pro-poor growth, and equity, beyond income inequality. We define inclusion as the result of a process of (re)-distribution of benefits and losses, and of power and decision-making, such as, for instance, those who are currently marginalized acquire more of a prominent role in deciding about the pathways to follow and in turn reap net benefits from these changes.[5] An innovation is considered to be inclusive when individuals who are currently excluded or marginalized from decision making and the gains accrued to previous innovations are then included in processes of economic development (as employees,

[5] Those who were excluded or marginalized from previous processes of economic development can be defined on the basis of income, or through discrimination against the social group they belong to, e.g., gender, ethnic or religious minority, migrant, or geographical.

producers, and consumers), and their needs are explicitly addressed as a result. An innovation is also considered inclusive when individuals from excluded groups are involved in the processes through which innovation happens, such as the design and development of new goods and services that address specific and/or local needs. For readability, henceforth we refer to inclusion as INC.

We acknowledge that the relation between innovation, structural change, and inclusion is non-linear, and subject to a number of feedback mechanisms.

Figure 12.2 plots these relations in a system dynamics framework. In panel (a) we reproduce the same relations as Figure 12.1: innovation in time *t* influences structural change and inclusion/exclusion in time *t* + *1*. In turn, outcomes of structural change may be (positively or negatively) related to inclusion. In panel (b) we plot the dynamic relations that include a feedback from structural change and inclusion in *t* + *1* to innovation in *t* + *2*. Innovation (INN) is expected to have a positive effect on structural change (SC) (moving to more sophisticated products), which in turn is likely to generate more innovation. As a result, we obtain the reinforcing mechanism plot on the left-hand side. On the right-hand side, we plot the relation between innovation and inclusion/exclusion (INC/EXC). At the top right of Figure 12.2 innovation is assumed to be inclusive (INC). The inclusion of individuals and organizations in the innovation process may, for instance, lead to an increase in their capabilities, which also has a positive effect on further innovation, or reducing capabilities by dispersing them. This may lead to a further reinforcing mechanism (top-right) or to a balancing one (where inclusion does not necessarily lead to learning and higher capabilities that facilitate future innovation). At the bottom-right



Panel (a): linear relations

Panel (b): dynamic feedbacks

Figure 12.2 Dynamic relations between innovation, structural changes, and inclusion

Notes: INN: innovation; SC: structural changes; INC: inclusion; EXC: exclusion; CAP: capabilities; R: reinforcing mechanisms; B: balancing mechanisms. Blue indicates a positive relation; red indicates a negative relation.

Source: Authors' own elaboration.

part of Figure 12.2, innovation is assumed to be exclusionary (EXC). The exclusion of individuals and organizations from the innovative effort may have a negative effect on capabilities, reducing further innovation. This leads to a balancing mechanism (bottom right). However, exclusion may lead to increased capabilities of a limited part of the population, which may in turn increase innovation: in this case exclusion also leads to a reinforcing mechanism. Finally, structural change (SC) too might be inclusive (INC) or exclusionary (EXC). If inclusive, the positive effect of innovation on structural change further reinforces innovation through inclusion in the next time period. If exclusionary, the positive effect of innovation on structural change may reduce innovation in the next time period, depending on the effect of exclusion on capabilities.

We then face the following questions: under which conditions, forms of interactions, and role of actors, does an innovation lead to (some form of) structural change and (some form of) inclusion/exclusion? Which aspects of structural change favor inclusion/exclusion? Which aspects of inclusion/exclusion favor structural change? To answer these questions, we remove the feedbacks (as in Figure 12.2 panel (a)). Questions about the reinforcing and balancing mechanisms (panel (b)) require replicating the framework for different phases of development, where each phase is shaped by previous outcomes in terms of structural change and inclusion: which aspects of structural change induce more innovation? Which aspects of inclusion and exclusion benefit or hinder further innovation? We will address these questions to some extent here, but leave their full conceptualization for future work, while we started an empirical test of the dynamic pathways in a different work (Saha and Ciarli 2018).

12.3.2 From Innovations to Structural Change and Inclusion: Illustrative Steps

To answer the questions above, we map the steps through which several conditions, actors, and interactions may affect the strength and direction of an innovation's impact on SC and INC (Figure 12.3).

First, an innovation is introduced; this may be indigenous (domestic or local), or adopted from somewhere else—leftmost column *Innovation*. The innovation may be of different *types*: product, process, organization, or market. Different local, national, and international *actors* may be sources and channels for the innovation; their *interactions* may be differently shaped by power relations, governance, physical and social distances.

Second, the innovation becomes part of the system as soon as individuals or organizations adopt it.[6] Adoption may in turn result in an upgrade of the product, the process, or the organization which produces/delivers it. The innovation then diffuses as other actors in

[6] The first adopter may be the local innovator.

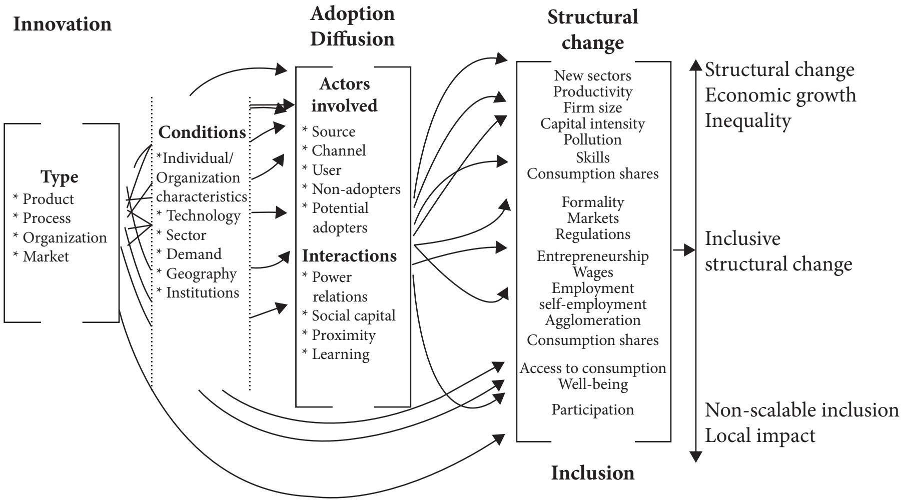


Figure 12.3 Innovation pathways to structural change and inclusion

Notes: Arrows represent pathways. The variables that represent conditions, actors, and interactions define the effect of innovation on adoption/diffusion, and on structural change and inclusion outcomes. Some pathways go through adoption/diffusion, while some variables have a direct impact on structural change and inclusion. Variables represent the innovation channels and sources, the type of innovation, as well as meso- and macro-conditions such as sectors, demand, geography, and institutions. In the extremes, innovation may have a positive effect on structural change, and a negative effect on inclusion (top end of the right axis), or no or negative effect on structural change and a positive effect on inclusion (bottom end of the left axis). The axis measures the trade-offs between structural change and inclusion outcomes. Structural change and inclusion are therefore not intended to represent different options—they are not mutually exclusive—but rather innovation processes may lead to different degrees of inclusive structural change.

Source: Authors' own elaboration.

the system adopt it. The extent to which the innovation diffuses in the system also depends on a set of actors, interactions, and conditions, for instance the capital intensity of the new technology, its scale, appropriability, adaptability, and cost. We distinguish between two types of variables: those that *enable the access (or production) of the new technology*; and those that *act as an incentive to adopt*. Examples of *enabling variables* are capabilities, access to resources, and other individual, organizational, institutional, and relational variables. Examples of *incentive variables* are demand (domestic or international), scale, factor costs, and other institutional variables (such as intellectual property rights).

Third, the diffusion of the innovation may result in different outcomes in terms of SC and INC, also depending on actors, interactions, and conditions. Some of these have a direct effect on SC and INC outcomes, that is they are not conditional on the innovation's diffusion. For instance, negative environmental externalities are a characteristic of rapid structural change, particularly with respect to manufacturers. Negative externalities are likely to have a stronger effect on parts of the population that are excluded, for instance within the transformation from agriculture to a manufacturing economy.

The extent of both the SC and the negative INC depends on the diffusion of the innovation. The larger the diffusion of the polluting innovation, the larger the SC, and the stronger the adverse effect on those negatively impacted. In contrast, the participation in the innovation process does not depend on the diffusion of the innovation. In general, SC outcomes are related to diffusion and upgrading, and are therefore shaped by actors, interactions, and conditions that characterize adoption. For INC outcomes, the role of diffusion depends on the types of inclusion considered. Following the inclusion ladder (Heeks et al. 2014), inclusion outcomes at the bottom of the ladder (e.g., access to goods) are also shaped by actors, interactions, and conditions that characterize adoption. For inclusion outcomes at the top of the ladder (e.g., participation in the innovation process), the adoption of the innovation is not particularly relevant.

Fourth, structural changes and inclusion are not unrelated. Some SC outcomes are complementary to INC, but most tend to be incompatible (before redistributive policies, which tend to consider only income-related aspects of inclusion). For instance, an innovation may decrease the price of a good that was previously only affordable to a limited part of the population, thereby increasing its access (e.g., milk in Kenya) (Saha et al. 2018). As a result, we observe an increase in the product's share of total household consumption, and an increased share in consumption of that good in relation to others in its category. While this is compatible with increased inclusion (measured as access to goods), in the short term an increase in the capital intensity of production will not result in increased employment: only the most skilled workers will have access to the available jobs, thereby leaving part of the unskilled population excluded.

12.4 Inclusive Structural Change: Bridging the Gaps in the Literature

12.4.1 Technological Upgrading, Structural Change, and Inclusion: A Brief Synopsis of the Existing Literature

There is limited literature that looks at the relationship between innovation/technological upgrading, structural change, and inclusion—let alone the three-way link under analysis here.

A first channel that leads from technological upgrading to structural change is through the mediated effect on productivity. Interactions in the process of adoption of innovative technologies help to close the productivity gap between pioneering firms, early adopters, and late adopters, which is essential to raising productivity levels across the economy, and generating structural change (Lundvall 2007). Where exposed to competition, domestic firms are pushed toward more efficient practices and to increase capabilities, with productivity growing in existing sectors and employment shifting toward more productive sectors (McMillan et al. 2014).

However, economic upgrading following structural change does not necessarily generate *social upgrading* (i.e., access to better work opportunities, including measurable standards, wages, and conditions, and enabling rights such as freedom of association and non-discrimination). For instance, the position of firms and workers within the value chain, the type of work performed, and the status of workers will influence the capacity to achieve inclusion and social upgrading through structural change (Barrientos et al. 2011, 2016a, 2016b; Bernhardt and Pollack 2016; Brewer 2011; Lee and Gereffi 2015; Milberg and Winkler 2011; Tokatli 2013).

At the *micro-level* of analysis, inclusion might result from technology transfer and technological upgrading, depending on a set of further conditions and contextual characteristics. The literature has identified, among these, the appropriateness of technology (Kaplinsky 2011; Hanlin and Kaplinsky 2016); measurable standards and enabling rights (Barrientos et al. 2011, 2016a, 2016b; Bernhardt and Pollack 2016; Brewer 2011; Lee and Gereffi 2015; Milberg and Winkler 2011; Tokatli 2013); user involvement (Foster and Heeks 2013; Kaplinsky 2011; Zeschky et al. 2011) and institutional inclusiveness (Acemoglu and Robinson 2012; Acemoglu et al. 2005; Altenburg 2009; Farole et al. 2011).[7] The mechanisms that affect inclusive outcomes of innovation are even less explored.

Paunov (2013) suggests that innovation affects inequality in three ways: first, through direct impact on income distribution (e.g., innovation favors the highly skilled and risk takers); second, by offering solutions for improving the welfare of lower and middle-income groups (frugal innovators); and third, by allowing lower-income groups to innovate with an ambition of greater welfare improvement (i.e., grassroots and informal-sector activities).

The literature has also highlighted that labor-intensive, cheaper and low-quality intermediate outputs and technologies produced and used by firms in *Southern* countries are more appropriate for firms in other countries in the South.[8] For similar reasons, these innovations are more accessible for SMEs and for disadvantaged groups, such as women (Hanlin and Kaplisnky 2016).

On the distribution of the returns to innovations, and how the initial income distribution influences innovation, recent literature has studied how market and technological innovation might usefully create new opportunities to include poor and marginalized people from low-income countries in the global economy (Chataway et al. 2014; Heeks et al. 2014).

At the *meso-level of analysis*, scenarios of growth and structural change entail a substantial heterogeneity in terms of inclusiveness and inequality, depending, amongst other things, on the *institutional configuration* of nation states. Acemoglu

[7] An exhaustive map of the literature dealing with the role of International Technology Transfer as a specific source of technological upgrading at the micro, meso, and macro levels is offered in Marquez et al. (2017).

[8] See Section 12.5.1 for a review of the South–South trade and its role in achieving inclusive structural change.

and Robinson (2012) distinguish between inclusive institutions, which promote learning and shared prosperity, and extractive institutions, designed to extract resources from society to benefit elites (see also Altenburg 2009; Farole et al. 2011; Hickey et al. 2014; Papaioannou 2014; Rodrik 2005; Teichman 2016).

At the *macro-level of analysis*, the relation between structural change that fosters economic development and *inclusion* has largely been framed in terms of how to achieve pro-poor growth (Anand et al. 2013; Atkinson and Bourguignon 1999): the rate at which the income of the poor rises for a given increase in national income (absolute), or with respect to the growth of the rest of the population (relative). According to Ravallion and Chen (2003), growth is distribution-neutral, and always has a positive impact on the poor, raising their income. Early stages of economic development, though, are often accompanied by changes in income distribution (Kuznets 1973; Ravallion 2004), which follow the economic transformation. Poverty reduction eventually is a combination of income growth, changed income distribution, and their relation (Bourguignon 2003). Some authors would argue that economic growth is always inclusive because of its effects on poverty reduction, but the degree of inclusiveness (how much poverty is reduced, if we use poverty reduction as a macro indicator of inclusion) depends on how equitably the increased income is distributed.

Since income inequality may directly affect economic growth, economists have attempted to explain the negative effect of inequality on economic development as depending on the political economy of redistribution (Acemoglu et al. 2005; Alesina and Perotti 1996), capital, insurance and/or labor market imperfections (Banerjee and Newman 1993), commons, and conflict (Esteban and Ray 2011). Lower levels of inequality measured as equal access to productive assets, economic opportunity, and voice, are claimed to have a positive effect on economic development (World Bank 2006). However, a wealth of empirical tests has not provided conclusive evidence on whether economic development leads to more inequality, at which stage of economic development, and even less on whether lower inequality leads to more or less economic growth.

Overall, there is a long way to go in terms of furthering empirical research to disentangle the three-ways link between innovation, structural change, and inclusion, as put forward in the analytical framework in Section 12.3. We reprise the issue and propose avenues of exploration below and in the subsequent Section 12.5.

12.4.2 Innovation for Inclusive Structural Change: Narrowing the Gaps

To summarize the key messages of our argument so far: structural change is a foundational component of economic development, which is generally poverty reducing. However, these processes may be relatively inclusive or exclusionary, depending on the initial income distribution and on whether there are sustainable opportunities created for the poorest.

Innovation and the accumulation of technological capabilities affect the extent to which structural change can be inclusive or exclusionary; however, the bulk of the literature mainly covers the emerging (rather than low-income) countries, the manufacturing sectors, and a few successful firms or clusters of small firms. The analytical framework proposed in Section 12.3 allows us to better identify the gaps in the literature that would need further research effort to be addressed.

First, we know little about *which innovations, in which contexts, lead to learning, technological upgrading, and eventually to structural change.* It has been argued that the innovations that are more conducive of learning might not necessarily be the most radical, but rather incremental (Bell 2009). The *latent bias toward radical, more disruptive innovations*, therefore, might be comparatively less inclusive or learning-conducive.

Second, the understanding of the relationship between innovation and inclusion has gained from conceptual developments and definitions of inclusiveness, *but the concept of inclusive innovation is still quite fuzzy and the understanding of how it can be achieved is limited* (Chataway et al. 2014; Cozzens and Sutz 2014). There is also limited empirical evidence on *who is included/excluded from a specific innovation and development process.*

Third, the understanding of *how inclusion and inequality influence successive phases of innovation and structural change* is even less developed. Also, the *evidence* on the effect of inclusion on structural change is far from conclusive. This relation is based on rather aggregate measures of inclusion, such as poverty and inequality, with little attention to exclusions based on ethnicity, geography, gender, and other non-economic dimensions. Most importantly *exclusion might occur at the level of access to information to inform decision making in investments and participation in the decision-making process*. We also know little about the *direction of structural change,* which is likely to depend on which innovations endure or dominate and which are replaced and disappear.

By proposing an analytical framework that accounts for all these aspects and the dynamics within them, our ambition is to direct empirical research toward addressing the gaps identified above. Going beyond a macroeconomic accounting perspective, our framework should be exhaustive enough to allow for the investigation of *how* the main driver of growth (innovation) influences the transformation that accompanies growth (structural change), and the (re)-distribution of the gains from innovation (inclusion/exclusion), and how the three dynamics are influenced by different conditions, actors, and their interactions.

In addition, we are aware that, in addressing the gaps above, it is important to build upon and go beyond the stylized dynamic relationships between innovation, structural change, and inclusion that have served the purpose of founding this framework. It is important to consider the trade-offs (and bottlenecks) that affect each link at each stage, and how these might be addressed through policy. We address this in the next section.

12.5 Inclusive Structural Change: Three Cases of Trade-offs in LMICs and the Role of Policy

Trade, investment, innovation, and diffusion proceed via the decisions and interactions of numerous public and private actors—artisans, civil servants, community workers, consumers, employees, entrepreneurs, farmers, and ministers, among others (Figure 12.3). These decisions together shape outcomes in terms of structural change and inclusion, and the trade-offs between them. While actors' decisions reflect their priorities and interests, they are also shaped by a series of policies, regulations, and incentive structures which influence these priorities and interests.

On the one hand, technological upgrading may promote structural change with inequitable patterns of winners, who reap the lion's share of rewards, and losers, who are left behind or carry a disproportionate share of the costs. Policies are needed to balance these trade-offs by changing or enabling new incentives and practices, resulting in a different and more equitable distribution of costs and benefits. On the other hand, innovation may take place in ways which are highly inclusive of currently marginalized groups, ensuring their participation in both the process of innovation and its outcomes, but with few structural effects. The role of policy can then be to enable access to the resources necessary to scale up structural change from these more inclusive processes.

This section reviews literature with respect to innovation, trade, and related policies, and their role in managing the trade-offs between inclusion and structural change, particularly in low-income countries. It considers three settings that may be more conducive of learning and the accumulation of capabilities than North–South transfer of more radical, disruptive innovation. These are (1) South–South trade and investment, (2) agglomeration economies that facilitate technology diffusion, and (3) indigenous grassroots innovation. It offers policy considerations for each setting: in which ways might public policy move outcomes toward the center of the structural change–inclusion spectrum (Figure 12.3), based on the state of current knowledge?

12.5.1 South-South Trade and Investment

Low-income economies tend to be characterized by two disparate groups of firms with very different levels of assets. The majority are low-productivity small or micro firms, often in the informal sector. These firms predominately operate in isolation from a much smaller group of large and more productive firms, including subsidiaries of foreign corporations (Altenburg 2009). Unlike in high-income countries, there is relatively limited productivity growth of firms in the first group, even those in the formal sector. While technology upgrading by these small firms does create needed jobs and contributes to productivity growth, structural change is largely determined by the larger and more productive firms (Van Biesebroeck 2005). These large firms are in a position to attract higher productivity labor, have better access to capital, and greater capacity to adopt new technologies. While the productivity increases by these firms support structural change, the outcomes are likely to exacerbate exclusion, at least in the short term.

Given that technology upgrading in low-income countries relies predominately on the diffusion of *new-to-market* technologies, rather than *new-to-world* innovation (Bell 2007), global value chains are a route to technological upgrading and higher value adding activities (Fu et al. 2018; Jaffee and Masakure 2005;). Which firms participate in global value chains, and how value-adding activities are distributed are frequently determined by the dominant or lead firm in the chain (Kaplinksy 2000; Ponte and Gibbon 2005).

Small and informal producers are generally excluded from Northern-firm-led value chains—unable to meet exacting standards, and hampered by low productivity and poor quality infrastructure which undermine their competitiveness (Dolan and Humphrey 2000; Maertens and Swinnen 2009; Poulton et al. 2008). On the other hand, where the lead firms are located in the South, there is greater likelihood of knowledge transfer and skills upgrading that enables firms to move up the chain into higher-value activities based on technology more similar to their own (Gold et al. 2017; Mohanty et al. 2019). A smaller technology gap within this network also enables technological diffusion via learning-by-doing, supporting diversification in manufacturing exports by local firms (Amighini and Sanfilippo 2014; Didier 2017).

Technology diffusion also depends on the human and financial resources and the absorptive capacity of firms (Cohen and Levinthal 1989; Keller 1996; Zanello et al. 2016). More advanced technologies from developed countries are more likely to be adopted by firms in the already productive group, which have the necessary resources and absorptive capacity to take up the technologies. Since these recipients of North–South technology transfer achieve higher productivity growth (Gold et al. 2017), the result is likely to be structural change without inclusion, as already larger and more productive firms pull further away from the rest. These exclusionary outcomes may be counter-balanced where they support employment growth; however, the evidence on the relationship between North–South vs South–South trade and employment is mixed (Gold et al. 2017; Mohanty et al. 2019).

The extent and type of trade and investment patterns are influenced by policy factors, including trade policy itself. Currently, although trade liberalization has led to an overall reduction in trade tariffs imposed by Southern governments, tariffs imposed on imports from other LMICs tend to be higher than for imports from developed countries (Jha and McCawley 2011). Policy in sectors that support trade is also relevant. For example, poor trade-related infrastructure and logistics, or infrastructure directed at supporting trade with countries in the North, rather than with other LMICs, undermines South–South trade (Jha and McCawley 2011). Another area is finance. Greater financial sector development in LMICs supports trade in technology and skill-intensive manufactures, and the effect is highly significant with respect to South–South trade (Demir and Dahi 2011).

Policies that support inclusive structural change will therefore address these trade-offs. One approach is to support structural change through North–South trade while introducing policies that enable those left behind to cope with or benefit from these changes, such as through social protection or significant public investment in human capacity development (Timmer 2009). Alternatively, trade policies may be geared toward (more inclusive) South–South trade, but coupled with efforts to build the capacity of small firms and their access to finance, contributing to greater productivity gains and growth (Mohanty et al. 2019). Of course, policies may also seek to strike a balance between these two alternatives.

12.5.2 Agglomeration Economies and Diffusion

Agglomerations and networks of enterprises and other economic actors, such as those found in industrial clusters and in cities, enable knowledge exchange and joint learning at relatively low cost. Outcomes may include technology adaptation, and diffusion, and increased productivity supportive of structural change—although these outcomes are not guaranteed (Wolman and Hincapie 2014). The contribution of clusters and cities to inclusive structural change depends on who has access to these spaces and networks, and the degree to which supply- and demand-side constraints to wide-scale productivity growth are addressed.

Clusters facilitate innovation through knowledge diffusion and spillovers, including the exchange of tacit knowledge, which is otherwise difficult to codify and transmit (Cumbers and MacKinnon 2004). Clusters are also distinguished by joint actions by the firms which comprise them, leading to greater collective efficiency (Schmitz 1999). Through encouraging the development of more specialized suppliers and creating demand for labor with specialized skills, clusters increase productivity (Porter 1998; Wolman and Hincapie 2014).

For LMICs, clusters enable small firms to achieve upgrading without having to invest across the entire production process. Instead, they can concentrate on taking much smaller risks in particular steps of the process, while other enterprises in the cluster invest in complementary tasks (Schmitz 1999). As a result, there is often an uncharacteristically high proportion of medium-sized firms represented in clusters in LMICs, although again this outcome is by no means guaranteed (Ibid.).

While clusters have mostly been studied in relation to industrial sectors, and to a lesser extent business services (Di Meglio et al. 2018; Meliciani and Savona 2015), clustering can also be applied to the promotion of agriculture (Galvez-Nogales 2010); highly relevant for LMICs. Agricultural clusters are based on the coordination of smallholders and agribusinesses to benefit from increased opportunities, reduced costs, and spillover effects.

Urbanization is another process of agglomeration taking place in LMICs, pulling people, enterprises, and resources into closer proximity, and, as for clusters, enabling valuable informal learning and the accumulation of knowledge. Cities allow for the sharing of infrastructure and distribution of risks, while improving the quality of matches between actors in the value chain, or between enterprises and employees with appropriate skills and knowledge (Duranton and Puga 2004). Cities thus offer knowledge, skills, and other resources, which enable innovation and upgrading, as well as a high density of demand (Srinivas 2014). This in turn creates a strong pull factor.

Despite obvious benefits, the distributional outcomes of these agglomerations are unlikely to be neutral. The fact that clusters support the free spread of ideas among smaller firms and informal enterprises (Kraemer-Mbula and Wunsch-Vincent 2016) means that they may enable more inclusive forms of innovation. On the other hand, clusters are not only spatial mechanisms but have a network aspect reliant on social capital, interpersonal relationships, and trust. As a result, clusters may exclude or further isolate firms led by those who are socially marginalized, based on ethnicity, religion, or gender, for example.

The benefits of agglomeration are also in tension with its burdens, such as increased urban crime, pollution, and crowding (Scott and Storper 2015; Storper and Scott 2016). These burdens adversely affect those who are negatively included in them. The key question is how the benefits and burdens of agglomeration are accrued or borne by different actors.

While the processes of coming together into clusters or cities often takes place spontaneously, driven by market and other forces, they may also be shaped by policy (Galvez-Nogales 2010; Wolman and Hincapie 2014). For example, people and enterprises may occupy different urban locations as a result of market forces, for example based on the price of land; or due to the actions of government authorities, for example through the provision (or not) of infrastructure and facilities (McGranahan et al. 2017).

Policies promote clusters where they address weak elements of the *ecosystem* by making land or transportation more available, offering relevant skills development programs, facilitating horizontal or vertical coordination, encouraging knowledge spillovers or networking, and fostering the growth of intermediary institutions and supporting services (Martin and Sunley 2003; Wolman and Hincapie 2014). However, there is little evidence of governments successfully creating entirely new industrial clusters in particular places (Wolman and Hincapie 2014). Moreover, subsidies that encourage, or regulations that restrict, investment in certain geographies can intentionally or unwittingly support or undermine cluster formation (Porter 1998).

Local authorities and urban planning policies may also intentionally (to discourage further migration) or inadvertently, exclude low-income residents and low-skill migrants from the benefits of agglomeration economies by confining them to certain areas of the city or denying them access to secure employment or basic services. However, where formal authorities recognize the legitimacy of these groups and their needs and capacities, policy may be formulated in ways that support their inclusion, while also contributing to greater effective demand. Urban planning and policy is also important in managing the production and distribution of negative externalities (Scott and Storper 2015).

12.5.3 Indigenous and Informal Sector Innovation

Trade and investment from both North and South offer sources of new-to-market technologies in low-income countries, supporting varying degrees of structural change and inclusion (as described above). Indigenous innovation involving technology adaptation in the informal sector of low-income countries offers an alternative pathway. It centers on incremental, learning-based innovations by firms with relatively low capabilities and minimal capital resources which adopt, adapt, and improve technologies. They may do so in response to specific constraints (Fu et al. 2018; Robson et al. 2009); or slight variations in the local market (McGranahan et al. 2017).

Closely related to the concept of informal sector innovation is that of *grassroots innovation* (Fressoli et al. 2014; Smith et al. 2014). Grassroots innovation refers to bottom-up efforts arising from communities and users who are directly involved in the process and/or outcomes of innovation. These are more deliberate and values-based alternative pathways of inclusive innovation and development. The focus is also on empowerment, such that groups achieve greater voice and control over their futures (Arza and van Zwanenberg 2014; Fressoli et al. 2014).

Indigenous informal sector and grassroots innovation supports inclusivity since groups that are normally marginalized move to the center of the processes of innovation and the benefits arising from them, as they meet local needs. Indigenous innovation in informal firms in LMICs has also been shown to increase labor productivity, and improve these firms' performance (Agyapong et al. 2017; Fu et al. 2018). There is nevertheless a wide gap between these locally developed solutions and achieving the widescale productivity growth necessary for structural change.

Time and financial resource constraints constrain the forms of innovation possible (Kraemer-Mbula and Wunsch-Vincent, 2016). Innovators that invest in new activities and new knowledge assets also lack any guarantee of their ability to appropriate the benefits (Hausmann and Rodrik 2003), acting as a further deterrent. Low population density (especially in remote rural areas) and/or weak spending power contribute to low effective demand, limiting the scale and reach of informal firms in localities with these characteristics.

There is little systemic policy guidance on innovation in the informal sector. Although attitudes are beginning to change, policymakers have often been blind to such processes, with policies that are geared toward suppressing informality rather than being supportive so as to enable innovation within it.

That said, enabling policies for informal innovation might include those that address general limiting factors, such poor quality infrastructure, informational constraints, a lack of skilled labor, poor access to finance and the weak skills of entrepreneurs (Bradley et al. 2012; Kraemer-Mbula and Wunsch-Vincent 2016). More innovation-specific measures would overcome initial barriers for innovators, for example by reducing regulations or requirements, providing low-cost credit or other subsidies, enabling linkages between informal and formal firms, or enabling entrepreneurs of high ability to *migrate* to the formal sector (Fu et al. 2018; Hausmann and Rodrik 2003; Kraemer-Mbula and Wunsch-Vincent 2016). These policies would ideally be matched by mechanisms that enable effective demand, for example by addressing distributional and delivery problems, overcoming informational problems, and raising incomes through wage policies or welfare regimes (Srinivas 2014). Policies that better enable networking, with support from intermediaries, can also be important to the diffusion of grassroots innovations (Hossain 2016).

12.6 Conclusions: A Research Agenda on Inclusive Structural Change

12.6.1 Summary of Key Themes

The chapter proposes a novel framework, which provides the analytical foundation of the concept of inclusive structural change, in order to inform future empirical research and policymaking. From the conceptual advance of this new framework, we seek to understand the dynamic relationship between innovation/technological upgrading, structural change, and inclusion.

The main conceptual building blocks of our framework are set out in Sections 12.2 and 12.3. Our ambition is to identify the main actors involved in these processes; to systematize the way they interact in processes of technology transfer, capability building, innovation diffusion, and delivering (virtuous or vicious) outcomes in terms of structural change, inclusion, and economic/social sustainability. Our overarching aim is to achieve generalizable knowledge that would help understanding of these processes in different low- and middle-income contexts. Ultimately, we aim to respond to the recently increasing demand coming from international institutions, inter-departmental research funds, NGOs and national ministries, for better knowledge to shape more effective innovation policy for sustainable and inclusive development in low-income countries.

Our analytical framework can be illustrated through the following narrative. A number of interacting actors (entrepreneurs, households, local communities, local government, managers, national ministries, and workers) are responsible for carrying out, channeling and adopting different forms of innovation. They do so not in a vacuum, but within a context affected by a number of variables. The creation of new goods and services by means of new processes and organizations is by all means a *destructive* phenomenon, in the best of the Schumpeterian tradition. The outcomes of these processes entail the creation of new activities and the obsolescence of existing ones; the need for new skills and others to become redundant or no longer in use; segments of the society benefiting as a number of their needs are newly satisfied, while others remain excluded. Structural change and inclusion might therefore reinforce each other in a virtuous circle; or rather be conducive of pathways of higher inclusion but lower structural change, or of more disruptive change that results in exclusionary outcomes.

As mentioned, our ambition is that the conceptual categories of our framework and the novel way of systematizing the actors, interactions, and outcomes of relevant processes will be used to test specific applications of it. For instance, technology upgrading leading to structural change depends fundamentally on existing local capabilities, absorptive capacity, the opportunities to upgrade both production and innovation capabilities, consumer preferences and needs, and not least on the ways in which the public sector and public research interact with the private sector within a context of aligned incentives. However, the gaps in the literature which need to be addressed and bridged remain substantial.

We have highlighted that the mechanisms that regulate inclusive outcomes of technological upgrading and structural change are comparatively less explored. These mechanisms are affected by a number of conditions, which are usually considered in the inclusion literature, yet they seem to be fairly overlooked in the literature on technology transfer. Our effort has allowed the identification of some of these mechanisms, such as the appropriateness of technology; the role of measurable standards and enabling rights; the degree of user involvement; and, finally, institutional inclusiveness. However, much work remains to be done.

We have devoted particular attention to highlight the trade-offs between innovation, structural change, and inclusion, that ideally could be counterbalanced by policy action. We have reprised these themes in the case of South–South trade and investments, and delineated some policy options to address the trade-offs between inclusion and scalability of the structural change that might result from these activities. Other cases of trade-offs between innovation, structural change, and inclusion can be found in the recent enthusiasm for grassroots innovation in LMICs. This, inclusive almost by definition, could be adequately supported by policies that point to a higher scalability. Similarly, we have looked at trade-offs in innovation and inclusion in specific spatial organizations such as clusters and cities in LMICs. Enabling clustering, networks and agglomeration economies in LMICs, in ways that include rather than exclude, would represent a particularly effective policy aim, one that builds trust and social connectivity, and at the same time facilitates learning and knowledge spillovers.

12.6.2 A Research Agenda toward a New Political Economy of Inclusive Structural Change

To achieve a thorough understanding of the positive and normative elements of inclusive structural change, a substantial effort should be devoted to test the analytical framework with further, more systematic quantitative and qualitative evidence.

Also, it is important to create space for more extensive reflections on the political economy of these processes, expressed through the integration of innovation, industrial and trade policies to align objectives that might currently be at odds with each other. Often the policy implications around innovation are targeted to contexts that are at best middle-income countries, whereas obviously LMICs represent a different challenge. Generating integrated evidence to inform development policy in LMICs is therefore the core ambition of this research agenda.

A number of policy implications emerge, based on both the policy options proposed in Section 12.5 to address the specific cases of trade-offs between innovation, structural change, and inclusion, and on the extensive interactions with stakeholders, academics, and policymakers that have received and discussed our results, and offered their own views and priorities. The implications thus identified highlight areas that need much further development, both at the analytical and, mostly, the empirical (quantitative and qualitative) levels, if we are to strengthen policy and theory of a *new political economy of inclusive structural change*.

12.6.2.1 Innovation and Technology Transfer for Inclusive Structural Change

We can imagine the innovation space as a continuum, that has at one extreme formal R&D and traditional technology transfer, and, at the other, indigenous, informal, and possibly grassroots innovation. Three main issues emerge: (i) R&D might not be as important as one might expect from theory, as it might not affect—in the short term—the capacity to generate change autonomously in local contexts; (ii) traditional channels of technology transfer, such as trade, FDI, and GVCs, might not be as important as in developed economies, due to issues of governance and specialization lock-in; (iii) however, much of the grassroots, local and informal innovations that might be inclusive locally, are likely to lack sufficient potential for scaling up and to ensure sustainable growth-enhancing structural change.

In this context, it would be important to start off with a process of local and endogenous change by ensuring scalability, and persistent change. If so, regional and local embeddedness should be prioritized over—for instance—entering GVCs prematurely (Lopez Gonzalez et al. 2019). In the context of inclusive structural change in LMICs, this needs revisiting and adapting the roles of trade, industrial, and innovation policy, and most importantly their integration. The case of South–South trade illustrated earlier is an exemplative case in this context.

12.6.2.2 Challenges for Innovation and Industrial Policies

The roles of industrial and innovation policy in LMICs should therefore be to *identify relevant opportunities for indigenous innovation* and make sure that this is scalable and made endogenous to change. Several challenges emerge.

First of all, the traditional technology transfer and innovation system narrative should be complemented with a careful consideration of the political economy of the whole process. Potential solutions that support a move in this direction entail either *feeding innovation incentives into existing market incentives that are beneficial to inclusion* and at the same time fighting perverse incentives or, alternatively, creating these virtuous (innovation + inclusion) market incentives from scratch. In this respect, the challenge is how to align incentives of actors as diverse as entrepreneurs, consumers, donors and policymakers, communities, private sector, and multinationals. The notion of an *entrepreneurial state* applied to LMICs is appealing but poorly equipped to account for the complexity of the necessary incentives (or lack thereof). For these incentives to be aligned, it would be important to make actors work collectively and with iterative measures to support incentive alignment, which is of paramount importance for development.

A second element that emerged from our analysis as under-explored and that yet would bridge the analytical and policy contribution of this work is *the role of demand*. Demand links structural change and inclusion: the income distribution that ensues from structural change might (or might not) support the effective demand for novel products or services, which might (or might not) then lead to better social and economic outcomes, in either a vicious or a virtuous circle. The political economy of value creation and redistribution as a result of structural change is therefore of crucial importance to ensure that innovation capacity is made sustainable in the long run and redirect pathways of innovation toward inclusive structural change.

Third, and related, is the importance of identifying needs, both those that are recognized by local communities themselves and also those that are not. This goes beyond the creation of effective demand in a Keynesian perspective: the creation of demand might not necessarily work toward satisfying needs. It may include, for example, accountability mechanisms through which needs are made known to policymakers. Fourth, the role of public procurement emerged as a fundamental element in any political economy strategy of structural change. This goes hand-in-hand with our initial reflection on the role of the government in identifying areas of technological opportunities.

12.6.2.3 Measurement and Indicators

Last but not least, the development of appropriate indicators that measure all the dimensions in our framework emerged as highly important from both our analysis and our interactions with academics, policymakers, and other stakeholders (Gault 2018).

Ideally, a radically new approach to measurement would entail including novel questions in surveys, that allow us to capture the value of upgrading and the degree of inclusivity of an innovation, for instance by including a question on innovation in Labour Force Surveys or in the Census. This has not yet been considered in relevant statistical offices. In addition, from the perspective of research and policy learning, devising properly designed mixed methods, that bridge data analysis and case studies, is a top priority. To achieve this, smaller-scale surveys rather than larger ones may be more focused, less resource-intensive and more informative when researchers and policymakers need to tackle the complexity of the issues outlined in this paper.

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13
Evolutionary and Interacting Spheres that Condition the Technological Capabilities Accumulation in Latin America

Gabriela Dutrénit, José Miguel Natera, Martín Puchet, and Alexandre O. Vera-Cruz

13.1 Introduction

The study of the processes of technological capability accumulation (TCA) for developing countries is long-standing. Since the early 1980s, there has flourished an extensive literature recognizing the importance of the TCA for economic development (Katz 1986; Lall 1987, 1992; Kim 1997). Several studies have allowed a better understanding of the nature of technological capabilities (TC) and the process of domestic TCA. The literature has transited from collecting empirical evidence based on case studies methodology and build taxonomies at the firm level, to broaden the analysis to measure TC at country level using an array of quantitative methodologies.

There is plenty of evidence to support the argument that there is a relationship between the TC of firms and their innovative performance. However, the connection between micro, meso, and macro level still requires a better understanding. In this line, more recently, there has been a special interest in understanding the factors that promote TCA, new levels of productivity, and improvements in living conditions. On one side, the studies of a few Asian economies showed that catch-up is a possible target (Lee 2013). On the other, the existence of a group of countries that does not overcome the middle-income trap suggests that it is necessary to look at other spheres that transcend the indicators associated with inputs and outputs of domestic science, technology and innovation (STI) capabilities. Development includes several dimensions that transcend the STI, like social, political, economical, and environmental, which interact with STI and must be taken into account for the analysis of TCA.

Some authors have recognized the need to connect these dimensions. Katz (1986, 1987) argued that macro and micro levels are intertwined and firms respond to changes in the macroeconomic context with modifications in their economic and

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technological behavior. Freeman (1995) stated that innovation systems (NIS) would generate spaces for accumulating TC according to conditions that transcended STI activities. He argues that there are five historical processes or sub-systems of society that influence the process of economic growth: science, technology, economy, politics, and general culture. In this line, some recent works have adopted a broader approach, a multilevel analysis, which means a multifaceted description and measurement of the various factors that contribute to shaping the domestic TC (or the innovative capability or absorptive capacity). They include variables of the economic and social spheres (Fagerberg and Srholec 2008; Cimoli and Porcile 2011; Castelacci and Natera 2013, 2016).

This chapter is built in line with the argument that we cannot understand what happens at the micro level without looking at the meso, macro, and even international level. Moreover, it argues that it is necessary to frame the TCA processes at firm and country levels in a broader context, which we call the techno-economic and environmental (TEES) and the socio-political (SPS) spheres. The evolutionary trajectory of countries combines these spheres differently, as they co-evolve and interact, which results in different development profiles. This is expected to have a systemic influence on TCA processes at the firm, sector, and country level. An implicit argument is that research, innovation, productivity, and economic growth lead to improvements in education, health, and democracy, as well as lower inequality.

Our analysis incorporates five dimensions that co-evolve: technical, economical, environmental, social, and political. Even though each dimension has its specificities, we took the decision to group those dimensions that converge more into two spheres and build two aggregated spheres. The TEES incorporates the technical, economical, and environmental dimensions, as the STI performance is highly associated with economics indicators of inputs, and considering that transition towards sustainable development requires simultaneously a more efficient use of resources, greener and more competitive industries, and STI. The SPS incorporates the social and the political dimensions as determinants of the conditions to orient the investment decisions and measure the possible risks of the projects associated with TCA. Even though this assumption can be arguable, it allows us to build the model and proposes a new approach to the analysis of TCA.

The objective of this chapter is to identify development profiles of Latin American countries based on the TEES and SPS, and discuss their implications for TCA. Grounded on this analysis, it explores some STI policy recommendations to strengthen TCA processes that take into account the heterogeneity and co-evolution, on the one hand, of TEES and SPS, and on the other, of the TCA process.

We recognize that there are methodological difficulties to address such complex analyses, at firm and country level. There is a lack of long-term indicators associated with STI and the environment, which would allow us to better characterize the TEES, and even more appropriate indicators to measure the performance of economies. We also miss long-term indicators for measuring the socio-political sphere of the countries (SPS). This lack of information makes it difficult to analyze how TEES and SPS interact with TCA, and impact on their evolution. In addition, as asserted by

Radosevic and Yoruk (2016), we still know little about the appropriate metrics for understanding the determinants of the TCA of the business sector. The lack of reliable indicators on firm-level TCA in the long term is even more serious. This is a challenge.

Hence, measuring TEES, SPS, and capabilities of the business sector involves making several analytical and methodological decisions. First, it is necessary to reflect on what kind of long-term indicators are necessary to achieve a better contextualization of the TCA at firm and country level, and to rethink how to measure that process, and, second, advance in new analytical frameworks to explain the TCA at firm level and at the country level with existing information.

This research focuses on the second challenge. It combines different steps and tools to analyze the countries' development profiles that affect the TCA of firms and countries, considering such profiles according to the evolution of their TEES and SPS over time. The period considered for this long-term analysis is 1980–2015. We verify the existence of cointegration between indicators of the TEES and SPS spheres and identify and estimate long-run paths to determine country profiles (Johansen 1991, 1995; Hendry and Juselius 2000).

The content of this chapter is as follows; Section 13.2 describes the Latin American context in terms of the economic volatility, inequalities, NIS, and the policies. Section 13.3 reviews the literature, discusses two spheres that are relevant for the TCA (TEES and SPS), and proposes a conceptual model to analyze their coevolution. Section 13.4 contains the research designs. Section 13.5 analyzes the countries' profiles based on the TEES and SPS. Section 13.6 discusses what can be learned from this model. Finally, Section 13.7 concludes.

13.2 The Latin American Context: Volatility, Inequalities, Innovation Systems, and Policies

In the last decades, Latin American economies have been characterized by volatility in GDP growth rates with alternating periods of ups and downs, low gross fixed investment of firms, different economic structures that emerge from the added value of agriculture, industry, and services, and low labor productivity without significant improvement. In terms of social and political conditions, it has to be added that countries are in a gradual process of bridging the gap in terms of life expectancy and schooling, and that there persist high and irreducible levels of inequality and corruption. Following the 2030 agenda and the sustainable development goals, but also as a result of some countries' own concerns, environmental care is being advanced at different paces in the region. In particular, the growth of economic activity, seen as an expansion of markets, and that of investment, viewed at the same time in terms of composition and the collection of external funds, do not seem to encourage technological or innovation processes. Unfortunately, in political terms, instability predominates in the region.

NIS have emerged in this context. They have been the result of heterogeneous processes of aggregation of different institutions, as well as public and private organizations that still operate in an uncoordinated way. This is due to several factors that create diversity in the quality of respective STI. On the one hand, historically, the assessment of STI-related activities has been poor and technical change based on local and systematic STI efforts has rarely been identified as an important factor in improving the performance of the Latin American economy. On the other hand, it seems that the activities of greater productivity in the Latin American market (at the industrial or service level) are not related to the efforts in innovation, that is to say, signs of short-term relative gain appear to be dissociated from innovation (Cimoli 2000; Viotti 2002; Cassiolato et al. 2003; López 2007; Dutrénit et al. 2010; Dutrénit and Sutz 2014).

The Latin American STI agencies were created around the 1970s, with a supply approach. They still play a central role in the NIS of the region, coordinating the design and implementation of national STI policies. In general, the institutional framework for STI activities has changed radically during the 2000s in most countries, following with a more paused-rhythm such international standards as those of OECD (2012, 2018). The systemic approach began to be adopted, but it was interviewed with the still predominant supply approach. The private sector maintains an underdeveloped culture of innovation, associated with the last approach (Crespi and Dutrénit 2014). While there are success stories of TCA at firm level, the protection of markets and macroeconomic instability did not generate an appropriate incentive structure to generate more dynamic technological behavior at firm level (Katz 1986, 2000; Vera-Cruz 2006; Arza 2007).

In general, the following features characterize the Latin American NIS (Dutrénit et al. 2019):

- Financial resources are scarce, with allocation problems.
- There is a small scientific community, with levels of excellence in some scientific fields in large countries, focused on research guided by curiosity, and with little incentive to conduct research oriented to national problems.
- The public sector remains the main source of funding.
- There is high geographical and institutional concentration of capacities.
- Firms make a little effort in R&D; however, much of their innovative activity does not appear to be captured by current methodologies for measuring innovation.
- There are limited links between agents.
- There is a strong distortion in the incentive structure.

In recent years, a number of achievements can be described, such as the emergence of new actors that form clusters, networks, and public participation organizations, and their impact on the internal connection and reconfiguration of NIS, the increase in the amount of R&D financed by the business sector, successful performance in specific areas, and increased productivity of research, among other factors (Crespi and Dutrénit 2014). However, some NIS traits undermine the processes of capacity building: problems of demand (e.g., weak demand that is associated with a small market, and problems of inequality, among other issues), supply weaknesses (e.g., lack of high-level human resources, or even engineers), shortage of private-sector investment, scarcity of private and public venture capital, complexity of the economic structure, and the effects of the rupture of the productive chains with the opening, among others.

While there has been a STI policy model for the region, largely following recommendations of international organizations, the countries have followed different dynamics in the design and implementation of their policies and have shown different degrees of independence with respect to these recommendations (Cimoli et al. 2009; Lemarchand 2010; Porta and Lugones 2011; Benavente and Bitrán 2012).

Overall, this has resulted in different performances in terms of STI. For example, since over a decade ago the international organisms have recommended the increase of Gross Expenditure on Research and Development (GERD) as a percentage of Gross Domestic Product (GDP) to 1 percent; countries have adopted these recommendations in various ways. At one extreme, Brazil has included STI as an important factor in its national development strategy, which has translated into a larger investment in R&D and in an increase of GERD/GDP until it reached 1.34 in 2015 percent in 2010 (UNESCO 2016, 2020). This investment has been accompanied by a combination of programs that have stimulated basic research as well as been a support for innovation in all types of firms. On the contrary, Mexico has not assigned that role to STI, and as a result, the GERD as a percentage of GDP has not surpassed 0.5 percent, beyond having a pretty modern design of STI policies (Corona et al. 2014, UNESCO 2021). In the case of Argentina, while recently a set of changes has been implemented at an institutional level, the financial effort that has been made is also limited (Suárez et al. 2014).

Even though, there has been a lot of experimentation, the designed programs largely represent adaptations of successful programs in other regions, which were designed for different initial conditions, with a more balanced composition of different actors. The specificities of the economical and social structural characteristics, governance system, and politics have not been properly taken into account.

Although advances have been made in the construction of STI domestic capabilities, the critical masses necessary to make leaps in the TCA do not yet exist (Dutrénit and Puchet 2011; Dutrénit 2017). Changes in the political regimes since 2017 suggest that the TCA cannot be isolated from other aspects of development: political, social, and environmental factors matter in the evolution of the TCA and the development process of these countries.

13.3 Techno-Economic, Enviromental, and Socio-Political Dimensions and TCA

This section reviews the related literature on TCA, discusses the incorporation of the context into the analysis of the TCA, and proposes a conceptual framework based on the TEES and SPS and the TCA.

13.3.1 Different Approaches to TCA

Since the early 1980s, there has flourished an extensive literature recognizing the importance of the accumulation of TC for technological and economic development (Katz 1986; Lall 1992; Kim 1997). Several studies have allowed a better understanding of the nature of TC and the process of domestic TCA. Initially, the papers focused on proposing ways to approach the study of domestic TC and define the concept (Enos and Park 1988; Westphal et al. 1985; Lall 1993; Kim 1992, 1997). TC was defined as the ability to make an effective use of technological knowledge for production, investment, and innovation (Westphal et al. 1985; Katz 1987; Teitel 1987; Maxwell 1987).

Subsequently, an immense arsenal of studies based on case study methodology provided evidence of these processes at the firm level, mostly of industrial firms (Dutrénit 2000, 2004; Figueiredo 2001; Vera-Cruz 2006; Hobday et al. 2004), drawing largely on the analytical framework constructed by Lall (1992) and Bell and Pavitt (1995). These taxonomies reflect that the TCA processes are gradual, from a stage in which firms have only minimal levels of knowledge (necessary for the operating) to the stage where they have advanced innovative capabilities (which include capabilities for conducting R&D). These taxonomies have been used to understand the processes of accumulation of firms in various countries and industries (Dutrénit 2000, 2004; Figueiredo 2001; Torres 2004; Vera-Cruz 2004; Bell and Figueiredo 2012; Figueiredo and Cohen 2019; among others).

Different bodies of literature have converged on the argument that there is a relationship between the TC of firms and their innovative performance. This firm-level work has explored the role of technological learning for TC building (Bell 1984; Katz 1976, 1986). More recently other studies have explored with quantitative methodologies the levels of TC at country level (Archibugi and Coco 2005; Fagerberg and Verspagen 2002, 2007; Archibugi et al. 2009), and some works have stylised the processes of catching-up, using largely R&D and patent data trajectories in Asian countries (Lee 2013).

Some studies have used surveys to construct explanatory models, mainly based on the innovation surveys. These works analyze TC based on information on different dimensions of R&D activities, firm size, percentage of highly trained employees, technology incorporated, among others, according to the access to microdata existing in the countries (Suárez 2014; Barletta et al. 2016; Suárez and Erbes 2016). From different microdata databases, other works propose the measurement of a threshold of TC. In this direction, Lee (2010) analyzes the dual role of R&D (knowledge generation and learning-improvement effect of technological competencies), its effects on the evolution of R&D and productivity, and the pattern of growth of the firm. He argues that there is a threshold, that is to say, to achieve sustained growth at least a critical mass of technological knowledge is required. In turn, the Crépon, Duguet, and Mairesse (CDM) approach proposed a methodology to analyze the links between research investment, innovation, and productivity at the firm level

(Crépon et al. 1998). Following this contribution, it has been possible to explore the relationship between TC with productivity and other indicators of firm-level economic performance.

At the macro level, among the pioneering work on domestic TC, Lall (1987) emphasizes that national TC are not the result of a simple addition of the capacities of the firms developed in isolation. Therefore, the links and synergies between the capabilities of individual firms matter. He also emphasizes that national capacities are integrated by three elements that interact with each other: capacities, incentives, and institutions, and proposes to use national indicators such as R&D expenditure, human resources size, education expenditure, and number of patents, among other gauges, to measure national TC. He recognizes that each country has a different combination and strength of the links between the three elements mentioned above, hence analytical frameworks designed to measure the national TC must be flexible enough to accommodate to heterogeneity (Lall 1987; Torres 2006). Lall (1987) also analyzes the role of policies to explain the acquisition of TC by Indian firms. He argues that policy interventions in a highly regulated economy like India's assumes great importance in determining the pace, nature, and success of technological development.

From a quantitative perspective, at the macro level, Archibugi and Coco (2005, p. 175) argue that in order to understand the role of technology in countries' performance and in their economic and social transformations, better indicators are needed to measure TC at national level. However, measuring TC is more complicated than measuring other economic and social processes, due to the nature of the technology, which makes it difficult to add its heterogeneous components into a single significant aggregate indicator. Archibugi and Coco (2005) developed the Technological Capabilities Index (ARCo), considering the heterogeneity in the distribution of TC among countries, the nature of technological change, and other indicators for measuring TC. This is a composite indicator that takes into account variables related to three different dimensions of technological changes for 162 countries in two years: (i) the innovative activity of the countries' economic system measured in terms of the number of patents and scientific publications, (ii) the diffusion of new and old information and telecommunications technologies (internet, telephone lines and cell phones), and (iii) the quality of human capital measured in terms of enrolment in higher education in science and engineering, average years of schooling, and literacy rate).

The variety of levels of analysis of the TCA enabled the bases of knowledge of this process to be enriched. Cases studies facilitated understanding of the processes of accumulation and differentiation by functions. Studies based on micro-survey data and national index made clear the connection of TCA with the economic performance of firms, sectors, and countries, and made it possible to evaluate the impact of TC on economic performance. But still we need to know about these processes, as nationally composed indexes do not consider the nature of TC available in each country and neglect the impact of the socio-political and environmental dimensions.

13.3.2 Recognizing the Role of the Context and the Existence of Different Interacting Spheres

Early on, several authors began to recognize that the context mattered for the analysis of the TCA and NIS. According to Katz (1986, 1987), Vera-Cruz (2006), Katz and Astorga (2013), Arza (2013), and Rasiah (2013), macro and micro levels are intertwined and firms respond to changes in the macroeconomic context with changes in their economic and technology behavior. In this vein, Katz (1987, p. 16–17) claims that the rate and nature of technical change, as well as the type of innovations and productivity advances that a given firm can undertake at a certain point in time, strongly depend upon: (i) strictly microeconomic forces emerging from the specific history of the firm; (ii) market variables related to the competitive environment in which the firm operates; (iii) macroeconomic forces characterizing the framework conditions; and (iv) the evolution of the knowledge frontier at the international level. In other words, the macroeconomic conditions affect the microeconomic processes of TCA.[1]

At the height of globalization and despite all its homogenizing tendencies, Freeman (1995) argued that NIS would generate conditions for the accumulation of TC according to conditions that transcended STI activities. He argues that there are five overlapping historical processes, considered as sub-systems or spheres of society, that look to be relatively autonomous; however, they interact and have major influences on the process of economic growth. They are science, technology, economy, politics, and general culture. As highlighted by Fagerberg and Verspagen (2020), the argument is that the evolution of STI depends on other subsystems or spheres, and on the congruence of the evolution between them, or in other words, that they converge and do not contradict each other. Later on, Freeman (2011) highlights the connection between social policy and inequality with technology and growth. Nelson (2020) refers to this type of analysis as the "reasoned history" approach.

Other works have adopted a multilevel analysis, which includes various factors that contribute to shape the domestic TC. This analysis includes variables of the economic and social spheres (Fagerberg and Srholec 2008; Cimoli and Porcile 2011; Castelacci and Natera 2013, 2016). These works focus on the analysis of TC at country level, and TCA is largely analyzed from the technical-economic sphere, and based on a set of indicators that does not take into account the development stages of countries (e.g., a wide use of indicators related to patents).

More recently some authors have paid attention to the TCA processes in middle-income countries (Radosevic et al. 2019). They observed that a very limited number of middle-income countries have been able to overcome the middle-income trap and become high-income countries. They argue that even though there are different explanations for the existence of the middle-income trap, blockages in the technology upgrading play an important role, such as those related to mismatches between changes in the existing economic structure and supporting institutions, and

[1] See Vera-Cruz and Torres (2013) for a detailed description of Katz's argument.

inequality and friction between social groups that prevent the construction of coalitions necessary for institutional improvement. These studies highlight variables at the macro and firm level. Radosevic et al. (2019) recognize the lack of appropriate metrics to evaluate the macro variables and even micro variables. As a result, the works mostly concentrate on conducting studies at the firm level (Yoruk 2019; Bernat and Solmaz 2019).

13.3.3 Different Dimensions in the Analysis of the National Innovation Systems

It is common to think that the process of maturation and development, and advances in the complexity and completeness of the NIS tend to turn them into techno-economic systems, that is, entities that privilege the transformation of knowledge resources of diverse nature into products, techniques, services, and so on, that are valuable strictly by economic criteria. However, the responsible research and innovation (RRI) perspective introduces other aspects to this unilateral perspective of innovation systems.

The RRI perspective introduces a component of "politics" that incorporates the dynamics of an SPS into the analysis of the innovation systems (Von Schomberg 2013; Stilgoe et al. 2013, Eizagirre et al. 2017). The enunciation of this and other aspects shows that in the operation of the techno-economic sphere, as well as for the innovation systems to obtain efficient and desirable results, it is necessary to observe how other features arise and are stabilized, which are of a social and political nature. Government guidance is not enough for the operation of the innovation systems; high levels of governance of collaborative actors (Turke 2008), as paramount, emerge to involve the innovation systems. In addition, this approach stresses the importance of the reduction of different types of inequality in the system. Unfortunately, the RRI approach (European Union 2012) is largely referred to the most developed countries from the point of view of maturity and evolutionary completeness of the respective innovation systems.

It can be argued that the evolutionary approach to development places the SPS as a main component of NIS. Both the accumulation of the multiple capacities required by the co-evolution of the substantive activities of the NIS, and the constitution of institutions that make structural changes possible and, in turn, emerge from them, operate through the SPS.

Environmental and ecological aspects are considered as goals by the RRI program of the European Union. These aspects include sustainable agriculture and forestry; marine and maritime and inland water research, and the bio-economy; secure, clean, and efficient energy; smart, green, and integrated transport; climate action, environment, resource efficiency, and raw materials.[2] However, the ideas to conceive, from an

[2] See "RRI Tools: Fostering Responsible Research and Innovation", www.rri-tools.eu/, accessed 27 January 2021.

evolutionary perspective, innovation systems of different scales that are sustainable, are incipient. Perhaps the most important efforts come from the literature on transition towards sustainability, based on a multi-level perspective (Geels 2010), which has built links with the innovation system approach (Köhler et al. 2019).

Finally, there are arguments coming from different bodies of literature that the evolution of the NIS involves and requires the interaction of the TEES and SPS.

13.3.4 A Conceptual Model to Characterize the Co-Evolution of TEES and SPS with the TCA: Micro, Meso, and Macro Interactions

Drawn on the literature reviewed in the previous sections, this chapter argues that it is necessary to frame the TCA processes at the firm and national levels in a broader context, which includes the TEES and SPS. TEES includes indicators of economic performance, such as GDP growth rate, labor productivity, manufacturing value added (% of GDP), among other factors, indicators of STI (inputs and outputs), and indicators of the environmental impact of economic activities, such as renewable energy consumption (% of total final energy consumption) and CO2 emissions (metric tons per capita), amongst other measures. SPS includes indicators of quality of living and political institutions, such as life expectancy, Gini index of inequality, corruption perception index, and democracy indexes, amongst other indicators. TCA corresponds to the micro behavior; it refers to firms' processes of TCA.

The evolutionary trajectory of countries combines these spheres differently; each one evolves and they interact, which results in different development profiles. This is expected to have an impact on TCA processes at the firm, sector, and country level. It is argued that social and political characteristics of the countries, particularly, level of inequality and consolidation of the democratic processes, and the STI domestic capabilities could condition the microeconomic processes of TCA. Figure 13.1 illustrates the proposed conceptual framework.

Probably, the main complication to determining the interactions between the spheres and the TCA is related to the capture, by means of suitable indicators, of the micro-, meso- and macroeconomic levels.

The natural environment is considered through variables that capture the generation of energy or the spill of negative effects on nature, in relation to pollution, landscape absorption for infrastructure use, and volumes of gases that are related to human populations. Likewise, the technological profiles are related to the use of inputs or the production of scientific or technological results, according to their relations with populations of different sizes, measured in terms of total, economically active, or occupied inhabitants. It could be said that there is a set of connections between natural and scientific-technological elements that condition the actions of people or decision makers, which are conditioned by exogenous factors to adapt to the context or to produce results.

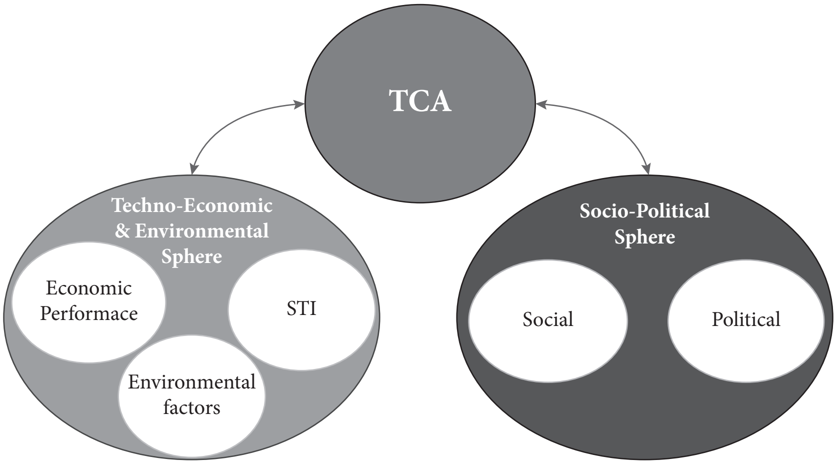

Figure 13.1 Conceptual diagram: co-evolution of TCA with TEES and SPS
Source: Authors' own elaboration.

The functioning of economic activity and its performance is approximated, in principle, by means of mesoeconomic variables such as the composition of production (e.g., manufacturing industry in the total), income (e.g., income from natural resources in value added), or expense (e.g., investment in fixed capital or direct foreign investment with respect to the total product). However, macroeconomic variables are also incorporated, such as economic growth and the magnitude of the opening of the economy. In turn, the evolution of the socio-political sphere is represented by macro variables that characterize the population as a whole, such as the Gini coefficient, the average years of schooling, the number of students in primary education, or perceptions of corruption, or democracy, or electoral competitiveness.

The relationships between the agents—individual or collective—and these variables of a meso or macroeconomic nature suppose conditions of the environment rather than restrictions on their decisions. In practical terms, the movements of these variables are part of the sets of information that these subjects will take into account for their behavior. The TCA is a microeconomic process whose emerging properties crucially depend on these meso and macroeconomic information sets. The existence of variables that make it possible to connect the three levels, in particular the existence of microeconomic variables that show how they are linked to other sectoral and national levels, is the main challenge of this approach.

13.4 Research Design

This section contains the reseach design, which has a structural nature; it considers the data that is needed for the analysis, the best available data, and the most suitable methods to describe the long-term development of eighteen Latin American country profiles.

13.4.1 Data that is Needed

For the analysis of TEES and STS, and their impact on TCA, robust long-term indicators, measuring dimensions at the micro, meso, and macro levels, are needed. For instance, we need long-term indicators revealing how the environment is reacting to changes in the development process. At meso level, it would be necessary to have access to indicators of training, occupations of university graduates and level of activity, which connect micro and macro. However, this long-term data is missing. We also lack robust series of human capital, learning, education, and technological change. In addition, as argued by Radosevic and Yoruk (2016), we still know little about the appropriate metrics for understanding the determinants of the TCA at firm level.

This lack of data, and of knowledge about the appropriate data, imposes methodological difficulties to address such complex analyses. This lack of information makes it difficult to analyze how TEES and SPS interact with TCA, and impact on their evolution. The lack of reliable indicators on the TCA at firm level in the long term is even more serious.

13.4.2 The Challenges of the Data

Empirical quantitative studies in the Innovation Studies tradition has mostly focused on advanced economies in the OECD area (Nelson 1993), leaving room for more empirical exercises for innovation systems research within the context of developing and less developed economies (Lundvall et al. 2009). The operationalization of the innovation system theoretical view in empirical studies is the main constraint since there are difficulties when measuring their dimensions in relation to countries' economic performance.

The analyses of NIS dynamics in a long-run perspective should consider a relatively long time span. Even the data we are using, which considers forty-five years in most cases, is a relatively short span, because there is a need of additional observations to implement complementary analyses, where recursive tools could be applied to better investigate the dynamic characteristics of the process. Furthermore, a clear limitation of this document is the lack of characterization of the causal structure that links together different variables. We took an alternative road, using only cointegrating relations and not analyzing the short-run structure, in order to incorporate a higher degree of dimensional complexity in the analysis. Other studies show that due to the lack of statistical data for a sufficiently long period of time, a great number of developing economies and the vast majority of less developed countries are neglected by this type of dynamic study.

Researchers seeking to apply quantitative analyses of innovation systems and development normally face a dilemma with respect to the data they decide to use (Castellacci and Natera 2011): they can focus on a small sample of (mostly advanced and middle-income) countries over a long period of time or they can study a larger sample of economies (including developing ones) but using a static approach. Both solutions are problematic. The use of multiple imputation methods and other data-mining techniques would be helpful to construct datasets that could solve this problem. However, since the available data points are still relatively short, in order to solve this issue there is a need to establish robust measurement systems at national levels, develop alternative data-mining methods, and wait for the course of time to take place.

13.4.3 A Proposal of Research Designs

We argue that TCA is a complex process, which is not only circunscribed to the firm, the sector, the country, nor the tecno-economic variables. TCA takes place in the firm, but is the result of an interactive process in which the firm is embedded in a vast environment, being a part of a system; that is why we aim at analyzing the implications of the TEES and SPS in the TCA process. This research identifies development profiles of Latin American countries, in terms of the evolution of TEES and SPS over time, and discusses their implications for TCA. The period considered for this long-term analysis is 1980–2015.

The exercise uses thirty indicators to characterize the TEES and SPS spheres. Indicators were chosen from available data from 1980 to 2015 for eighteen Latin American countries: Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, and Venezuela. According to the World Bank, most of the countries correspond to the upper-middle-income countries' category. Within this, El Salvador, Honduras, and Nicaragua are classified as lower-middle-income, and Argentina, Chile, Panama, and Uruguay correspond to the high-income segment. This selection covers eighteen Latin American countries; the sample satisfies two conditions: it includes countries of different sizes and relative position in the regional economy and it considers quality of the data that countries provide.

Indicator selection comes from a detailed analysis of the literature of innovation systems. Following Castellacci and Natera (2011), we have selected the most accepted available indicators used for international comparisons in the literature. They provide information in two direction that are worthy for our study: (i) they have surveyed the empirical analysis related to innovation systems, in order to find the most suitable proxies that could express countries' evolution; and (ii) they make available a dataset with complete information (including observed and estimated data) that makes the most out of the available data for time series and panel analyses.[3] Based on this, we

[3] Castellaci and Natera (2011) discuss the indicators to measure innovation systems at a national level.

selected some indicators and organized them in terms of our proposed conceptual model, namely the TEES and the SPS.

13.4.3.1 TEES Indicators:

(i) Indicators of economic performance (7): Gross fixed capital formation (% of GDP), Openness Indicator (Import+Export)/GDP, Labor productivity per person employed in 2010 US$ (converted to 2010 price level with updated 2005 EKS PPPs), Total natural resources rents (% of GDP), Industry value added (% of GDP), FDI Inward Flow (% of GDP), Domestic credit provided by financial sector (% of GDP).

(ii) Indicators of STI inputs and outputs (7): GERD as % GDP, School life expectancy (years) Tertiary Education, Total Researchers per million inhabitants (FTE), Scientific and technical journal articles (per million people), Patent applications—residents (per capita), High-technology exports (% of manufactured exports), Fixed telephone subscriptions (per 100 people).

(iii) Indicators of Environmental impact of economic activities (8): Renewable energy consumption (% of total final energy consumption), CO2 intensity (kg per kg of oil equivalent energy use), Total greenhouse gas emissions (kt of CO2 equivalent), Water productivity—total (constant 2010 US$ GDP per cubic meter of total freshwater withdrawal), CO2 emissions (metric tons per capita), Fossil fuel energy consumption (% of total), Combustible renewables and waste (% of total energy), Urban population (% of total).

13.4.3.2 SPS Indicators

(i) Indicators of quality of life (4): GINI index, School life expentacy Primary to Tertiary (years), Government expenditure on education (% of GDP), Primary School enrolment (% gross).

(ii) Indicator of the political context (4): Corruption Perception Index, Index of Democracy and Autocracy, Legislative Index Electoral Competitiveness, Executive Electoral Competitiveness.

The evolution of the different economies is identified based on per capita income, for reasons of comparability between countries and data availability. We are aware of the limitations and difficulties that this measure exhibits to interpret the trends of economic growth and the variations of welfare. However, this indicator is widely used and makes it easy to identify relationships within a variety and diversity of indicators that we select to analyze the trajectories of countries.

For each country, the income per capita was defined as the dependent variable; the independent variables included in the analysis are conformed by the following indicators: (i) for TEES: indicators of the economic performance (EP, 7), of STI inputs and outputs (STI, 7), and of environmental impact of economic activities

(E, 8); and (ii) for SPS: indicators of quality of life (QL, 4), and of political context (PC, 4). We carried out a co-integration analysis. The objective of this analysis, multi-countries and multi-periods, was to find evidence supporting the view that the dependent variable and some indicators of each type are linked together in the long run.

The co-integration shows that a subset of indicators for a country evolves, in a joint manner, among them and with the determined variable. It is possible then to say, for example, that two or more variables have the same tendency or that they co-integrate. More technically, the difference between the dependent variable and a subset of indicators follows a trajectory that has a zero mean and a constant variance. The analysis could allow for full endogenization of variables and the estimation of theirs cross effects within a system. When having a longer span it is possible to incorporate information from the past to explain current states (Greene and Zhang 1997). However, when having forty-five datapoints for each country, we faced a trade-off between the number of factors that could be included and the possibility of fully explaining the dynamic features of the model. In this research design, we were very interested in identifying the main development paths for each country, so we decided to explore the long-run pattern by increasing the number of factors that explain them; as follows:

- The co-integration methodology has been selected because of its suitability for empirical analyses of the NIS and economic development. It offers the flexibility that the analysis of NIS needs, it recognizes history as the main source of information, and it evaluates the relationships as the result of mutual effects among different dimensions. Time series co-integration, in which a single country data is evaluated over a given period, is useful to incorporate the highest level of heterogeneity in the data. Hence, the individual evaluation makes it possible to identify specific events in each country; it is the closest version to using empirical analyses in a case study fashion (Hendry and Juselius 2000). Also, it is possible to distinguish different relationships: (i) the long-run relations, which are at the core of the system as in this case, and (ii) the short-run structure, which represents how the system reacts to changes, and is not realizable for these short-time series (Hendry and Juselius 2000; Juselius 2006).
- Co-integration aims at describing the full space in which variables interact. In its system version (Johansen 1991, 1995), we find many restrictions in terms of the degree of freedom we have, since the time span is relatively short. In order to include a wider number of variables (that could represent the complexity of each dimension), we decided to restrict our analysis to the long-run stable part of the model, by using co-integrating equations. Therefore, we are not able to look at the causality structure or the way that the system reacts to different changes in variables levels. We will evaluate, nevertheless, the relationship between variables that constitute the system's long-term development.

The research design includes the following steps:

1) To verify the existence of co-integration between the dependent variable and the indicators of the TEES and SPS spheres

We estimate a co-integrating equation, using per capita income as a signal of the level of development, relating TEES-economic performance, TEES-STI performance, TEES-environmental performance, SPS-quality of life, and SPS-political context indicators. Therefore, five equations per country were estimated, three for the TEES and two for the SPS. We will use real GDP per capita (in PPP) in order to estimate how each of these dimensions affects development.

In this first step, the analysis was executed in the following manner: for each of the five types of indicators we explored whether the set or some subsets co-integrated with the GDP per capita. We tested for each type all the possible combinations of indicators that could co-integrate. For example, in the case of the seven indicators of economic performance, we tested 2,286 (127 combinations per 18 countries) models to detect co-integration of different sets of variables and, in this form, subsequently for the other four types of indicators.

2) To identify and estimate long-run models

We considered the inter-relationships among the dependent variables and the indicators of each type with the objective of understanding the reciprocal effects and the interdependence pattern that determine the trajectory of the GDP per capita in the long run.

In this second step, we needed to choose the better of all co-integration models for each type of indicators. We chose in terms of two joint criteria: i) the highest number of indicators included in the significant model specifications and ii) the representativeness of the model, measured by the frequency of significant indicators that appear across the different configurantions.

3) Based on long-run models to identify development profiles of the countries

The long-run models of the countries were identified and estimated; they conditioned the paths of the countries. This third step consisted of the following:

- Mark the independent variables of each co-integration equation that are significant and positive.
- Identify the development profiles of countries based on the independent variables of the long-run paths that are significant and positive.

We tested different models to find stable patterns for the set of variables, in order to undertake a comprehenisve analysis of the cointegrating spaces.

13.5 Countries' Development Profiles

Based on the previous results (compiled in the supplementary material online at www.oup.co.uk/challengesoftechnology), we mark the independent variables of each co-integration equation that are significant and positive. They receive "1" in Table 13.1 and Table 13.2. This exercise made it possible to identify the development profiles of Latin American countries.

In order to achieve such a task, we undertook an exhaustive exploration of all possible combinations of the indicators, aiming at producing the most detailed picture of the cointegration spaces. Furthermore, we included three different types of time-dummies in order to better appreciate the effect of external shocks in the cointegration space. All in all, this implied the analysis of 29,106 models, from which we excluded the ones that did not show evidence of cointegration in order to present a lean analysis. The results we show, therefore, are the outcome of a careful selection of relationships that are based on a meta-analysis of cointegration spaces: here we present those coefficients that are positive and significant in relevant models.[4]

It should be noted that the profiles reflect the result of the evolution of a set of variables. These variables have measurement limitations; therefore, their individual value has many limitations. However, the aggregate is useful for understanding the behavior of the interdependence pattern.

In general, the last rows of Table 13.1 and Table 13.2 show the significant and positive effects of TEES and SPS indicators on the income per capita. By type of indicators, the results are the following:

- EP: the labor productivity and the gross fixed capital formation are the more relevant indicators for ten countries or more.
- STI: the production of scientific and technical articles is important for two-thirds of the countries and also school life expectancy of tertiary education has an impact on GDP per capita growth.
- E: the combustible renewables and the waste, the water productivity and the CO2 intensity for, practically, two-thirds of the countries have a positive effect on the income per capita.
- QL: the indicator of better income distribution—the inverse of Gini Index—did not turn out to be positive and significant for most of the countries; in countries with profile III and in another four in profile II this relationship is positive and significant, as we will see below. Hence, in the majority of the

[4] We expressively decided not to take the size of the coefficients, and used only their sign and significance level. We acted like this to produce a better comparative exercise between variables of multidimensional characteristics (and avoid the problems that might arise from coefficients standardization). Addittionally, the research design is strong enough to provide a rich set of information in which intensity could be relegated to a second step for future research.

Table 13.1 Cointegration equations: Variables with significant and positive effects in the long term: TEES

Country Group	**I**			**II**												**III**		
Country* Indicators	**Arg**	**Chi**	**Mex**	**Bol**	**Cri**	**Ecu**	**ElS**	**Gua**	**Hon**	**Nic**	**Pan**	**Par**	**Per**	**T&T**	**Ven**	**Bra**	**Col**	**Uru**
GERD as % GDP	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
School life expectancy Tertiary education	0	1	1	1	1	0	1	0	0	0	0	0	0	1	0	1	1	1
Researchers per million inhabitants	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	0	1
Scientific and technical journal articles	1	1	1	1	1	1	0	0	1	0	0	1	1	1	0	1	1	1
Patent applications, residents	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
High-technology exports	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fixed telephone subscriptions	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gross fixed capital formation	1	1	1	1	0	1	0	1	0	0	1	0	0	0	1	1	1	0
Openness Indicator	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Labor productivity per person	1	1	1	0	1	1	0	1	0	0	0	0	1	1	0	1	1	1
Total natural resources rents	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	1	0	1
Industry, value added	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0
FDI Flow Inward	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0
Domestic credit provided by financial sector	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1
Renewable energy consumption	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
CO2 intensity	1	1	1	0	0	1	0	1	1	1	0	0	1	1	1	1	0	0
Total greenhouse gas emissions	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Water productivity, total	1	1	1	1	0	1	0	0	0	1	1	0	1	1	0	1	1	1
CO2 emissions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Fossil fuel energy consumption	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Combustible renewables and waste	1	0	1	1	1	0	0	1	1	0	1	1	1	1	0	1	1	1
Urban population	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
# of significant and positive effects	9	8	10	6	7	7	1	6	3	3	4	5	6	7	4	10	8	8

Source: Authors' own elaboration.

Table 13.2 Cointegration equations: Variables with significant and positive effects in the long term: SPS

Coutry Group	**I**			**II**												**III**		
Country* Indicators	**Arg**	**Chi**	**Mex**	**Bol**	**CRi**	**Ecu**	**ElS**	**Gua**	**Hon**	**Nic**	**Pan**	**Par**	**Per**	**T&T**	**Ven**	**Bra**	**Col**	**Uru**
Corruption Perception Index	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0
Index Democracy and Autocracy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Legislative Index Electoral Competitiveness	0	1	0	0	0	1	0	1	1	0	0	0	0	0	0	1	0	1
Executive Electoral Competitiveness	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
GINI index	0	0	0	0	1	0	0	0	1	0	1	1	0	0	0	1	1	1
School life expectancy Primary to Tertiary education	0	0	1	0	0	1	1	1	0	0	1	0	0	0	0	0	0	1
Government expenditure on education, total	1	0	1	1	1	0	0	0	0	0	0	1	0	0	0	1	1	1
School enrollment, primary	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	1
# of significant and positive effects	1	2	2	1	3	2	2	4	3	0	2	3	0	0	0	3	3	5

Source: Authors' own elaboration.

countries, the improvement of the income distribution is not enough to generate a positive impact on the GDP per capita. The government expenditure on education converges with this distributive result. These results reveal one of the key problems of development in Latin American countries: the high levels of inequality associated with a low investment in education.

- PC: the legislative index electoral competitiveness is the only indicator of PC with a confirmed effect, a third of countries has a positive result of this electoral competitiveness on the income per capita. The corruption perception (0 for most of the countries) means that the levels of corruption are neither positive nor significant for the GDP per capita. Apparently, the institutional quality moves at a different pace to the changes on the GDP per capita.

The exercise made it possible to identify different profiles. Figure 13.2 illustrates these profiles. The vertical axis reflects the TEES (and its dimensions: EP, STI, and E), and the horizontal axis the SPS (and its dimensions: QL and PC). The position of a country in the figure shows the number of the regressors (or dimensions) that are significant and positives in the respective sphere. It is important to observe that each indicator (of a type and of a sphere) is always present, and that the value on the axis is the number of regressors significant and positive of each sphere correspondent with an axis. Three profiles were identified:[5]

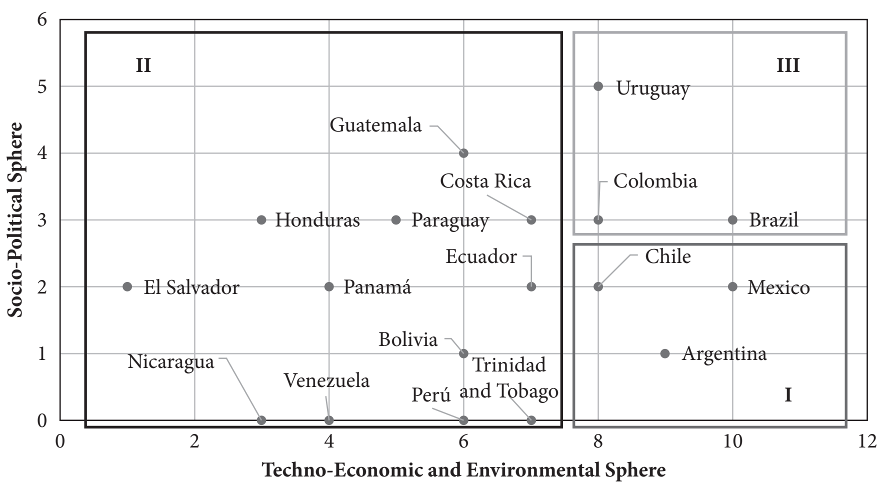

Figure 13.2 Development profiles of Latin American countries
Source: Authors' own elaboration.

[5] Countries are distributed in the figure according to the results of the cointegration analyses. Countries with emerging NIS and still low performances were grouped on the left side. Countries with relatively more structured NIS were grouped on the right side, but which differ in terms of the SPS. Based

Profile I. Biased towards the TEES, and lacking in SPS development: Argentina, Chile, and Mexico.

Countries biased towards TEES indicators, where labor productivity has a positive impact on GDP per capita, and lacks a favourable presence of the SPS (little positive impact of these indicators on GDP per capita).

Profile II. Biased towards the SPS and lacking in TEES: Bolivia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, and Venezuela.

Countries biased towards a positive influence of the SPS, but still with low impact of these indicators on GDP per capita, and lacking a favorable presence of the TEES.

Profile III. More balanced systems: Brazil, Colombia, and Uruguay.

Countries with more balanced systems between both spheres. They have the better impact of SPS on GDP per capita.

The three profiles illustrated in Figure 13.2 also suggest a reflection: there seems to be a trade-off between techno-economic-environmental performance and socio-political performance. It seems that the economy continues to extract resources that it does not distribute and for that it uses political mechanisms that privilege its extractors. There is mixed evidence, on one hand, during the Washington Consensus, governments favored the entrance of FDI investments that affected the domestic environment with limited economic results (Rodrik 2008). On the other, there is evidence of processes of domestic TCA with negative spillovers for income distribution (Crespi et al. 2018; Pérez et al. 2013). This argument deserves more research.

13.6 What We Can Learn from This Model?

Nelson (2020, p. 1) interpretes the "reasoned history" approach in the following terms:

> The qualitative aspects of our understanding usually are sized, shaped, and pinned down to some extent by numbers and often by statistical relationships as is Freeman's analysis, but as his study shows, these quantitative aspects of our understanding do not make sense on their own. Our qualitative understanding transcends them and is essential in indicating what those numbers mean.

In this section some lessons are drawn from reflecting on the data, the methodology of co-integration, and the construction of the proposed model.

on this reality, described in Section 13.2, the lines were drawn to help with reading the different profiles. UNESCO (2021) provides evidence in the same direction.

13.6.1 Limitations of this Type of Model Based on Co-Integration Methods

The approach proposed in Figure 13.1 relates areas in which agents, organizations, and systems act with comprehensive processes of accumulation of TC that are immersed and conditioned by the evolutions of these spheres and their co-evolutions. Undoubtedly, in this set of relationships of interdependence and multiple interactions there are causal sequences between variables that must be verified by evidence. The following paragraphs discuss some of the difficulties of making this approach operational through an empirical model such as the one proposed in this chapter.

From a conceptual point of view, data on key variables are concentrated on indicators designed for other purposes. For example, it is difficult to have macro or mesoeconomic data that are focused on capturing productivity or investment rates with reference to the fact that production and accumulation take place in the respective NIS or innovation subsystems. At the same time, the fact that the spheres described work, each, through networks of internal relationships and interrelationships between them, is captured in a weak, and probably biased, way. This is because individual tests of variable significance are made per variable instead of testing by subsets of variables or, moreover, defining causal test orders for those subsets.

This difficulty of conceptual adaptation of the design of the indicators to the proposed approach is complemented by the fact that the available data for existing indicators are scarce and, in many countries, of low statistical quality or of low transverse or temporal comparability. The wide range of available sources used in this work to construct the empirical model showed compatibility gaps between definitions by country or by macro, meso, and microeconomic levels of datasets, information gaps by country and by periods, inaccuracies and lack of adequacy, and even inconsistencies between the data and those facts whose evolutions were known through collateral sources or according to other evidences. The results presented are based on the best available practices of multiple source assessment and data processing.

Additionally, there are limitations in the methodology that transcend the state of knowledge. The panel data co-integration method relies on specification and long-term trend detection tests that make the quantified model resulting from modeling extremely robust. At the same time, the way in which this model incorporates the dynamics of the processes for determining the variables explained is consistent with an evolutionary view such as the one proposed here. No doubt, those were the reasons for this methodological option. However, the notion of equilibrium underlying co-integration, despite all its conceptual and statistical robustness, is confined to processes where the linear relationships between the long-term trajectories of the variables (or transformations of themselves) play the relevant role. In the evolution of relations between sets of interdependent variables, and with high degrees of feedback, this linearity is possibly inadequate.

Despite these limitations and difficulties, from the methodological point of view, the following result should be appreciated. We have run an exhaustive analysis of the cointegration spaces for the selected variables; this implies making the most out of the available information in order to make a rigorous exercise. Each point marked in Figure 13.2 comes from a meta-analysis designed to look at the different angles of the cointegration spaces. The co-integration models that support the dimensions of each sphere (TEES and SPS) are based on a reasoning that seeks to maximize the use of empirical information and privilege the criterion that the data show the long-term evolution of the countries. This strategy reveals the interrelationships between their characteristics aspects, and allows the emergence of a pattern of interdependence between them. The methods and techniques used conceive the database as a generator of long-term regularities between sets of indicators, instead of constructing composite indicators outside the available information. The set of variables behave stochastically and their interactions are unknown; that constitutes the environment from which these regularities are extracted. The models were selected according to their degree of statistical robustness, that is by the amount of information that, in recorded history, it is feasible to capture about the pattern of interdependence that arises from trajectories of the greatest possible number of variables.

The experience of putting into practice an approach like the one proposed here also meant that lessons have been learned that open new methodological horizons for research. In particular, we highlight the following: (i) consider those indicators that have a significant negative sign effect, and (ii) make an analysis of the set of significant effects (negative or positive) that are recorded in all the specified co-integration models, in order to establish selection criteria more relevant and make possible the specification of systemic co-integration models in which the dependent variable is multiple.

13.6.2 Some Lessons Learned on the Countries' Profiles for STI Policy

Beyond the limitations of the information mentioned above, particularly that the indicators used are not the best ones to measure the performance and evolution of the NIS, the information allows the identification of development profiles of eighteen Latin American countries. This section reflects on the implications for STI policy that emanated from the identified development profiles.

First of all, this chapter argues that the two spheres must be included to explain how the TCA determines each evolutionary stage in which an economy is located. In general, as it was observed, coordination between spheres is weak and there is an imbalance between them. But each country is endowed with different initial conditions and has different aptitudes to adopt policies that lead it along a path of catching up towards development.

The evidence suggests that countries differ in terms of their development profiles, and particularly the balance between TEES and SPS, and that might be a link between the country profile and the characteristics of TCA at firm and country levels. Thus, instead of having a general analytical framework to generate quite similar recommendations for all countries, the design of STI policy has to take into account these different initial conditions. As Liu et al. (2017) argues for the case of China, a new innovation policy is required to move from the middle-income stage to catch-up.

Three general lessons can be learned from this analysis. First, according to the long-term evolution of TEES and SPS, three Development Profiles were identified. However, in general, countries still confront, in different degrees, a set of problems that undermine the processes of capacity building, such as: limitations in the demand, supply constraints, low private-sector investment, shortage of private and public venture capital, and rupture of domestic productive chains, among others. The design of STI policy should take into account these particularities of the TEES, the SPS, and their connection, as well as the specificities of the NIS agents to be able to design efficient programs in economic, environmental, social, and innovative terms. These limitations may have effects on firms behavior and hence of the TCA.

Second, the evidence revealed a weak balance between the TEES and SPS, and this certainly has impact on TCA. While the ultimate goal of development is embodied in broad national economic, social, and environmental objectives, the ultimate goal of STI policy in Latin America continues to be to build capacities in STI, especially in innovation, to meet productivity, competitiveness, and economic growth. The weakness of the balance between TEES and SPS suggests the need to pay more attention to other societal needs, such as poverty, food production, diabetes, renewable energy sources, and water supply, amongst other needs. This requires more coordination within several ministries and putting into practice the transversality feature of STI policy. The STI policy should include the goal of social welfare in addition to those of improvements in productivity and competitiveness. This would contribute to making TEES, SPS, and TCA stronger, and actually to make clear the role of TCA to development processes.

Third, it is clear that instead of having a model of STI policy for Latin America, we need different types of STI policy strategies to strengthen the firms' TCA process in accordance with the countries' development profiles (I, II, III), which in turn will make the construction of domestic capacities stronger:[6]

- For countries with Profile III, which have more balanced systems between the TEES and SPS spheres, the focus should be on increasing productivity and improving innovation performance to approach the technological frontier; at the same time, to keep the balance with the SPS, policy also might include attention to the solution of national problems.
- For countries in Profile II, which have a bias towards the SPS and lacking in TEES, the focus should be to promote learning, imitation, adaptation, and a

[6] Dutrénit et al. (2019) analyze the link between stages of TCA at firm level and country profiles for six Latin American countries.

variety of innovation activities; at the same time, they may keep the balance with the SPS, hence policy also might include attention to the solution of national problems.

- For countries in Profile I, with high TEES performance but a weak SPS, the attention to national problems should be at the center of the STI policy. The challenge is how to keep productivity increasing with the solution of national problems and an improvement of the SPS.

13.7 Final Reflections

Latin American countries do not overcome the middle-income trap, including those more developed countries within the region. This suggests that we should change the lenses we used to analyze TCA and look at other dimensions that transcend the indicators associated with inputs and outputs of domestic STI capacities and capabilities. Even though these indicators have been appropriated for developed countries, including those Asian countries that have done the catch-up already, they result in a narrow approach to promote TCA in countries that face this trap. This chapter argues that upper-middle-income countries of Latin America still face problems to overcome the middle-income trap, and that surpass aspects related to TCA. In addition to STI performance, other dimensions of the TEES, such as economic and environmental aspects should be included in the analysis, as well as several social and political dimensions, included in the SPS.

The aim of this chapter was to identify development profiles of Latin American countries (in terms of TEES and SPS) and discuss their implications for TCA. It proposes a research design based on three steps, which combines different statistical tools: (i) to verify the existence of co-integration between the dependent variable and the indicators of the TEES and SPS spheres, (ii) to identify and estimate long-run models, and (iii) based on long-run models to identify development profiles of the countries.

Concerning the development profiles of Latin American countries, the evidence reveals that countries differ in relation to the balance between the TEES and SPS. Three profiles of countries were identified: Profile I: biased towards the TEES, and lacking in SPS development (Argentina, Chile, and Mexico); Profile II: biased towards the SPS and lacking in TEES (Bolivia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, and Venezuela); and Profile III: countries with a more balanced system in terms of TEES and SPS (Brazil, Colombia, and Uruguay).

As argued by Radosevic and Yoruk (2016), our knowledge about the factors that explain successful TCA, at the firm and national levels, is still limited. They pose that existent metrics do not capture all the technology activities observed in developing countries and emerging economies. The evidence of this chapter suggests that the STI policy oriented to strengthen TCA processes at the firm, and then country level, cannot center only on technology-related aspects, but also on the co-evolution between the TEES, the SPS, and the TCA process. We need more research to disentangle the links between the TCA processes within their broader context, including the techno-economic and environmental sphere and the socio-political sphere. In this sense, it is not simply a matter of moving from efficiency to innovation-driven growth, and then continuing the shift from "shifting wealth I" to "shifting wealth II." According to Radosevic et al. (2019), this latter means that further growth of emerging economies will be based on productivity growth supported by upgrading in technology. We agree that the middle-income trap is a blockage in the structural transformation, which cannot easily be explained. However, we disagree with the arguments that the constraints to these changes are mostly related to belonging to global value chains. This chapter suggests that the particularities of the countries' context, seen in terms of their TEES, SPS, and their interaction, are a powerful explanatory of the restrictions. We argue that we have to look at the development profile of the countries, based on their TEES and SPS.

By means of articulating into the analysis the TCA, TEES, and SPS, this chapter follows the insights of Freeman (1995) and Katz (1986, 1987), and moves their approach one step further in the direction of identifying relevant dimensions and variables, and quantitatively exploring different country development profiles. It adds to different streams of literature which have made important contribution to the understanding of the TCA processes, but they do not explore the role of TEES and SPS in their explanation of the TCA. A first stream has focused on the analysis of TCA, largely at firm level, but the authors tend to neglect the effect of the SPS (Bell and Pavitt 1995; Dutrénit 2000, 2004; Figueiredo 2001; Bell and Figueiredo 2012; Radosevic and Yoruk 2016; Radosevic et al. 2019). A second stream has centered its attention on the catching-up processes, largely at sectoral levels, but they do not look at the links with TEES and SPS (Rasiah 2003; Lee 2016; Liu et al. 2017). A third stream looks at the link between NIS and development, and refers to TCA processes; but even though the SPS is included in the analysis, they do not distinguish stages of TCA and do not explore empirically the links between TCA and SPS (Castellacci and Natera 2013, 2016; Katz 1986; Katz and Astorga 2013).

Following the "reasoned history" of Freeman (Nelson 2020) and by exploring the interaction between SPS, TEES, and the process of TCA, this chapter is contributing to opening the discussion on a topic that is usually neglected: the political economy of the TCA. In particular, our argument takes up the Latin American tradition of connecting new theories, such as advances in evolutionary theory, with an institutional and structural framework inherited from the Latin American perspective of economic thought. Fagerberg and Verspagen (2020, p. 1) highlight that: "As Freeman would have been the first to recognize, the open-ended nature of economic evolution implies that such explanatory frameworks and the theoretical perspectives underpinning them will be in constant need of scrutiny (and possibly revision): 'As Time Goes By,' as he put it."

Finally, some words about the available data and the cointegration model are relevant. We do not have the data we need for this type of analysis of process of TCA, and their coevolution with the TEES and SPS, which could allow us to use evidence to inform policy and make strong recommendations. As pointed out by Radosevic and Yoruk (2016), it is necessary to build new indicators that reflect the micro behavior of different stages of the TCA, and the links between micro, meso, and macro levels. The design of new indicators and the bases for the collection of new data is itself an area of urgent research. Even though the co-integration model has conceptual and statistical robustness, the underlying notion of equilibrium is confined to processes where the linear relationships between the long-term trajectories of the variables play the relevant role. Certainly, coevolutionary models need to overcome these restrictions and move away any type of linearity.

More research is also needed on temporal variations in profiles as an evolutionary process of capability development and on how each country's profile is affected by important policy changes. But more data is needed for this type of analysis that allows for making test of structural change. Also it would be interesting to incorporate other spheres into the analysis; for instance, the geopolitical sphere certainly also affects the TCA, particularly in those countries that are more connected to global value chains or those that have an intense participation in regional integration agreements. Finally, as mentioned in Section 13.5, the evidence of the development profiles suggests a trade-off between techno-economic-environmental performance and socio-political performance; this behavior requires more research.

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PART IV

INNOVATION POLICY FOR TECHNOLOGY UPGRADING

14
Using Large-Scale Programs to Help Develop Technological Capabilities

Cases in China

Xudong Gao

14.1 Introduction

Although China is a developing country, it has made impressive progress in economic growth and technological capability development (Fu 2015; Lee et al. 2017; Zhou et al. 2016; Zhao 2018). For example, in the telecommunications industry, before 3G, Chinese firms, including Huawei and ZTE, were followers in most key technological fields. Through the development of TD-SCDMA (time division synchronous code division multiple access), which became one of the 3G international technology standards for wireless communication, local firms began to play important roles in international technology standards. In fact, in 4G and 5G, China firms, mainly China Mobile, Huawei, ZTE, and Datang, have become industry leaders in related technological fields.

Why has China been able to make rapid progress in technological capability development? Our study indicates that one strategy that proved to be of special importance is the use of large-scale programs to help with technological capability development. By "large scale programs" we mean local firms' development and deployment of complex product systems (CoPs) (Davies and Hobday 2005; Hobday 1998) to build up large technical systems such as railway systems, power transmission systems, etc. (Hughes 1987). In sectors such as the telecommunications industry, the high-speed rail industry, the power generation equipment industry, the power transmission industry, the subway equipment industry, etc., China was lagging behind the technological innovation frontier before the related large-scale programs but is now among the world leaders.

The high-speed rail industry is illustrative. Although China did not invent the high-speed rail technology, China has made an impressive achievement in building up its high-speed rail system. In 2004 the former Ministry of Railway (MOR) decided to massively transfer technology from multinational enterprises (MNEs) to help with China's high-speed rail development. On 26 October 2010, CRH380A,

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a highly localized high-speed train went into operation. On 3 December 2010, CRH380A reached an operation speed of 486.1 km/h, the highest in the world. Locally developed and manufactured new generation high-speed trains went into operation on 26 June 2017, indicating that local firms had developed strong technological capabilities in not only manufacturing but also designing and engineering. By the end of 2017, China had more than 25,000 km of high-speed rail under operation, accounting for about 60 percent of high-speed rail in the world. In 2017, more than 7 billion people traveled by high-speed trains in China.

In this chapter we try to answer the following questions: (1) How the large-scale programs were initiated, (2) What strategies the key stakeholders used to implement these programs, and (3) What theoretical and practical insights we can draw from these programs. Because of the exploratory nature of the study and the limited number of sample programs, we applied a case study method (Glaser 1978; Glaser and Strauss 1967; Yin 1989). We find that these large scale programs were initiated based on strategic intent of the central government or of large firms (Hamel and Prahalad 1989; Park 2012) to deal with perceived serious problems in the existing user–producer relationships and/or huge opportunities in changing the existing user–producer relationships (Lundvall 1992). We also found that different initiators faced different challenges, and different strategies were applied to address these challenges.

This chapter has two key contributions. First, it identifies the key factors affecting the initiation of large-scale programs and their effectiveness, so there are clear practical implications. Second, it provides new insights into the key factors affecting the evolution of CoPs and large technical systems in a large developing country context, which have important theoretical implications.

The chapter is organized as follows. First, we review the related literature. Second, we introduce the research methods and discuss the research background, data collection, and data analysis. Third, we report the key findings. Finally, we discuss the implications of the findings from this study.

14.2 Theoretical Background

We rely mainly on three streams of literature to guide our research. The first stream of literature is about CoPs (Davies and Hobday 2005; Hobday 1998; Prencipe 2000). Different from consumer goods, CoPs are complex, high-value capital goods, which tend to be produced in projects or in small batches (Editorial 2000). The capital goods nature also means that the user often plays a central role in the production of CoPs, and that non-market forces such as government policy have an important role (Davies and Hobday 2005; Edquist and Zabala-Iturriagagoitia 2012; Mazzucato 2016; Park 2012).

The balance of breadth and depth of technological capabilities is an important issue in the development and deployment of CoPs. For example, Prencipe (2000) states that engine manufacturers need a deep understanding of components' inner functioning in order to be able to specify, assess, test, and integrate components produced externally into the engine. This implies that there is no perfect overlap between the technological boundaries and the production boundaries of firms developing complex, multi-technology products such as aircraft engines.

The development and deployment of CoPs is usually done through projects which involve multiple stakeholders such as users, suppliers, government agencies, and regulators. This also implies that the creation of temporary multi-firm alliances with highly sophisticated systems integration and project management capabilities is essential (Editorial 2000; Davies and Hobday 2005).

Although we have developed important understandings about CoPs, a lot of questions remain to be answered. For example, what are the most suitable organizational forms for producing CoPs, how do firms go about building the required project capabilities, how do CoPs relate to the wider technological systems in which they are embedded and vice versa, and how can governments avoid the common problem of lock-in to major infrastructure projects (Editorial 2000)?

The second stream of literature is about large technical systems (Carlson 1991; Hansen and Rush 1998; Hughes 1987; Walker 2000). Large technical systems evolve in accordance with a loosely defined pattern and go through different stages such as invention, development, innovation, transfer, growth, competition, and consolidation (Hughes 1987). For example, the so-called "reverse salients," which could be defined as components in the system that have fallen behind or are out of phase with the others, drive the progress of growth, competition, and consolidation. Moreover, large technical systems are not purely technology determined but socially constructed. During invention and development, inventor–entrepreneurs solve critical problems; during innovation, competition, and growth, manager–entrepreneurs make crucial decisions; and during consolidation and rationalization, financier–entrepreneurs and consulting engineers, especially those with political influence, solve the critical problems.

Large technology systems usually involve huge investment and high risks, and cannot be developed without social commitments, usually including legal (especially in the form of contracts), organizational (involving producers, users, and financiers), and political (involving various actors associated with the state commitments). Huge investment and high risks also imply that much more attention needs to be given to the maintenance of reversibility and adaptability in infrastructural development (Fu 2017; Walker 2000).

The third stream of literature is about strategies and challenges in developing countries' development of large technology systems and adoption of CoPs. By definition, developing countries are followers (Amsden 1989, 2001; Amsden and Chu 2003; Kim 1997, 1998; Lall 1978, 1992; Lee 2013) and do not have as strong technological capabilities in making CoPs to build up large technology systems, so they usually rely on developed countries and MNEs.

However, relying on developed countries and MNEs in CoPs and large technology systems comes with a lot of challenges such as very high cost, problems in providing on time maintenance, etc. (Fu 2017). These challenges often induce developing countries to develop internal capabilities. In fact, there are examples showing that it is possible for developing countries to make progress in CoPs to build up large technology systems. Iran is able to leverage its local market to transfer technology, and develop not only manufacturing capabilities but also systems integration capabilities in electricity generation systems (Kiamehr et al. 2013). Brazil is very effective in the aircraft manufacturing industry (Vértesy 2017). South Korea is very successful in producing complex telecommunications equipment (Lee and Lim 2001) by developing networking capabilities among actors, acquiring knowledge and skills, and leveraging policy will and institutions (Park 2012).

All three streams of literature are important in our study. For example, all three streams of literature suggest that innovation and capability development in CoPs, which are capital goods, is different from that in mass-produced consumer goods. Both the literature on CoPs and the literature on large technology systems indicate that huge risks and high investment are involved, complex coordination among many stakeholders is required, and non-market factors need to be considered.

Furthermore, the literature on CoPs emphasizes the importance of users and user–producer links. The literature on large technology systems suggests the importance of how various kinds of commitments are made. The third stream of literature suggests the advantages and disadvantages of relying on MNEs vs. local firms in the adoption of CoPs and building large technology systems.

However, there are important questions that are not well addressed by the extant literature. For example, in the era of globalization, MNEs have a lot of advantages, and firms in developing countries usually have to join the value chain and innovation network dominated by MNEs (Ernst 2002, 2009; Ernst and Kim 2002). A good example in China is the passenger car industry. Although China has been the largest passenger car maker in the world for many years, it is MNEs rather than local firms that are leading the industry. In fact, all the top three firms are joint ventures (SAIC-VOLKSWAGEN, FAW-VOLKSWAGEN, and SGMW) led by MNEs (Volkswagen and GM).

Given the obvious advantages such as the strong brand influence of MNEs, and the big challenges such as high risks, huge investment, and complex coordination of various stakeholders, who are motivated to make the necessary risky commitments in developing and deployment of CoPs to build up large technology systems? If some stakeholders choose to do so, what are the key challenges facing them, and are they technological challenges or capabilities to coordinate various stakeholders (Gawer and Cusumano 2002; Lee and Malerba 2017; Lundvall 1992; Porter 1990)? In addition, the specific strategies used to address these challenges also need to be considered. As will be reported, our study could provide important insights into these questions and make a contribution to the extant literature.

14.3 Research Methodology

14.3.1 Research Background

Because of the exploratory nature of the study and the limited number of samples, we applied a case study method (Glaser 1978; Glaser and Strauss 1967; Yin 1989). More precisely, this chapter is based on three case studies, focusing on eight large-scale programs (Table 14.1).

The first case study is about China's telecom equipment industry, which offers a rich opportunity for the study of technological catching-up and technological leapfrogging. In the 1980s, China opened its domestic telecom equipment market to MNEs, which dominated this market for many years. However, local firms such as Huawei and ZTE were able to gradually improve their technological capabilities and are now industry leaders. For more than twenty years, we have been systematically studying this industry, focusing on how local firms have been able to change from technology followers to leaders (Gao 2011, 2014, 2019; Gao and Liu 2012).

Table 14.1 List of programs studied

Programs	Brief description
Yun 10	Initiated in 1972 and ended in 1986. First try for China to develop large civil aircraft. There are a lot of debates about the success and failure of the program.
The three Gorges program	The program created the opportunity for local power-generating equipment makers to improve technological capabilities and gradually provide advanced products such as 1000MW class ultra-super critical turbine.
Localization of subway equipment	Initiated in the late 1990s by Shenzhen Metro and has proved to very successful in helping local firms develop advanced subway equipment.
3G/TD-SCDMA	Initiated mainly by Datang, key technology developer for TD-SCDMA and TD-LTE/TD-LTE Advanced (3G and 4G international standards).
High-speed rail	Initiated by the former MOR. Started by transfer technology from MNEs but proved to be able to provide opportunities for local firms to develop leading technology and products.
C919	Initiated in 2008 by the central government. (After Yun 10.) New try for China to develop large civil aircraft.
UHV Transmission	Initiated by the State Grid, the largest power transmission company in China.
Xiqidongshu/ CNPC	Initiated in 2000 to transport natural gas from the western part of China to the eastern part, because most of China's natural gas resources are in the western part of the country, but the consumption is mainly in the economically more developed eastern part.

Source: Composed by authors.

The second case study is about technological innovation at state-owned enterprises (SOEs). In China, SOEs are important players in the economy. For example, in 2018, the sales revenue for SOEs was RMB 58.75 trillion Yuan. In fact, 120 firms from mainland China made the list of 2018 Fortune 500, and eighty-three of them are SOEs.

Specifically, in the past ten years we have participated in a series of studies about technological innovation at large SOEs sponsored by different divisions of the State Owned Assets Supervision and Administration Commission of the State Council (SASAC) and the National Development and Reform Commission (NDRC) (Gao 2019; Ralston et al. 2006; Shen and Feng 2010; Shi 1998). Firms studied include China CNR Corporation Limited (CNR, which merged with China CSR Corporation Limited, CSR, in 2015 to form the current CRRC, the key supplier of high-speed rail equipment in China), Harbin Electric Corporation (HEC, one of the top three power generating equipment makers in China), Dongfang Electric Corporation (DEC, one of the top three power generating equipment makers in China), State Grid Corporation of China (SGCC or State Grid, the largest power transmission company in China), China National Petroleum Corporation (CNPC, the largest oil and gas producer in China), China Petrochemical Corporation (Sinopec Group, the second largest oil and gas producer in China), and the Shenzhen Metro Group Co., Ltd. (Shenzhen Metro).

The third case study is about user-sponsored technological innovation, started in 2018 and sponsored by the State Grid, focusing on the ultra-high-voltage (UHV) transmission system, the Beijing–Shanghai high-speed rail line, the three Gorges program, the large civil aircraft sector (Yun 10 and C919), and the automobile sector. The aim is to develop a deep understanding about why some sectors have been very successful in technological capability development (for example, the UHV transmission system), while some are not (for example, the traditional car sector).

14.3.2 Data Collection

Although data collection proved to be a time-consuming and challenging process, we are able to collect sufficient data because of strong support from sponsors of our research. Data were collected mainly through semi-structured interviews, complemented by archival documents and public information. In the case of Yun 10, which was initiated in 1972 and ended in 1986, we relied mainly on secondary sources (for example, Wang 2012).

People interviewed included executives, middle level managers, engineers, and scientists, and frontline employees in firms, government officials at different levels, and scholars from universities and research institutes. These people are familiar with the programs studied, and in many cases, played important roles in making decisions to initiate and implement these programs, and made technological contributions. We interviewed more than 140 people, and an interview usually lasted one to two hours.

14.3.3 Data Analysis

Because a case study methodology was used, it was necessary to conduct data collection with data analysis simultaneously. Any data collection provides the basis for a certain level of data analysis, and any data analysis guides further data collection (Glaser 1978).

The process of continuous iteration between data collection and data analysis led to the emerging of new theoretical concepts. For example, the concept of strategic intent to change the existing user–producer relationships (Davies and Hobday 2005; Lundvall 1992) emerged quickly and turned out to be the key concept to connect other theoretical concepts.

Specifically, we learned that all key initiators of the eight programs studied showed strong intention to change the existing user–producer relationships, although they faced huge challenges, given the dominant position of MNEs in related sectors. In fact, in all of the programs discussed in this chapter, before the implementation of these programs, MNEs' influence was obvious. From a user–producer relationship perspective, local firms as users were in a highly passive position. They usually had little choice but to accept high cost and bad service. Accordingly, they were highly motivated to change the status quo, although this means that they had to face many challenges, because the change would involve high risks and impact many stakeholders such as the government and the public, let alone the users and producers themselves (Carlson 1991; Clarkson 1995).

In addition to the strategic intent to change the existing user–producer relationships, other theoretical concepts included the following: (1) Strategies addressing key challenges in changing existing user–producer relationships, (2) The complicated impact of government policy and more broadly speaking, the social environment such as various people's attitudes towards opening the market to MNEs and the promotion of indigenous innovation, (3) Outstanding leaders, who are powerful leaders in important positions for a long enough time to carry out the strategic intent, and (4) The varied effectiveness of changing existing user–producer relationships, which is indicated by the changed or unchanged user–producer relationships and local firms' technological capabilities.

For example, the concept of the complicated impact of government policy and the social environment indicates that government policies and the social environment in China are not always supportive (Kshetri et al. 2011), which is closely related to the idea of innovation as a complicated sociopolitical process (Gao 2014; Tushman and Rosenkopf 1992).

The concept of "outstanding leaders" is also of crucial importance. Because government policies and the social environment in China are not always supportive, and the programs usually lasted for as long as more than ten or even twenty years, the role of key people became really important. For example, in the case of 3G/TD-SCDMA, when government policies were full of ambiguities, the role played by key people such as Mr Tang Ruan, Mr Zhou Huan, and Mr Li Shihe became the key for the program to be successful (Gao 2014; Gao and Liu 2012).

14.4 Key Findings

In this part we report some of the most important findings as illustrated in Figure 14.1.

14.4.1 Initiation of Large Scale Programs Based on Strategic Intent

Given the high investment and high risks involved, and strong commitment needed (Davies and Hobday 2005; Hughes 1987; Walker 2000), why did related organizations choose to initiate the eight programs? The first finding of the study was that these programs were initiated based on initiators' strategic intent, which reflected perceived serious problems in existing user–producer relationships and/or huge opportunities to change the existing user–producer relationships (Lundvall 1992), although the key initiators could have different identities (firms or government agencies, users or producers).

Specifically, we found that the eight large-scale programs were initiated by three kinds of organizations: government agencies, users of CoPs to build large technical systems, and producers of CoPs. For example, in the case of the three Gorges program, the central government was the initiator. We can also put Yun 10, C919, and even the high-speed rail program into this category. In the case of UHV transmission, the State Grid was the key initiator. To some extent, the subway equipment program and the Xiqidongshu/CNPC program could be included in this category. In the case of TD-SCDMA, the central government played a very important role, but Datang should be recognized as the key initiator.

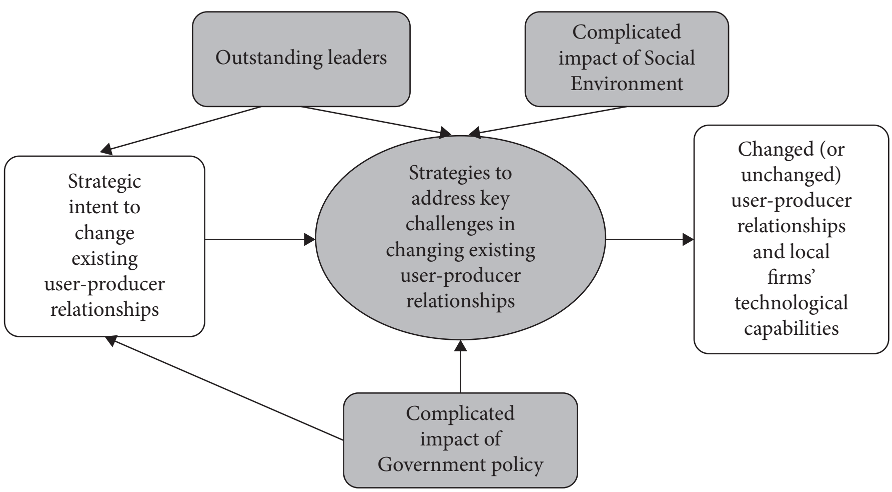

Figure 14.1 Key factors affecting programs studied

It is also found that clear strategic intent was behind the initiation of the eight programs, although the specific contents of the strategic intent could be different. For example, in the case of the Three Gorges program, the central government had a clear understanding that this program was a good opportunity to change the existing user–producer relationship, which was dominated by MNEs, by transferring advanced technologies from MNEs and helping improve local firms' technological capabilities (Zhang 2018). In fact, the program was so important that key MNEs in the power equipment industry were willing to cooperate with the Chinese central government in order not to lose out in competing with each other. Under this situation, the Chinese central government's policy was to leverage this program to not only buy products from MNEs but also transfer technology and improve local firms' indigenous technological capability.

In the case of UHV transmission, the State Grid's strategic intent was to deal with a mismatch in China's energy production and energy consumption: key production regions are not key consumption regions. In China, coal is the most important energy source, accounting for more than 60 percent of energy consumption. The challenge is that coal is mainly located in the western part of the country, while economic centers are mainly located in the eastern part. Transporting coal from the west to the east is needed. However, coal transportation is costly. This means that using coal to generate electricity in the west and transmitting electricity to the east through UHV transmission network is a much better choice. The then CEO/Chairman of State Grid, Mr Liu Zhenya, strongly believed in the benefits of UHV transmission and pushed the development of UHV transmission networks during his tenure (2004–16). In this case, the change in the existing user–producer relationships is reflected in State Grid's taking the lead to push and coordinate MNEs (and local equipment suppliers) to make highly customized UHV transmission equipment and network, rather than passively using products made by MNEs (Liu 2012).

In the case of the subway equipment industry, the strategic intent was to develop a world-class subway company with the help of local firms, in addition to MNEs, which not only charged very high prices but also failed to provide on-time maintenance. Specifically, in the 1990s, MNEs dominated the Chinese subway equipment market, and the cost of building subway lines was extremely high. Usually it would cost RMB 600~800 million Yuan to build up to 1 kilometer of subway line. Under this situation, in 1995 the State Council issued a regulation and stopped new subway construction in China, worrying that the government could not provide sufficient financial support in a sustainable manner. This regulation turned out to have flaws, because more and more cities in China showed a strong interest in building their subway systems. As a response, in 1999 the central government agreed to allow for subway construction, conditional on subway equipment localization in order to reduce investment cost.

The Shenzhen Metro regarded the policy change as a good opportunity to develop a world-class subway company and actively helped local firms to improve their technological capabilities. This has proved to be successful. Local firms have gradually developed their technological capabilities and are increasingly able to compete with MNEs through advanced products and timely services at much lower costs. Local firms are now providing 80 percent of subway vehicles, 70 percent of traction systems, and 70 percent of braking systems in the domestic market. In addition, local firms are also exporting their products not only to developing countries but also to developed countries. For example, the US subsidiary of CRRC signed a contract in January 2015 to make 284 subway vehicles for MBTA's red line and orange line in Boston.

In the case of TD-SCDMA, why was Datang interested in strongly promoting the TD-SCDMA program? Two factors are important. First, Datang's history and its identity (Mourkogiannis 2006; Schein 1992). Datang was transformed into a profit-driven firm from the China Academy of telecommunications Technology (CATT), which was set up in 1957 by the former Ministry of Posts and Telecommunications, with the mission of developing advanced technologies for the Chinese telecom industry. Even when Datang was clear that it did not have the required resources to support the development of TD-SCDMA, it did not choose to give up but took huge risks to continue the exploration work. In fact, it once put its headquarters building in pledge in order to obtain bank loans to support the development of TD-SCDMA.

Datang's top management team has strong beliefs about the importance of indigenous innovation, and is committed to making contributions to indigenous innovation. For example, Mr Zhou Huan, the former Chairman of the Board and CEO of Datang, was once the Director General of the Department of Science and Technology of the former Ministry of Posts and Telecommunications. He supported the development of SCDMA, one of the most important bases of TD-SCDMA, using government money. Mr Zhou also created a favorable environment within Datang to support the development of TD-SCDMA. He was clear that his performance evaluation by SASAC could not be high with this kind of decision, because the financial return of promoting TD-SCDMA must be risky, slow, and uncertain when few people believed in the success of TD-SCDMA. However, he was willing to take the risk. This is why many people argue that Mr Zhou is not managing Datang as a company but as a state research institute.

Second, Datang wanted to improve its industry position. In the early 1990s, Datang was as famous as Huawei and ZTE in the telecom equipment industry. However, by the late 1990s, it was obvious that Datang was lagging behind. Because Datang was the leader in TD-SCDMA technology, it believed that TD-SCDMA could be an important opportunity for it to catch up and even leapfrog.

14.4.2 Key Strategies to Build New User-Producer Relationships

The second major finding was that different strategies were employed according to the key challenges of the eight large-scale programs. Specifically, when the central government is the key initiator, technology transfer from MNEs was more likely to be the key challenge, so leveraging the huge domestic market to transfer technology is an important strategy. However, when the key initiator is a firm, especially a producer, the key challenge is more likely to be the so-called "latecomer disadvantage," which means that locally developed technologies and locally produced products are hard to be accepted by the market (and other institutions), because people believe that MNEs' technologies and products must be more advanced (Gao 2007; Liberman and Montgomery 1988, 1998).

Take the high-speed rail program as an example. In 2003 the MOR wanted to modernize China's railway network: in that year, China's railway was 72,000 km, and MOR decided to increase this number to 100, 000 km by 2020. The number was further increased to 120, 000 km in the 2008 adjusted plan. In order to develop an advanced railway network as quickly as possible, the MOR decided to transfer advanced technologies from MNEs rather than waiting for local equipment makers' technological progress. However, MNEs were interested in selling products at very high prices rather than transferring technology. To deal with this challenge, MOR decided to deploy the strategy of "trading market for technology," making it very clear that technology transfer is a precondition for winning orders in the Chinese high-speed rail market (Mu and Lee 2005).

MOR's policy changed MNEs' behavior. Alstom, Bombardier, and Kawasaki Heavy Industries agreed to transfer technology in the first round of bidding and won big orders. Simons refused to transfer technology in the first round of bidding and did not get any orders, so the firm changed its behavior dramatically in the second round of bidding and won big orders.

The situation of TD-SCDMA, which was mainly initiated by Datang, a CoPs maker, is very different. Although the central government was interested in improving local firms' technological capabilities, and decided to make China an innovation oriented country in 2006, Datang (and other organizations promoting TD-SCDMA) faced a lot of challenges. Specifically, these challenges included the following: (1) telecom service providers, including domestic ones, were not willing to adopt TD-SCDMA; (2) other telecom equipment makers, including domestic ones, were reluctant to adopt TD-SCDMA; (3) the central government had ambiguous policies towards TD-SCDMA.

For example, among the six domestic telecom service providers, only two small firms, China Tietong and China Netcom, once showed some interest in adopting the TD-SCDMA standard before the restructuring of the telecom service industry in China in 2008. China Mobile, which officially adopted TD-SCDMA in January 2009, had been very reluctant to choose this standard (Li 2006).

The support from the Chinese government is also full of ambiguity. According to Dr Li Shihe, the then vice president of Datang, "TD-SCDMA will die soon, because government agencies have not developed a clear plan about TD. No one has made it clear whether TD will be used in China. No one knows which service provider will use TD" (Li 2008).

In order to deal with the above challenges, Datang relied on a lot of strategies such as the development of a strong “informal social network” including non-major stakeholders such as noted scholars, government officials (including retired ones), and people in the media (Clarkson 1995).

One function of the informal social network was to help government officials, especially top leaders, make informed decisions. For example, most people believed that WCDMA and CDMA2000 were more advanced than TD-SCDMA, and this created huge negative impact on the development and adoption of TD-SCDMA in China. To address this problem, Datang asked some noted scholars to help. Professor Li Jinliang at the 7th Research Institute of the China Electronics Technology Group Corporation is a typical example.

One of Professor Li’s key research conclusions is that TD-SCDMA enjoys big technology advantages over WCDMA and CDMA2000. Professor Li also argues that the obvious technology advantage of TD-SCDMA would lead to low cost advantage (Li 2006). Because Professor Li is a noted expert in wireless telecommunications in China, his study and publications directly helped the government build up confidence in supporting TD-SCDMA.

The strategies for programs such as the UHV transmission, with the key initiators as users, also have their characteristics. On the one hand, these programs also suffer from the huge negative impact of “latecomer disadvantage.” On the other hand, because the key initiators are users, they could leverage their big internal market to reduce the negative impact. The comparison between the subway equipment program and the TD-SCDMA program is illustrative.

When Shenzhen Metro told local equipment makers that it would procure from local firms, these local firms were highly excited and promised to invest in R&D and production even if they were not making money from the first order, arguing that the opportunity provided by Shenzhen Metro to improve their technological capability was more important than making money in the short term.

In contrast, in the early days of TD-SCDMA, although Datang took special measures such as sharing its propriety technology with its direct competitors, including ZTE and Huawei, a highly controversial practice, which could negatively impact Datang’s future competitive position, most local firms were still reluctant to invest in TD-SCDMA. However, the situation began to change dramatically when China Mobile, the largest telecom service provider, began to take the lead in promoting TD-LTE, the next generation technology. Local firms were very active in joining China Mobile to adopt TD-LTE.

14.4.3 Impact of Government Policies and the Social Environment

The extant literature emphasizes the importance of the government catching up in CoPs and large-scale technical systems (Fan 2006; Mu and Lee 2005). For example, South Korea is very successful in TDX, CDMA, and WiBRO, and a key reason is the creation of favorable conditions such as financing R&D and assuring commercialization through the domestic market (Park 2012). In contrast, this study finds that the impact of government policies and social environment is complicated (Carlson 1991; Hughes 1987; Walker 2000). We first look at the impact of government policies. In contrast to the argument that the Chinese government is always very supportive of local firms' technological capability development (Kshetri et al. 2011), our research indicates that the role of government policies in China is complicated. The following are three examples.

The first example is the subway equipment localization. In this case, the key initiator was the Shenzhen Metro, but the central government's policy was supportive in the sense that it created a favorable environment. Specifically, because local governments are the owners and investors of the subway companies, they usually faced a big dilemma. On the one hand, they saw huge benefits from successful localization of subway equipment because the financial burden for them would be lower after localization. On the other hand, they did not want to expose their subway systems to a higher rate of operation risks, especially serious accidents, by using locally made equipment, because they did not believe that locally made equipment could be as reliable as that of MNEs'.

In this situation, the policy of the central government proved to be very important and supportive. In February 1999, the State Council issued a regulation, requiring that the localization rate of all subway vehicles and other equipment reach 70 percent in order to get approval for a city to build up its subway systems. NDRC also provided financial resources to support locally developed equipment. Leveraging the policy of the central government, the Shenzhen Metro was able to gain support from local government to promote subway equipment localization.

The second example is the Yun 10 program, which could indicate the changing and ineffective nature of government policies. This program was started in 1972 and stopped in 1986. This is the first attempt by China to develop large civil aircraft. Although Yun 10 did its first fly test in 1980, it became more and more difficult to get support from the central government. In 1982, even after the Shanghai Municipal Government promised to provide half of the budget to continue the program, the central government refused to provide more financial support and the program was stopped in 1986.

Although there are many debates about the success and failure of Yun 10, policy change seems to be the key factor. Specifically, from the early 1980s, China began to explore the possibility to co-develop large civil aircraft with MNEs. In fact, in April 1985 China signed a contract with McDonnell-Douglas Corporation to assemble MD-82. It turned out that the collaboration with MNEs to develop large civil aircraft failed (Wang 2012; Zhao 2018).

The third example is the TD-SCDMA program. Why was it so difficult to promote TD-SCDMA in China, even when it became clear that technology transfer from MNEs was becoming more and more difficult and indigenous innovation was becoming more and more important? One reason is the transitional nature of government policy (Gao 2014). On the one hand, a key policy of opening the Chinese economy to the outside was to transfer technology from advanced economies. In fact, to some extent, this policy proved to be very successful (Zhang 2000).

On the other hand, the policy of encouraging indigenous technological innovation reflected an inevitable trend. MNEs were becoming more and more reluctant to transfer technology to local firms. This meant that local firms have had to rely more and more on internal technology development. Without indigenous technological innovation, it'll be very hard for local firms to survive.

For a specific firm, it might be easier to balance technology transfer and indigenous technological innovation. However, for government agencies, the internal conflict between the two policies is obvious and big. Specifically, when some stakeholders argue that choosing WCDMA or CDMA 2000, which are mainly based on MNEs' technologies, rather than TD-SCDMA, is following the policy of opening to the outside, it'll be very hard for the government not to support these stakeholders. However, this means that the support for TD-SCDMA has been weakened.

Now we turn to the discussion of the impact of the social environment. As analyzed previously, a key policy of opening the Chinese economy to the outside is to transfer technology from advanced economies, and this policy proved to be successful for many firms. The impact of this is obvious: Chinese society had a strong faith in the benefits of technology transfer. In this situation, it proved to be very difficult to believe in indigenous technological innovation, let alone to provide strong support. However, society is not homogenous. It's not hard to find stakeholders who have different opinions about the technology transfer policy and strongly believe in the benefits of indigenous technological innovation. It proved that these stakeholders could play very important roles, even though they are in the minority.

As mentioned earlier, Datang developed an informal social network to help promote its TD-SCDMA technology. Although most people and organizations were not active in supporting or even opposing TD-SCDMA, some highly influential stakeholders could change the balance between those supporting TD-SCDMA and those opposing it.

For example, although the industrialization trials showed that TD-SCDMA was suitable for building large-scale nationwide telecom networks in July 2005, service providers were not interested in conducting commercialization trials. To deal with this challenge, Datang invited three noted scientists (the president of the Chinese Academy of Sciences, the president of the Chinese Academy of Engineering, and the Chairman of the Chinese Association of Science and Technology) to provide support. These three scientists wrote a letter to the top leaders of the central government, requesting that the government support TD-SCDMA. The result was that some top leaders asked related government agencies to support TD-SCDMA. This proved to be of crucial importance, and the development of TD-SCDMA entered a new stage.

14.4.4 The Crucial Role of Outstanding Leaders

The eight programs have had different degrees of success. In addition to the previously reported factors, the role played by "outstanding leaders" is of crucial importance (Chandler 1977, 2005; Chandler et al. 1997; Schein 1992). To some extent, this factor might be the most important factor affecting the success or failure of a specific program.

Our study indicates that these "outstanding leaders" have several characteristics: (1) They are in important positions and could mobilize a large amount of resources to support the development of the programs; (2) They are highly passionate about the strategic intent of the programs and are willing to take high risks in realizing the strategic intent; (3) They are able to stay in the important positions for a long time, in some cases, for more than ten or even twenty years.

According to the extant literature, the importance of the above characteristics of "outstanding leaders" is understandable. For example, the deployment of CoPs and large technical systems usually involves high investment (Davies and Hobday 2005), so the holding of important positions might be a precondition to mobilize the high investment needed.

Holding important positions for a long time is as important, if not more important, because the deployment of CoPs and large technical systems usually takes a long time and involves high risks. Take the Shenzhen Subway program as an example. Mr Jian Lian was one of the key leaders of the Shenzhen Metro when the firm was established in 1998, and retired in 2019. Mr Jian Lian did several things during his long tenure at Shenzhen Metro.

First, he initiated this program from the start of the firm when most subway firms in China were highly reluctant or even refused to do similar things. In addition to the requirement of localization by the central government, Mr Jian Lian pointed out that he initiated the program because he wanted to make Shenzhen Metro a leading company in the world based on digital technology. However, he realized that he could not rely on the existing MNEs to realize this ambitious goal because these firms were not responsive enough. He had to rely more on local firms.

Second, Mr Jian Lian had to implement his plan step by step because of the huge negative impact of "latecomer disadvantage." Specifically, he had to start the localization process from technologically less sophisticated equipment and gradually move on to more advanced equipment. In fact, the whole localization process took about twenty years, almost the whole tenure of his Shenzhen Metro experience.

Third, Mr. Jian Lian was well positioned to manage big risks in the program. For example, he was in charge of both equipment procurement and daily operations of the firm. Leading equipment procurement gave him the power to procure equipment from local firms, and leading daily operations provided the power to test the performance and reliability of the locally procured equipment. In fact, many problems were found during the testing process, and local equipment suppliers could improve their equipment based on the problems found. Having two important positions made it much easier for Mr Jian Lian to create opportunities for local equipment suppliers to develop and improve their technology and products.

Compared with the subway equipment program, the Yun 10 program was largely a failure. Why did the Yun 10 program fail to move on to the next steps of further development and commercialization after the successful development of the aircraft? A key reason is the absence of strong support of "outstanding leaders." It was true that the Shanghai Municipal government was highly supportive, but there were no higher level leaders at the central government to provide strong support (Wang 2012). This is also in sharp contrast with the three Gorges program, which was initiated by the Chinese central government and significantly helped improve China's power generating equipment sector. For example, from the 1980s, Mr Li Peng, first as Minister of the Ministry of Electricity, then as vice Prime Minister, and finally as Prime Minister and Chairman of the standing committee of the national people's congress, served as either the direct leader of the program at the State Council level or as state leader providing strong support to the program.

14.5 Discussion and Conclusion

14.5.1 Evolution of Large Technical Systems in Large Developing Countries

Our study provides new insights into the key factors affecting the evolution of CoPs and large technical systems in developing country contexts (Bonaccorsi and Giuri 2000; Carlson 1991; Hughes 1987; Walker 2000). For example, the extant literature argues that "reverse salients" drive the evolution of large technical systems (Hughes 1987). What are "reverse salients" in a large developing country context? Our study indicates that MNEs' charging extremely high price and failing to provide timely service could play the role of "reverse salients," and result in the development of CoPs and large technical systems, with local firms as leaders. Theoretically, this might change the dynamics of the evolution of large technical systems dominated by MNEs.

The extant literature also suggests that large technical systems are socially constructed, and different people such as inventor–entrepreneurs, manager–entrepreneurs, and financier–entrepreneurs and consulting engineers play crucial roles at different stages (Hughes 1987). Our study shows that in China both government officials and large firms' executives, who are not inventor–entrepreneurs, could initiate and manage the development of CoPs and large technical systems. More importantly, "outstanding leaders," who could be firm managers or government officials, are able to be successful in initiating and managing the development of CoPs and large technical systems.

14.5.2 Key Challenges Facing Large-Scale Programs

Given the characteristics of CoPs and large technological systems such as high investment and high risk, there could be many challenges. Among all the challenges, what is the biggest one? Our study seems to illustrate that it is the huge negative impact of latecomer disadvantage (Gao 2007; Liberman and Montgomery 1988, 1998).

More specifically, the biggest challenge of latecomer disadvantage shows up when the initiator of a large-scale program is not a government agency but a firm (either a user or a producer). In fact, when the government is the initiator, as discussed earlier, technology transfer from MNEs is relatively easy. This is because the government has strong bargaining power, especially when it chooses to leverage the huge domestic market in China. This can also help explain why South Korea is very successful in catching and leapfrogging in CoPs (Park 2012).

When a firm, especially a producer, is the key initiator, the situation can be very different. In fact, although latecomers in any country face latecomer disadvantage, at the firm level, the negative impact in China is much bigger. First, China chose to join the existing value chain and innovation network dominated by MNEs in the early 1980s. Second, China's economy experienced very fast growth for many years until at least the 2008 economic crisis started in the US. During those years, people gradually developed deep trust about opening the economy, transferring technology from MNEs, and joining the MNEs-dominated value chain and innovation network. Accordingly, latecomer disadvantage became very big, and it was very hard to make changes such as carrying out large-scale programs aimed at changing the existing value chain and innovation network dominated by MNEs.

Table 14.2 is an example to illustrate the huge negative impact of latecomer disadvantage in the process of developing TD-SCDMA in China.

14.5.3 Special Role of Large Firms

If latecomer disadvantage is a major challenge, how could this disadvantage be overcome? Our research shows that large firms (which are mostly SOEs in today's China), could play a unique role (Chandler 2005; Chandler et al. 1997). In fact, in the large-scale programs we studied, all key initiators were SOEs or government agencies (and these government agencies ultimately need to rely mainly on large SOEs to carry out the programs). These SOEs have the resources and capabilities to carry out large-scale programs.

First, large SOEs as users could create demand to "pull" participants to carry out large-scale programs to change the existing value chain and innovation network dominated by MNEs. The UHV Transmission program is a good example. In order to carry out the program successfully, the State Grid actively played the leading role of network coordination (Cusumano 2010; Gawer and Cusumano 2002) by showing

Table 14.2 The impact of latecomer disadvantage: The case of TD-SCDMA

People and organizations	Perceptions and views
Government officials	
Song, Zhiyuan, Vice Minister of the former MII	January 1998: when the majority of the participants of the Fragrant Hill Meeting did not support the idea of proposing TD-SCDMA to ITU, Song, Zhiyuan said: "I suggest we agree. Even if it failed, it could be regarded as a success, because it could help us accumulate experience".[a]
Minister level government official of the former MII	December 2002: When visiting Datang, the government official asked: "Why Datang insists that we develop TD-SCDMA when MNEs have developed WCDMA and CDMA2000?"[b]
Minister level government official of the former Informationization Office of the State Council	October 2005: "Why we do not give clear support to TD-SCDMA? No support is the biggest support. We are waiting to see if TD-SCDMA would become mature".[c]
People from firms	
Zhou, Huan, Former COE of Datang	March 2002: "I am not expecting that the government would make TD-SCDMA the only 3G national standard. What I am expecting is that the government could say that TD would be used even with 10 preconditions: TD is mature, is reliable, is low cost, is of high quality, . . . now the government is not giving enough support to TD".[d]
Yang, Zhiqiang, Former Vice Director, Technology Department, China Mobile	August 2003: "WCDMA is the best choice for China Mobile to move to 3G, and TD-SCDMA could be a complement".[e]
Wang, Xiaochu, former Chairman of China Telecom	March 2006: "The customers are the underlying forces for choosing which 3G standard", indicating that China Telecom favor WCDMA.[f]
Li, Shihe, Datang Mobile, Father of TD-SCDMA	April 2008: "TD-SCDMA will die soon, because government agencies have not developed a clear plan. No one has made it clear whether TD-SCDMA will be used in China. No one knows which service provider will use TD-SCDMA".[g]
Former VP of Strategic Planning, Huawei	July 2011: "Why Huawei was not active in investing in TD-SCDMA for a long time? The government policy was not clear. It was not clear whether or not TD-SCDMA would be used in China. Huawei is a company, so we have to listen to the market".[h]
Other people	
Liu, Chunhui, Telecom Reporter	February 2005: "Professor Hu, Angang from the Tsinghua University made unfair comments on TD-SCDMA in his 3G report. He did not mention problems occurred in testing other 3G technologies but highly exaggerated that in TD-SCDMA".[i]
Li, Jinliang, Former Chief engineer, 7th Research Institute of the China Electronics	February 2010: In commenting on the argument that TD-SCDMA is a failed patriotic experimentation, Li, Jinliang said: "In the future when we reflect on TD, we'll realize that it's not a wwdead 3G standard but a classic textbook on indigenous innovation from 3G to 4G".[j]

[a] Yang and Lu (2010).
[b] Interview at Datang (January 7, 2011).

[c] Interview at former Informationization Office of the State Council (June 8, 2007).
[d] Interview with Zhou, Huan (2002, March 25). Retrieved from http://www.yesky.com/NetCom/218424581927469056/20020325/1603507. shtml.
[e] Yang, Zhiqiang's speech at TD-SCDMA Summit. Retrieved from http://tech.sina.com.en/it/t/2003-08-28/1632226667.shtml.
[f] Wang, Xiaochu: China Telecom has developed a complete 3G plan. Retrieved from http://www.21cbh.com/HTML/2006-3-27/29065.html.
[g] Li, Shihe, Father of TD: TD is suffering an euthanasia. Retrieved from http://tech.sina.com.en/t/2008-04-21/11532151035.shtml.
[h] Interview with former VP of Strategic Planning, Huawei (July 8, 2011).
[i] Liu, Chunhui: Hu, Angang's comments on TD-SCDMA are unfair. Retrieved from http://biz.163.com/05/0224/10/lDBM3PTF00020QED.html.
[j] Li, Jinliang refute the claim that TD-SCDMA is a failure. Retrieved from http://www.dvbcn.com/2010-02/03-44888_3.html.

Source: Gao and Liu 2012, p. 537.

State Grid's high commitment, setting up clear and specific goals for the UHV technology system and that of the participants, and offering attractive support, including financial support. This not only increased the confidence of the participants but also helped them develop a clear understanding about the benefits of supporting State Grid in the development of UHV technology (Liu 2014).

Second, large SOEs, with their long history and accumulation of capabilities, including technological capability, are capable of leading the implementation of large-scale programs. For example, in 2018, CNPC was the largest oil and gas supplier in China, and the second largest company in China. In 2018 CNPC's revenue was more than 2.35 trillion RMB.

Investing in R&D is a basic condition for technological progress (Fan 2006; Kim 1997, 1998; Lee and Lim 2001). This study found that large SOEs have the strength to make a high resource commitment in R&D. For example, both CNPC and Sinopec Group have comparable R&D investment to MNEs. In as early as 2010, CNPC's R&D investment was $1.4b, which surpassed that of Exxon Mobile (about $1b).

In the case of high-speed rail, before technology transfer from MNEs, the MOR had developed the DJJ2 high-speed train, which was based on internally developed proprietary technology. DJJ2 reached a speed of 321.5km/h in an experiment conducted in November 2002. High-speed trains based on transferred technology did not reach this speed until April, 2008 (Interview, NCR President and vice Chief Engineer, 29 July 2010). This accumulation of internal capabilities is the basis for the absorption and improvment of high-speed train technologies transferred from MNEs (Cohen and Levinthal 1990).

To summarize, this chapter applied a case study methodology and studied eight large-scale programs. The essence of these programs was to change the existing value chain and innovation network, which was dominated by MNEs, to create local firms led new user-producer relationships (Davies and Hobday 2005; Lundvall 1992). Generally speaking, most of the large-scale programs have proved to be effective. Facilitated by these programs, local firms have made impressive progress in improving their technological capabilities, and reshaping the user–producer relationships.

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15

New Industrial Innovation Policies in a World of Global Value Chains

Carlo Pietrobelli

Globalization and fragmentation of production have been a defining feature of the international economy during the last two decades. Global Value Chains (GVCs) have spread to cover many countries and sectors, structurally changing the way business is organized, and production is traded internationally. Different shares of value are generated in different segments of the chain, and companies struggle to position themselves and retain competitiveness in the most profitable activities along the chain (Gereffi et al. 2019; Kaplinsky 2000).

This process has deepened over the years, in spite of recent setbacks and the rising protectionist tendencies. The foreign value-added content of exports ("backward participation," i.e. the value that is imported by a country and contributes to its exports) in most major economies represents substantial shares of gross exports (Figure 15.1). Although we record substantial differences across countries, data on foreign value-added of manufactured exports confirm that most countries participate in this mode of organized international production. The share of intermediate imports in gross imports—a way to look at GVCs from another perspective—is also steadily high, with most countries exceeding the 50 percent mark (Figure 15.2).

Interestingly, developing countries appear to record higher foreign value-added shares than Japan, the US, and Europe. Whilst this share has been falling from 2005 to 2015 in China, as a consequence of growing industrial maturity and of a rising domestic consumption of what the country produces, it is still increasing in a country like South Africa. South Korea seems to be following the steps of China, but with a lag. Lee et al. (2017) come to similar conclusions with different sources of macro and firm-level evidence: GVC integration occurs in different ways in different countries, and accompanies different development strategies.

Some changes in GVCs have been observed in a recent report (McKinsey 2019). These include the lower trade-intensity in value chains, with exports declining as a share of gross output in goods-producing value chains. Moreover, the role of services is growing (Figure 15.3), and GVCs are becoming more knowledge-intensive and reliant on high-skill labor. The latter occurs together with a remarkable increase in the investments in intangible assets such as R&D, brands, and intellectual property.

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DOI: 10.1093/oso/9780192896049.003.0015

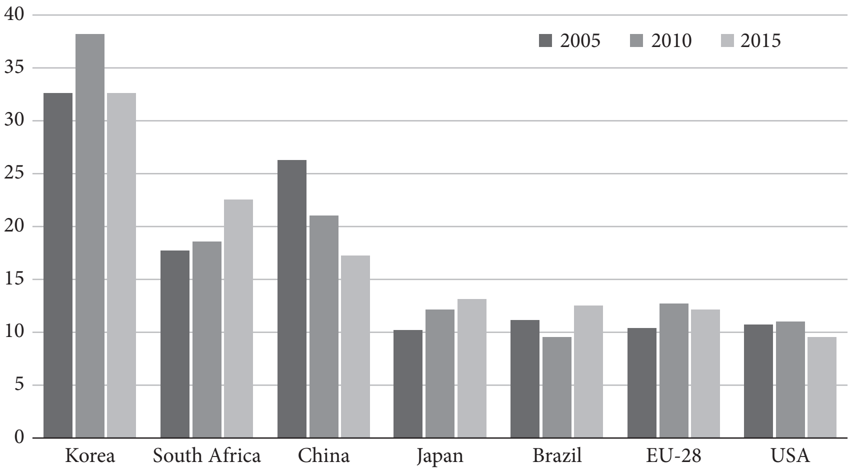

Figure 15.1 Backward participation in GVCs: Foreign value-added share of gross exports. selected countries, 2005, 2010, and 2015
Source: Pietrobelli and Vezzani mimeo, from OECD data.

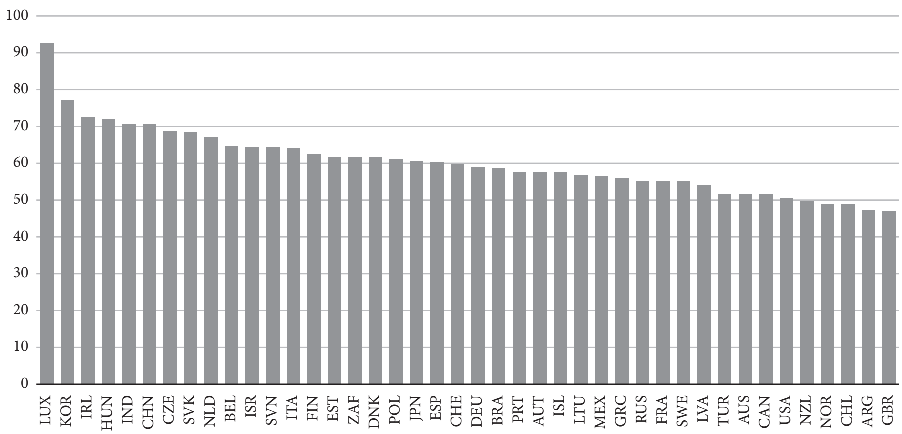

Figure 15.2 Share of intermediate products in gross imports, 2015
Source: Pietrobelli and Vezzani mimeo, from OECD data.

Finally, the regionalization of GVCs, that to some extent has always been a typical feature, is rising, with companies establishing production in proximity to demand, especially in Asia and Europe. According to the report, three forces would explain these changes: (i) emerging countries are consuming more of what they produce and exporting a smaller share; (ii) they are building more comprehensive domestic value chains, less reliant on imported intermediaries; (iii) new technologies such as automation and the Internet of Things, as well as cross-border data flows, are beginning to reshape the organization of GVCs.

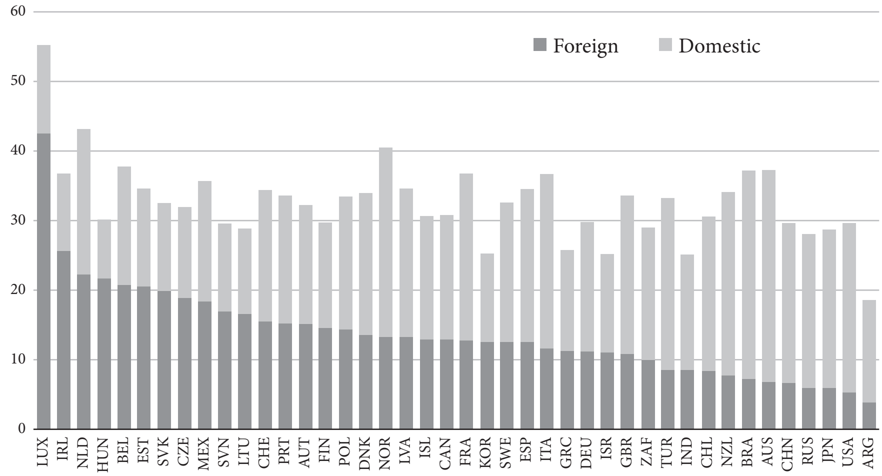

Figure 15.3 Services value-added embodied in manufactured exports, 2015
Source: Pietrobelli and Vezzani mimeo, from OECD data.

An additional fact that has been noted is the large presence of services in international trade. Services value added accounts for between 25 percent and 40 percent of the content of manufacturing exports in most advanced countries, suggesting that services play an important integrating role in GVCs (Figure 15.3). The domestic share of services value added is greater than the foreign share, especially for larger countries, further indicating that many countries are strengthening their domestic participation in GVCs (OECD 2018).

In sum, we are undoubtedly in what has been defined a value chain world (Ponte et al. 2019). The spread of GVCs has offered emerging countries opportunities for innovation and upgrading, but the process has been far from automatic and widespread (World Bank 2019). Reaping such opportunities requires active policies to promote the development of absorptive capacities and local firms' technological capabilities (OECD 2013). In this perspective, it has also become crucial for emerging countries to strengthen innovation systems to absorb the knowledge drawn from GVC integration, and nurture the coevolution between GVCs and innovation systems (Pietrobelli and Rabellotti 2011; Lema et al. 2019).

However, the implication that such a world has for public policies, and in particular for policies oriented to foster innovation and productive development has attracted less systematic attention, and a consistent framework for analysis is still lacking. Governments and international organizations have increasingly used the GVC terminology and insights in their policies and programs (Gereffi 2019). However, a systematic theorizing has lagged behind.

This chapter represents a first cut into this issue, and starts defining a theoretical structure to analyze public policies in a "GVC-world." I will first discuss what are the essential traits of new industrial innovation policy as outlined in the literature (Section 15.1). Then I will elaborate on a possible typology of these policies (Section

15.2) and extend it to a concept of "GVC-oriented policies," that is those policies that target the fostering of production and technology upgrading through GVCs (Section 15.3). In the following sections I will illustrate examples of how GVCs change the nature and meaning of policies in three areas: policies to promote international trade, investment attraction, and innovation. All these examples confirm that a radical rethinking and theorizing of policies is necessary and urgent.

15.1 Key Traits of a New Industrial Innovation Policy Approach

On the basis of the literature, and of all the many interventions tried and implemented in many countries, what are the main desirable traits that industrial policies should have? After several decades of implementation, the model adopted by some East Asian economies may be identified today as a "traditional" approach to industrial policy (Rodrik 2019; Cherif R. and Hasanov F. 2019). In the paradigmatic East Asian cases of South Korea and Taiwan, notwithstanding the differences between the two (Guerrieri et al. 2001), the hypothesis was that policy solutions were known, and that they could be pursued by honest and competent administrations. The policy packages included a prioritization of sectors and a series of sectoral (vertical) incentives conditional upon demonstrated success in international markets.

However, this approach required the fulfilment of several demanding conditions, and many countries decided not to apply it, sometimes advised by foreign organizations. Thus, in many instances a minimalist approach prevailed, equating industrial policy simply to a better "business climate," like for example the enforcement of property rights, and the administrative norms and practices required to carry out business (World Bank 2018). However, these policies often fell short of providing the necessary and comprehensive support needed for industrial development, and gradually a more modern approach developed, both in the literature and in policy practices (Santiago 2015). We may call it a new industrial innovation policy approach, which gives uncertainty and incomplete information a central role, does not presume that policy solutions are known, but instead that need to be discovered, and that a process of institutionalized collaboration and dialogue is essential to achieve this target (Hausmann and Rodrik 2003, 2006; Hausmann et al. 2008; Kuznetsov 2019; Rodrik 1996, 2004, 2019; Bruno et al. 2020; Lall and Pietrobelli 2002). These policies should include both selective and vertical interventions, a dedicated institutional design and the effort to strengthen the institutions required (Crespi et al. 2014). In accordance with a burgeoning literature (Pietrobelli 2016), this approach should explicitly share at least the following traits:

1. The neoclassical justifications for industrial policies were based on a very strict definition of market failures, and the premise that well-functioning markets would produce the desirable result. However, it is always hard to determine the

existence and location and magnitude of market failures and constraints, and the required knowledge is diffused widely within society; it is "embedded" in it (Rodrik 2019). Policymakers live in a world characterized by vast uncertainties and imperfect information. They cannot know beforehand what the right policy interventions are, and need to set up a process to *discover* them. Therefore, they can benefit enormously by understanding the apparently failed behavior of market agents, and need to ask what prevailing market and coordination failures are inhibiting market functioning.

2. Such a discovery process involves substantial *learning* based on tentative, even experimental, policy design and implementation with a built-in capacity to iterate and adjust as a matter of refining policy (Sabel and Zeitlin 2012). Solutions are local, contextual, and unknown ex ante. Experimentation must be encouraged and rewarded, and also consider a calibrated risk of failure. Policies need to be designed to be evaluable, and are discontinued unless validated by a pertinent evaluation, in order to allow the necessary learning (Crespi et al. 2014).
3. The process of discovery of the appropriate industrial innovation policies requires smart, "high-bandwidth" and iterative collaborations between the government and the business sector, with the aim of uncovering where the most significant bottlenecks are. Modern industrial innovation policies need the complementary pieces of knowledge available to the business and to the public sectors, and have to enhance the collaboration to harness them (Fernandez-Arias et al. 2017). The business sector has privileged knowledge of some aspects of business and a profit motivation. The public sector has different direct knowledge concerning policy design, implementation, and evaluation. However, the business sector also has strong incentives to manipulate the government, and appropriate systems of incentives need to be designed and put in place (Rodrik 2019; Crespi et al. 2014). Carrots to reward conducive behavior, and sticks, to punish rent-seeking and opportunism, are both essential components of modern industrial innovation policies.
4. The institutions behind the policies play an essential role, and condition success and failure. Institutional capabilities are needed to explore, design, implement, monitor, and evaluate policies. Without them, the policy treatment may be worse than the disease (Crespi et al. 2014; Lall 2004). Most importantly, institutions may be built and may be strengthened with appropriate investments. With the right incentive schemes, they may be induced to learn and improve. Policy interventions need to be chosen in light of the existing institutional capabilities, and of the efforts to build such capabilities. The institutional capabilities required include—among others—the capability to coordinate actions across public-sector agencies, to protect agencies from undue political pressure, and to ensure public–private collaboration Devlin and Moguillansky (2013) and Pietrobelli (2020). If institutions are weak, the preferred policies should be simple and consistent. However, the process of strengthening appropriate institutions is an essential part of modern industrial innovation policies.

5. This approach needs to be pragmatic and empirically based. Lessons from past successes and failures need to orient the design of future policies and institutional arrangements, and solid evaluations are required to this purpose. As a result, conclusions are dependent on the context, and there is no best practice to emulate. Rather than recommendations based on best practices defined in the vacuum and supposed to work in different circumstances, clever solutions need to be worked out each time.
6. The debate on what industrial policy and what innovation policy are is not useful and often misleading. Innovation is an essential component of industrial policy. Long-term development is intrinsically tied to technological innovation, and the development of industry requires nurturing and supporting innovation.
7. Industrial policies aim at inducing structural transformation in open competitive international markets. The outward orientation is central in this approach, as it provides a key benchmark for comparisons, as well as the opportunities of knowledge flows from abroad. Structural change is also a fundamental objective of these policies.

15.2 Classification of Industrial Policy and Why it Matters

The search for standardized solutions to repeated problems of development in many countries has generated a very varied and nearly endless list of industrial and innovation policies. For example, whilst some governments give matching grants for business innovation projects, or finance incubation services for start-ups, others focus on reducing the number of days to start a business, open offices abroad for export promotion, or offer tax exemptions for tourism activities. Some governments put in place cluster development policies and try to attract foreign direct investments, others subsidize training to close the skills gap for the mining or the electronics sector. The focus on GVCs and the development of local providers is shared by most, whilst the instruments may differ: some provide cold storage facilities for fresh flowers, whereas others create public research organizations for the electronics or the biotechnology sectors. Are all these industrial and innovation policies?[1] Why such a variety? How can we make sense of such a wide assortment?

The large variety of policies is not a problem in itself, and sensitivity to different contexts is needed. Each government should rightly look for policy responses that are specific to the context it wants to influence, and that take into account the peculiarities of the actors involved, their systems of incentives and objectives. However, such a large variety often makes it difficult to understand the rationale and

[1] For an extended discussion on definitions, see Aiginger and Rodrik 2020.

the logic of design and implementation of each policy, may induce errors and limit cross-learning and exchanges of experiences. Indeed, interventions may be classified, and a typology can help analyze their logic as well as their qualities and their risks. Following a highly influential policy report (Crespi et al. 2014), we focus on two dimensions that are useful and practical to generate a simple analytical framework to analyze industrial innovation policies. Later, we shall also use this framework to argue that the logic of these policies needs to be revisited in light of the emergence of GVCs (Table 15.1).

The first dimension is the *scope* of policies, depending on whether they focus on specific sectors, or instead do not target any specific industry in particular. In this regard, the terminology often distinguishes between vertical and horizontal policies. A public center for phytosanitary controls or a tax break for software are examples of vertical policies; a one-stop window for business registration and simplification of business-related procedures is an example of a horizontal policy.[2]

The second dimension of policy refers to the *type of intervention*. In fact, public support cannot only be offered by providing public inputs or public goods, but also by intervening in markets and altering market prices. A market-based intervention would intentionally influence relative prices through taxes or subsidies, and therefore induce agents' behavior in a desired fashion. A tax rebate on R&D expenditure is a classic case of a market-based innovation policy. On the other hand, the government may also intervene thorough the provision of a public good to enhance the competitiveness of a sector (or of the whole economy), such as the setting of norms for certification of quality control or building a new research center on palm oil.

In Table 15.2 we build a simple 2x2 matrix to present some of the many possible industrial innovation policy interventions. A form of horizontal policy through public inputs provision is clearly the promotion of public (and publicly-sponsored) research. The creation of public technology research centers, such as for example the CITE-Vid in Peru, the center devoted to the technological development of the pisco industry in Peru (OECD 2011), is a case of vertical public provision of public inputs. Examples of horizontal market interventions include the typical matching grant schemes for R&D implemented in many countries that co-finance the innovation efforts of firms regardless of the sector considered. If the tax rebates or exemptions are geared towards a specific sector—and the innovative efforts therein—like for example in tourism or biotechnology, this would represent a vertical form of market intervention.

Why does a typology like this matter? First of all, the variety of forms of industrial and innovation policies is already huge, and such a diversity does not help the clear

[2] To some extent, it has been argued that all policies are always vertical, and a fully horizontal policy does not exist in practice (Chang 2002). Building a road with public resources implies favoring the sectors that would benefit from that road, and not all sectors. Subsidizing research and innovation favors innovation-intensive sectors more than traditional sectors that use less innovation. Training is also necessarily specific to specific tasks and skills, and so on. However, we retain here this distinction as it serves as a useful didactic metaphor.

Table 15.1 A typology of innovation policy interventions (examples)

	Horizontal	Vertical
Public Inputs	Funding of basic Research	Sectoral Public Technology centers
Market interventions	Matching grant for innovation	Tax rebates for innovation in biotechnology sector

Source: Adapted from Crespi et al. 2014.

Table 15.2 A typology of GVC-oriented policy interventions (examples)

	Horizontal	Vertical
Public Inputs	• Monitor opportunities for attraction • Streamline procedures for FDI and lead-firm (e.g. One-stop shops)	• FDI and selective lead-firm attraction • FDI in S&T to increase location attractiveness for international research centers (via IP laws and enforcement, or tax concessions, a market intervention). • Skills training center • Quality, Standards, Certification Organizations • Policies to reinforce linkages and potential spillovers between GVC participants and the local knowledge base (e.g., cluster policies, policies for technology transfer, etc.)—may also operate through market interventions;
Market interventions	• Generic R&D&I subsidies for local providers' capabilities • Matching grants for collaborative R&D (regardless of sectors but conditional on collaboration) ✓ *Force* externalities via training commitments and suppliers' development • Policies to encourage international mobility of talent (may also be vertical and through public inputs)	• Selective temporary tax exemptions to new local providers • Local content policies (forcing lead firms to buy locally) • Selective R&D&I subsidies/grants • Promotion of innovative entrepreneurship, e.g., ease access to capital

Source: Author's elaboration.

analysis and decision of which policy would be more appropriate in one context and circumstance than in another. Classifying instruments according to a logic definitely helps policymakers and the private sector choose the appropriate mix of instruments to achieve a selected target, and facilitates cross-learning from policy experiences.

Secondly, public policy considerations to guide the assessment of merits and drawbacks of each instrument change in each quadrant of the matrix. This is especially useful when the risks of rent-seeking by particular groups and lobbyists need to be assessed and checked, as well as when the difficulty of putting in place a specific instrument, and the institutional requirements related to it, need to be considered. Let us briefly see some examples that may help to understand this remark.

Horizontal public goods are often the easiest interventions to put in place: strengthening respect for (intellectual) property rights or reducing the costs of "doing business" (as argued by the World Bank's "Doing Business" Reports) may be relatively straightforward, with a negligible chance that small groups can appropriate all the benefits of the policy. However, these interventions are often so general that they almost represent a pre-condition for productive development, preliminary to any form of active policy. Horizontal market interventions do not aim at favoring specific sectors, but rather specific activities across many different sectors, like for example training, foreign investment, or R&D expenditure. These interventions tend to be automatic and recurring, and therefore difficult to discontinue once the market failure they intended to address has been solved, and the policy would not be needed anymore. Moreover, they may inevitably remain very general and lack focus.

Vertical public inputs are arranged by the state to offer benefits for specific sectors. Because of the difficulty of selecting the beneficiary sectors, and because they are directed to few sectors, and therefore intrinsically more prone to being captured by isolated rentiers, they have often been more controversial in several countries. However, it is also true that most public inputs, due to their very nature, tend to benefit specific sectors. The technological needs of a non-traditional agri-business sector are likely to be very different from the needs of the software industry. The former often requires norms and institutions (e.g., laboratories and metrology) to comply with and certify phytosanitary and biological standards, whilst the other requires universities graduating highly specialized engineers, and standards and certification of a different nature. Confining state action only to horizontal public inputs, without addressing the specific needs of specific sectors, would imply giving up most options to enhance productivity and markets' functioning. This would amount to remaining oblivious of the "need to choose" that Governments face in any country all the time (Hausmann and Rodrik 2006). Moreover, in this latter category the collaboration and co-financing of the private sector is often natural, with public policies supporting the productive efforts of the private sector.

Vertical market interventions often take the form of subsidies or tax rebates and exemptions granted to specific sectors. For their very nature, they may lend themselves to favoritism and arbitrariness.[3] However, if properly designed and managed, they offer substantial benefits. This may be the case of policies oriented to solve problems of coordination in sectors with latent comparative advantage, whose exploitation is hindered by the difficulty of coordinating the investments of many different actors. The policies adopted by the Costa Rican Government to develop the tourism

[3] See, for example, the case of policies for the rice sector implemented in Argentina and Costa Rica, and how the latter was remarkably affected by the shortcomings of vertical market interventions (Crespi et al. 2014, pp. 48–9).

sector in the mid-eighties included a series of sector-specific incentives such as tax breaks for hotel investments, transport, travel agencies, and others, to provide powerful signals to the economy that tourism was a sector with a clear dynamic comparative advantage. Later, as the industry started to take off, most interventions moved to the quadrant of vertical public inputs to foster the emergence of sustainable tourism, through among others the creation of a national brand, the conservation of natural areas, and a program of sustainable tourism certification (Monge-González et al. 2010). This experience may even hint that in many instances there is likely to be a preferable sequence between horizontal—in the initial phases—and vertical—in later developments—interventions. Of course, specific circumstances may suggest different conclusions, and isomorphic solutions do not offer the same results in different contexts.

This typology of industrial innovation policies may lend itself to useful categorizations of policies in a variety of other domains. In the next section we will discuss in detail how the emergence of GVCs forces a rethink of the logic of public policies, and the adoption of a renewed approach. This typology will prove useful in structuring the ensuing policy discussion.

15.3 GVC-oriented Policies: A Change in the Policy Vision

The need for policies oriented to GVCs is becoming evident in the choices of many advanced countries' governments Gereffi, (2014). For example, the European Union has recently approved a "Communication" and a Strategy paper that openly stress the need of strategic policies for GVCs: "…a successful industrial strategy should build on Europe's strengths and assets in strategic value chains in new technologies, which often requires joint, well-coordinated efforts and investments by public authorities and industries from several Member States;…(to this aim it) is necessary to foster new Important Projects of Common European Interest (IPCEI)" (EC 2017). The need to *fill missing links in relevant value chains* is often called for in these documents, and is expected to be followed by active interventions soon.

The acknowledgment that the existence of GVCs imposes a multidimensional and systemic approach is widespread. Whilst trade, border and investment policies are needed to improve GVC participation, encouraging industrial and technology upgrading requires policies in the area of industrial, innovation, entrepreneurship, and skill development (Kergroach 2019). A recent study has been perhaps the first effort to systematically classify national policies operating through and explicitly taking into account the existence of GVCs. On the basis of the European Commission/OECD Science, Technology and Innovation (STIP) database, and of a clever keyword-based search, Kergroach (2019) selected the major national policy initiatives of fifteen OECD and emerging countries dedicated to attracting Foreign Direct Investment (FDI) and supporting the internationalization of Small and

Medium-sized Enterprises (SMEs) and those promoting industry and technology upgrading. The results reveal that all countries have many policy interventions for upgrading and productive development through GVCs. Interestingly, the policy density for such policies is not related to the development stage of a country. Moreover, the public policy interventions to improve a country's technological and productive capacities through GVCs take different forms and mobilize different instruments. They are not limited to FDI-related policies and programs to support the internationalization of firms, adopt a cross-cutting approach, and spread across various policy areas. Of these, industrial and cluster policies remain the most popular channel for promoting GVC participation.

In an earlier piece on industrial policy with vertically specialized industrialization, that is, reflecting GVCs organization, Milberg et al. (2014) had convincingly argued that governments must look at lead firms and their strategies (as well as states and non-state actors) in creating policies, strategies, and campaigns. They also reminded us that an effective policy focus needs to consider also the regulation of the links with the global economy, in a period of intense changes in the institutions in charge of global governance.

Both the last two chapters agree with us that new industrial innovation policy needs to explicitly consider the implications of the presence of global value chains. Public policies neglecting this dimension risk missing the point and producing undesired and often counterintuitive results. In what follows I will briefly discuss the theoretical implications, propose a taxonomy of GVC-oriented policies consistent with the previous 2×2 approach, and present three concrete examples of areas where public policies are intrinsically related to a "GVC world."

The academic debate has rightly acknowledged that country strategies to further integration in GVCs may target "building" or rather "joining" a value chain (Baldwin 2011). Therefore, some countries may wish to build the entire value chain and maintain the leadership over the sequence of chain layers and across the variety of inter-firm linkages. For example, decades ago South Korea started with subcontracting, limiting FDI, and favoring joint ventures, in order to achieve its long-term target of entering international markets in radically new sectors and nurturing its own lead firms and value chains. However, in the newly prevailing context regulated by the WTO and with a very large number of countries and companies that firmly established their leadership in a variety of sectors, a strategy to build the entire value chain appears hardly feasible. When countries like South Korea, Taiwan, and Singapore started their process of accelerated industrial development, the international context was very different, and the "policy space" much larger (Chang 2002).

What the new context offers, rather, is the possibility for firms and countries to target specific niches in a value chain by developing strong competences, skills, and assets in specific tasks and value chain layers. For example, instead of developing a comparative advantage in the whole garment sector, countries may prefer to target a specific intermediate product (e.g., buttons, or zips, dyed cloth, or packaging for final retailers) and sell it at a large scale through large buyers or traders operating at a global scale (Gereffi and Sturgeon 2013).

Following a GVC perspective to understand international trade has often attracted the interest on designing and implementing policies to "join" and get access to value chains in order to penetrate international markets. However, as countries also pursue a development objective, policies should also target the complementary and equally important objective of "capturing the gains" and maximize the (potential) benefits offered by GVC integration. The evidence has shown that the benefits from GVCs are far from being granted and automatic, and require much more than "joining" a GVC.

Therefore, in order to capture the gains, the policies to target and attract foreign investors, as well as large GVC lead firms and traders, with their first and second tier of suppliers, need to target the sectors and firms that are likely to interact more and better with domestic firms. Such attraction policies also have an important infrastructural component, with the related necessary logistics that include airports, harbors, and roads, as well as efficient telecommunications and broadband facilities. However, the public policy interventions for capturing the gains from GVCs are not limited to FDI-related policies and programs to support the internationalization of firms and SMEs (Kergroach 2019). Initiatives can span several policy areas, and special attention needs to be paid to the activities attracting intangible assets such as knowledge and technology flows. Moreover, simpler, certain and streamlined regulations affecting business may also help. In general, what really makes the difference is the set of programs and initiatives required to increase the value added captured by local firms, and exploit the opportunities for learning and innovation offered by GVCs (Pietrobelli and Rabellotti 2007). Local suppliers need to develop their technological capabilities to usefully interact with chain leaders and learn from the interaction (Morrison et al. 2008, Pietrobelli 2016).

In turn, this process of interaction also depends on the Innovation System (IS) in which firms are embedded, and that provides them with the necessary public goods (Pietrobelli and Rabellotti 2011). Capturing the gains is in effect related to the development of a local supply base, that in turn needs the public goods related to research and technology development. Research organizations may offer the results of their research, and training and technical education should produce the necessary advanced technical skills, and laboratories, testing, and quality centers should help firms comply with the sophisticated standards that lead firms' and international markets' demand. Standards compliance is a tremendously important area that extends to technical as well as phytosanitary and environmental requirements and certifications. Sometimes specific supplier development programs can also be designed effectively to match the demands of lead firms with the supply of domestic producers (Pietrobelli and Staritz 2017). Countries often use industrial cluster policies to promote enterprise upgrading through GVCs (Kergroach 2019).

Indeed, the relationship between the IS and the GVC and its governance often works two ways and coevolve (Lema et al. 2019): an advanced and smoothly functioning innovation system may attract GVCs prone to local interactions and help local firms learn and innovate and benefit from the GVC, but at the same time GVCs may contribute important pieces of knowledge and organization to the IS. The more advanced technological capabilities are in local firms, the more GVCs are forced to engage in fruitful productive interactions. This indeed reflects the different forms of learning possible along a GVC, that may go from simply an increased pressure exerted by lead firms and their first-tier of suppliers ("competition effect"), to lead firms deliberately transferring knowledge and being directly involved in the learning and innovation process, to the unintended knowledge spillovers generated from GVC interactions (Pietrobelli and Rabellotti 2011).

Summarizing, the emergence of GVCs requires a deep rethinking of policies for productive development, and the acknowledgment of the role played by coordination and intense interactions among many different entities and actors operating in globalized open markets (Pietrobelli and Staritz 2018). In this regard, we may define GVC-oriented policies as those policies that target the fostering of production and technology upgrading through GVCs. Two important features of these policies stand out and are worth emphasizing:

i. GVC-oriented policies are inevitably multidimensional, cross-cutting policies, affect many different dimensions, and require a systemic vision and the coordinated action of many different entities. Thus, for example, trade policy in the form of import protection without the awareness of the complexity of GVC organization may hinder a country's export capacity. Investment attraction needs to reward investments with a stronger potential for local linkages. Innovation systems have to be coherent with GVCs and leverage their mutual interdependence. Education, training, and migration policies also need to consider GVCs, and attract and develop talents consistently.
ii. GVC-oriented policies go far beyond the domestic economy focus of import substitution industrialization (ISI) policy regimes (Gereffi and Sturgeon 2013). Their focus on developing local firms and their capabilities through direct interventions as well as improving the innovation system may lead to a misleading interpretation of their apparent resemblance with old-style ISI. GVC-oriented policies' immediate link to the international market and their reliance on international production networks and on imported intermediate products and services make them radically different from the past.

Also, GVC-oriented policies may be classified according to the 2×2 framework proposed: they may have a horizontal or vertical nature, depending on whether they target specific sectors (Table 15.2). Horizontal policies may involve setting up the rules and streamlining the procedures to approve and facilitate FDI and lead firms willing to invest and establish their activities in the country. Prior to this, investment attraction agencies may also be strengthened and equipped with the capabilities to attract and interact with GVC leaders. Such attraction can—and often needs—to be selective, targeting specific firms or sectors, like in the Costa Rican example below.

Horizontal GVC-oriented policies could also use market-based interventions, for example strengthening the technological and innovation capabilities of actual and potential local suppliers through instruments like subsidies for Research and Development and innovation (R&D&I) investments, or matching grants for collaborative research between lead firms, local providers, and universities. In order to achieve the objective of maximizing the gains to the local (national) economy, the positive externalities from GVC integration should be fostered and sometimes "forced." Some countries (e.g., Singapore, Costa Rica), in their attraction effort and later interaction with foreign investors and lead firms, induced the latter to invest in supplier development and in training to an extent greater than what would be necessary to the foreign investor only, thereby creating capabilities in excess to the benefit of the host country.

Vertical GVC-oriented interventions can sometimes use the same instruments, but with a vertical, sector-specific, concentration. For example, the policy of firm-level skills training may be strengthened through sectoral technology and training centers (e.g., the palm research center in Colombia in Crespi et al. 2014). Similarly, local firms and potential suppliers, in order to get access to a GVC and comply with the technical and quality requirements, often need to be supported by a solid Quality System, including accreditation and standard bodies, metrology organizations, inspection bodies, and testing and calibration laboratories (Guasch et al. 2007).

Such a broad policy rethink is called for in many areas of activity. Countries need coherent policy packages of the various instruments, all inspired by the same logic acknowledging the new nature of industrial organization in international markets. In the remaining part of the chapter I will briefly discuss some examples of how GVC-oriented policies require revisiting trade policies, investment attraction policies, and innovation policies.

15.4 GVCs and Trade Policies

In a world where more than half of trade is represented by intermediate exchanges, the empirical assessment of trade policy must acknowledge which country is the source of the value that is embedded in trade (Antimiani et al. 2018). Thus, the emergence of GVCs imposes a radical rethinking of the logic and the application of trade policy to understand who is effectively paying the cost of protection. As goods now cross borders many times, first as inputs and then as final products, barriers at the border become costlier and have a cumulative impact along the value chain (OECD 2018). Figure 15.4 reveals how average ad valorem tariffs are higher if one considers direct and indirect tariffs on inputs, in addition to tariffs on final exports. Therefore, protection would be higher for an economy requiring a large share of intermediate imports to produce its exports (Cusolito et al. 2016). In addition, the production activities which are linked to the GVC, are also affected by tariffs faced in the destination market and across different countries (Balié et al. 2019).

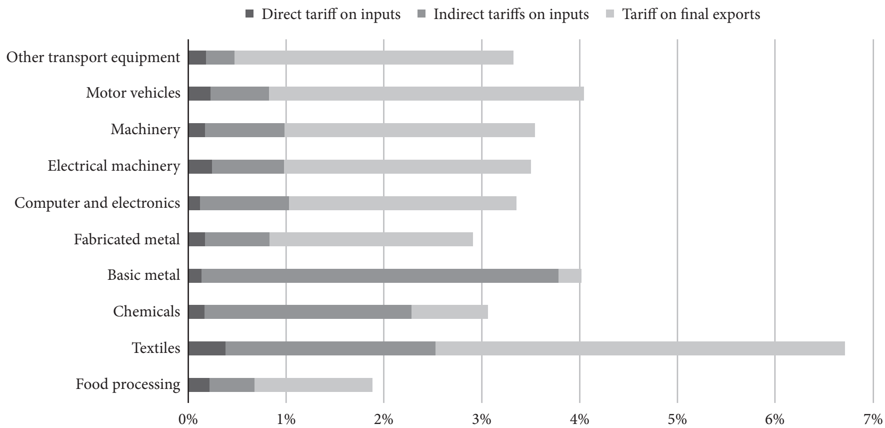

Figure 15.4 Average ad valorem tariffs along the GVC, selected industries, 2015
Source: OECD 2018.

In this line of analysis, Antimiani et al. (2018) present an interesting measurement of trade restrictiveness taking into account the existence of GVCs. They show that the total impact of tariffs can have a significant cumulative impact because of trade in intermediates. According to their analysis:

> Bilateral nominal tariffs and trade flows are not sufficient to provide an accurate picture of the impact of protectionist measures through backward and forward linkages. On the one hand, the value of the index for the domestic value-added (reflected) component relative to the foreign direct value added is indicative of the harm inflicted to domestic producers providing inputs to the exporting sectors of the foreign country. This shows the "beggar thyself" content of protectionism. (Antimiani et al. 2018, p. 28)

At the same time, the importer's tariffs towards third countries also play a very significant role in assessing the overall protection faced, because the value added is exported both directly and indirectly.

In a related paper, Blanchard et al. (2017) develop a value-added approach to modeling tariff setting with GVCs, in which optimal policy depends on the nationality of value-added content embedded in home and foreign final goods. They estimate the influence of GVC linkages on trade policy with newly assembled data on bilateral applied tariffs, temporary trade barriers, and value-added contents for fourteen major economies over the 1995–2009 period. Their findings indicate that GVCs already play an important role in shaping trade policy. Governments set lower tariffs and curb their use of temporary trade protection where GVC linkages are strongest. In sum, the actual structure of protection from imports changes in light of the possible integration of some segments of the economy into GVCs. This may imply the need for lowering tariffs in GVC-intensive sectors.

15.5 GVCs and Investment Attraction Policies

Investment attraction has been traditionally a major focus of policies in developing countries, trusting to benefit from foreign direct investments (FDI) by multinational corporations (MNCs) in the form of increased employment, investments, access to markets and technology, and so forth. With the fragmentation of production and the organization of transactions following the logic of GVCs, this area of policy activity also needs to be reconsidered. To this aim, Costa Rica offers an insightful example of selective attraction of FDI in the GVC spirit, with various interventions through both market instruments and public goods provision, mainly of a vertical nature. This will help us make the more general case.

In their analyses of Costa Rica, Bamber and Gereffi (2013) and Gereffi et al. (2019) studied the electronics and the medical devices sectors and their experience of upgrading. As far as the latter sector is considered, they argue that a key dynamic that facilitated firm upgrading was "…the identification by lead firms themselves of critical 'GVC gaps' in Costa Rica's technical capabilities, which was followed by targeted FDI recruitment efforts by national development institutions (CINDE and COMEX)" (Gereffi et al. 2019).[4] A close look at the selective attraction policy implemented by the Costa Rican agencies suggests that a new consideration of the role and organization of GVCs needs to encompassed in the activities of investment attraction agencies.

The medical devices sector was one of a few sectors targeted by Costa Rica, through CINDE, to attract FDI.[5] The sector had been expanding at healthy rates since Baxter first came to Costa Rica in 1987, and reached nearly $1.5 billion in exports in 2014. However, medical devices range across various levels of complexity, from simple disposable devices (such as catheters) to surgical and medical instruments (such as biopsy forceps), to therapeutic devices (such as heart valves), which go into the body to stay, to complex medical equipment (such as MRI machines).

As of 2007, Costa Rica had been highly successful in attracting multinationals to the sector. But they were mainly producing low-complexity disposables, and not, for example, heart valves or other cardiovascular devices. A careful analysis to "discover" the likely solution revealed that in order to sell them, they needed to go through the process of sterilization, not available locally at the time. Producing them in Costa Rica would have required shipping them to the US to have them sterilized, and then shipping them back for packaging—complicating the logistics and adding greatly to the costs.

Why did not any activity of sterilization develop in the country? With no heart valves and other similar products in production, there was no demand for sterilization

[4] CINDE (*Coalicion Costarricense de Iniciativas de Desarrollo*) is the Investment attraction agency of Costa Rica, and COMEX is Costa Rica's Foreign Trade Ministry.

[5] This case draws from and adapts the evidence analyzed in Box 9.4. in Crespi et al. 2014, and Bamber and Gereffi 2013.

services, and with no demand, there would be no supply: a typical "chicken-and-egg" problem. CINDE quickly realized that the market would not solve the problem by itself. Yet, having a sterilization process in the country would have helped the more complex links of the value chain to develop. CINDE's efforts paid off in early 2009, with the arrival of BeamOne, a contract sterilization processor headquartered in the US, followed by Sterigenics in 2011. Within three years of inauguration of the BeamOne facility, Costa Rica had successfully attracted several companies in the cardiovascular sector, including Boston Scientific in 2009, Abbot Vascular in 2010, and St. Jude Medical in 2010. In 2013, Costa Rica exported nearly $300 million in the therapeutics category of medical devices, and an additional $500 million in surgical and medical instruments. The share of disposables fell from 90 percent in the early 2000s to less than half.

Why did CINDE target sterilization? Because it adopted the logic of GVCs and of a "discovery" process, and realized that a segment of the value chain was missing, and that the market alone would have not solved the problem. Moving Costa Rica into the more profitable sections of the value chain, and capturing more value, required selectively attracting foreign investors in that specific segment. This made it possible for other local firms to discover and develop into new and higher-value stages of the GVC.

15.6 GVCs and Innovation Systems

GVCs are not only, or mainly, a trade-related phenomenon, because this form of industrial organization hinges on dense flows of knowledge exchanges, and as such change firms' behavior in a fundamental way. Capturing the gains from GVCs crucially implies an active attitude of local firms investing in learning, in technology adoption and absorption, and in developing the capabilities necessary to interact with lead firms and upgrade in GVCs Grazzi and Pietrobelli (2016).

This process of capturing the gains reflects a number of underlying conditions: first of all, access to GVCs is unequal across countries and regions (OECD 2018); secondly, local suppliers differ in their capacity to absorb, master, and adapt knowledge and capabilities that leading firms can transfer to them (Pietrobelli and Rabellotti 2007); thirdly, governance patterns have heterogeneous impacts on learning mechanisms in value chains: for example, in modular chains, learning can be the result of a pressure to match international standards and comply with them, or sometimes lead firms can facilitate learning through direct involvement if suppliers' competence is low and if the risk of non-compliance is high, and even enjoy mutual-learning with two-way knowledge flows (Pietrobelli and Rabellotti 2011).

However, local suppliers' upgrading efforts, and their interactions with buyers, are also contingent on the prevailing local innovation system, its level of depth and maturity. In turn, the development of the IS also hinges on firms' capabilities, and their GVC integration. A true "co-evolution" of GVC and IS occurs, that can lead to

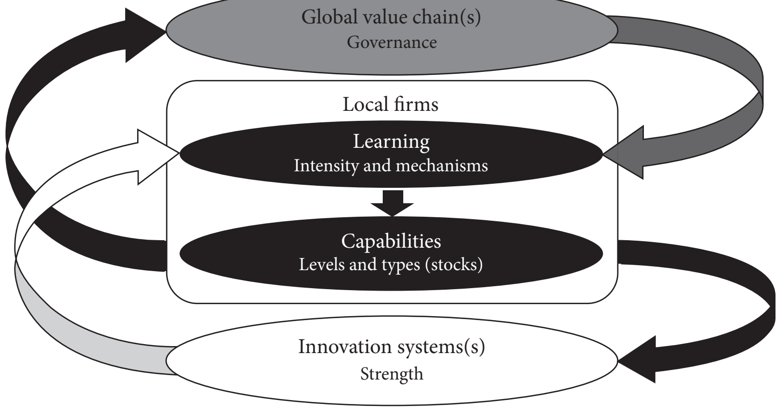

Figure 15.5 The co-evolution of GVC and IS with regard to firms' innovation capabilities
Source: Lema et al. 2019.

widely different results in terms of firms' upgrading performance (Lema et al. 2019), and also to widely different policy implications. As we explain in a different article, such co-evolution follows two-way flows that affect both the mechanisms through which ISs and GVCs contribute to the process of accumulating and shaping firm-level capabilities and learning, and also those mechanisms through which innovative firms, via their evolving capabilities, influence local IS characteristics and GVC governance (Figure 15.5 and Lema et al. 2019).

This coevolutionary approach has powerful implications for public policies. Thus, firm-level upgrading along GVCs can benefit—and in turn needs—a well-developed IS, and IS will not develop without firms and other actors requesting its improvement. We illustrated some possible co-evolution trajectories, ranging from *gradually increasing, to leap-wise increasing*, *stagnating* and *reverting*. For example, Lee and Shapiro (2018) highlight how China's and South Korea's strategies of GVC integration consisted of processes of moving "*in a GVC and out and in again,*" in parallel developing and deepening a national IS to foster local suppliers' upgrading processes up to becoming true leaders of newly created GVCs.

Consistently with this approach, a policy geared towards capturing the gains of GVC integration needs to encompass new industrial innovation policy. Strengthening the IS by fostering firm-level innovation (e.g., through matching-grant programs), technology adoption and absorption, collaborations with universities, in a way that is coherent with the characteristics and requirements of (present and future) GVCs in the country are examples of GVC-oriented policy.

Similarly, targeted training programs, that is, to create the skills local firms need for their integration into and upgrading within GVCs, and investments in public organizations to provide technology services in the areas of standards, metrology, testing, and certification (upper right-hand side quadrant in Figure 15.2) pertain to this group of policies.

15.7 Conclusions

Global value chains are changing not only the way firms organize production but also the policies that influence social and economic development. This is occurring in several areas and require a framework apt to encompass these developments. In this chapter we made a first effort to develop and illustrate this framework. After outlining the essential traits of new industrial innovation policy, I presented a typology of industrial innovation policies and extended it to "GVC-oriented policies," that are those policies that target the fostering of production and technology upgrading through GVCs. The examples from trade and foreign investment policies, and from innovation policies, confirm that a radical rethinking and theorizing of policies is necessary and urgent. Future research will need to move further and deeper in this direction.

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16
Experimentalist Governance for Technology Upgrading

New Industrial Policy Process

Yevgeny Kuznetsov

16.1 Introduction: Why is This Chapter Included in This Book?

Strong state capabilities are central to both economic development and innovation. Just contrast chapters on Brazil and China in this book: firm-level technical capabilities of the most advanced firms in Brazil are comparable to those in China, yet it is capabilities of the state which propels innovation advance in China (Xudong Gao, Chapter 14, this volume) and jeopardizes, if not halts it in Brazil (Alves et al., Chapter 7, this volume).

We know how the desired or ideal state capabilities should look like: these are capabilities for accountable experimentation. In this book, Jeong-Dong Lee at al. (Chapter 4) lists among desirable "innovation commons," "socio-cultural institutions to favor accumulation of trial and error"; similar emphasis on trial and error experimentation processes are advanced in Rodrik (2004), Forray (2018), Lee (2016), Radosevic (2017) and Dutz, et al. (2014). In short, the call is to extend familiar Schumpeterian notion of creative destruction to the public sector as well. The state, as far as innovation and industrial programs are concerned, should be able to experiment, recognize, admit, and correct mistakes. Capability for error-correction signals accountable as opposed to open-ended experimentation. Apart from some exceptions (the most glaring of them is China), such capacity for accountable experimentation is missing. So in terms of state capacities we know our starting point, just as we know, at least in generic terms, the end point to which we want to arrive: normative sections on policy recommendations in the chapters of this book attest to that. It is the trajectory from "here" to "there" that is unknown. The issue is not *whether*' some kind of innovation and industrial policy should be put in place, but how to do it. The single objective of this chapter is to reflect on what such a trajectory might look like.

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More specifically, it is a near-consensus in the literature that vertical industrial and innovation policies—focused on "picking winners"—are futile in the modern fast-changing world, while horizontal policies—focused on background conditions—are insufficient (Rodrick, various years; Dutz et. al (2014); Breznitz and Ornston, various years). Hence the central policy dilemma of technology upgrading and economic catch-up is how to make and implement strategic choices of new domains without "picking winners". Conceptually, new industrial policy (NIP) resolves this dilemma by shifting focus from *one-time* choice of domains (sectors, industries, firms, clusters) to experimental *process*—with corresponding attention to governance—of error-detection and error-correction of the continuously shifting and erring choices. This process is experimental and it requires appropriate governance, which is different from hierarchical principal–agent governance. The chapter intends to advance the theory of new industrial and innovation policy[1] both conceptually and empirically.

Policy discussion of technology upgrading and economic catch-up, including that in this book, usually focuses on normative implications: what stakeholders, particularly governments, *should do* (Amsden 1989, Kim 1997, Mazzucato 2013, Forray 2018). This chapter proceeds from a contrasting vantage point: it focuses on what government *could do: on* the process of incremental institution-building in an unfavorable institutional environment. In other words, the focus is on the policy process as endogenous variable rather than an afterthought of positive analysis. As the most recent thorough review paper (Breznitz et al. 2018, p. 884) puts it: "[W]hereas first-generation policies used the power of the state to achieve economies of scale… their second-generation counterparts are based on a spirit of "entrepreneurialism" (Mazzucato 2013), "experimentation" (Dutz et al. 2014), or "discovery" (Rodrik 2004, Rodrik and Hausmann 2003). In other words, the "new industrial policy" is based on a series of bets along an uncertain and rapidly evolving technological frontier, dropping unprofitable projects and offloading successful ones to create space for new initiatives'.

The chapter asks (and endeavors to respond to) two questions about the management of this experimental (i.e., subject to high uncertainty and trial-and-error) policy process. First, how is it organized: what are the relevant operational and governance procedures—both in a normative and a positive sense? Second, what is the incubation cycle of NIP programs and policies: how are they conceived, corrected, and terminated (discontinued)? In neo-Schumpeterian analysis, this latter question is central: there is extensive literature on the life cycles of industries and sectors (Klepper 1996, 1997), incubation cycles of technology start-ups (Hodgson and Kuznetsov 2014), and policy analysis on the basis of these life cycles (Keun Lee 2017). I find it surprising, therefore, that neither the "old" nor new industrial policy

[1] In this chapter, the terms "new industrial policy," "new industrial and innovation policy," and "experimental industrial policy" will be used interchangeably.

literature posits this central question about the incubation cycle of programs, let alone endeavors to answer it.

Consequently, the NIP process is examined in two steps organized in six sections. As a first step, Section 16.2 sets the stage by establishing a conceptual notion of a new—open economy and experimentalist—industrial policy process. As a second step, we focus on new industrial policy programs and their operational and governance procedures (Sections 16.3–16.5). Section 16.3 considers how new industrial policy programs are organized and how they fit within the Weberian public sector and the increasing shift to new public management (NPM) procedures. Section 16.4 dwells on key operational procedures of new industrial policy: chief among these procedures is diagnostic monitoring—the systematic evaluation of the portfolio of projects to detect errors as each of the specific projects evolves and to correct the problems (including the weeding out of inefficient projects) in light of implementation experience and other new information. Section 16.5 distinguishes NIP process "in the small" (iterative correction of a specific project and program) and NIP process "in the large"—a long-term evolutionary process of emergence of NIP programs as institutional experiments outside the direct control of the policymaker.[2] This is motivated by an observation that most successful NIP episodes emerge as a result of such evolutionary process, never from scratch. Finally, concluding Section 16.6 summarizes the available evidence of design and implementation of new industrial policy as a series of paradoxes.

In terms of the literature context, the chapter brings together three broad strands of the literature: neo-Schumpeterian discussion—which this volume is devoted to, with particular attention to scholarship on the role of governance in technological and economic development (Amsden 1989; Breznitz and Ornston, various years; Rodrick, various years; Teubal and Kuznetsov 2012), literature on public-sector performance and policy learning[3] in the public sector (Rose 1993, Carpenter 2001, Jordan et al. 2013) and a small but rapidly growing body of literature on experimentalist governance.

The principal insight of the latter is that "the exact nature of the problems faced by the street level bureaucrats is not known in advance" (Sabel and Zeitlin 2010). Hence policy goals cannot be established ex-ante but rather need to be redefined in the process of policy design and implementation. Furthermore, there is no clear separation between policy design and implementation: recursive learning through continuous error-detection and correction of the initial design. Toyota-style simultaneous design and implementation is at the center of this approach and applied to an intriguing diversity of problems: new industrial policy (Sabel, various years, Kuznetsov and Sabel 2011, 2017), migration policy and high skilled talent diasporas

[2] This distinction echoes distinctions between industrial policy "in the large," and "in the small" done in a different context Hausmann, Rodrik, and Sabel (2008).

[3] Our definition of policy learning follows Jordan, Turban, and Wils-Samon 2013: "the generation of new information, the transmission of that knowledge upwards and horizontally across the system, and acting upon that information ('implementation')."

(Kuznetsov and Sabel 2008, Kuznetsov, 2013), architecture of the European Union (Sabel and Zeitlin 2010), customized social and education policy, and other policies of the new welfare state (Sabel 2012a) or so-called high-reliability organizations (in which the costs of human error are catastrophic, such as atomic power stations, Sabel et al. (2006).

The chapter is explicitly exploratory: its goal would be accomplished, if the reader takes seriously a mere *plausibility* of the argument as demonstrated in a diversity of real-life examples. Examples, some of which are presented as text boxes, are thus more central to the argument than is customary in the literature. To save space, most sections present a summary table outlining the main argument.

16.2 Making Choices without Picking Winners: NIP Process[4]

A key question of the open economy industrial policy is a pragmatic "how to" question: how policymakers can set priorities despite rent-seeking public sector which has neither a panoramic view of the economy nor perfect capabilities to learn (draw lessons from its own and from the world at large)? In other words, this chapter starts from the premise that policymakers invariably make mistakes, both intentional and unintentional. That requires a shift of focus from a *one-time* choice of winners (sectors, industries, firms, and other organizations) to a *process* of error-detection and error-correction of such choices (with corresponding attention paid to governance). As a second premise, we take obstacles to reaching informed and accountable choice (influence of entrenched interests, low capabilities of public sector, etc.) as endogenous variables, or objects of analysis in themselves. Four of them are particularly important:

- *Power of vested interests.* Entrenched interests are likely to derail the search from the provision of public goods toward self-dealing and rent-seeking. In particular, the disengagement of the public sector proves to be much more difficult than its engagement, even in successful and promising cases of industrial policy.
- *A necessarily partial view of the economy.* No actor has a panoramic view of the economy or complete knowledge of the distortions which the public sector is supposed to correct. In today's fast changing economy, neither economists and public officials, nor private actors know where the relevant market failures are.
- *Weak capabilities of governments and other economic agents to undertake industrial policy tasks.* In low-income and middle-income economies in particular, public support for the connections with the world economy can become

[4] This section draws heavily on Kuznetsov and Sabel (2011) and Kuznetsov and Sabel (2017).

self-defeating due to non-existent capabilities. The issue is how to generate such capabilities.

- *Paucity of examples to draw practical lessons from*. Examples of so-called global best practice are numerous, but they are usually too remote from a local implementation context: they can inspire but provide little guidance on how to resolve everyday implementation problems, which is largely tacit knowledge. Unlike the cases of vertical and horizontal industrial policy, this is a devastating obstacle for NIP process. Since correction of design and implementation errors is crucial, it is (largely, yet not completely) tacit experience of policy-making "kitchen" that matters: no matter how good cooking recipes (best practice recommendations) are it is "cooking"—putting them in practice—that matters.

The shift from one-time choice to a process where obstacles represent endogenous rather than exogenous variables occurs by positing *a real sector project* or program (and related project portfolio) as a key unit of both action and reflection on the action. Such a project is an investment—a set of activities which are at once finite (i.e., with clear objectives and resources) and malleable (i.e., amenable to adjustment: both objectives and resources are supposed to be provisional and are expected to change). It is for this reason, project or program rather than policy that will be the main unit of our analysis. In this view, a policy (say, to promote technology entrepreneurship) can be conceived as a portfolio of related public or private–public projects or programs (support to venture capital, change in relevant laws, etc).

In contrast, in vertical industrial policy, the central unit of action is *strategy*—an exercise in informed imagination whose weight derives from an elaborate approval process. In horizontal industrial policy, the action unit is *a regulatory action* of a (well-functioning) public-sector organization, particularly a court. Courts are capable of both assuring and maintaining an "even playing field," as well as of restraining their own powers and prerogatives. Both vertical and horizontal industrial policy approaches, for all their apparent differences and contrasts, proved problematic in practice. In contrast, placing the focus on a project is at once a humble (in the short run) and an ambitious (in the long run) undertaking. In the short term, one relies on the institution of a *project manager*—an individual who demonstrates practical acumen, creativity, and tenacity, even if the environment around her is highly problematic. The project manager is the very institution which experiments, makes mistakes, and learns from them.

Evidence for the new open economy industrial policy process understood as continuous search for new domains, or, more generally, for capacity-enhancing connections to the world economy through the management of project portfolios, comes from small open economies such as Israel, Taiwan (China), Ireland, or Chile. Israel achieved this through the formation of a globally connected cluster of technology start-ups, culminating with venture capital program Yosma (see Teubal, various years, and Box 16.1 in the next section of the chapter). In a similar way, Taiwan

Box 16.1 Yozma: New Industrial Policy Program

Yosma—a government fund of funds, created in 1992 to increase the amount of venture capital for Izraeli technology start-ups, and to inject knowledge of the American financial and product markets in the Israeli high-technology sector.

- Target Level of Capital Aimed at 250M$ (Government Support- 100M$)
- 10 Privately owned Israeli VC Funds each managed by a local management company (formal institution) & involving Reputable Foreign Financial Institution.
- Government Participation in each Fund-8 million dollars (up to 40% of fund's capital)
- Strong Incentive to the "Upside"- a 5-year option to buy the Government's share at cost
- The Yozma Program attracted or induced the creation of a wide variety of agents such as MNEs, foreign investment banks, service providers of highly specialized marketing and technological knowledge and top-tier foreign venture capitalists. Today Israeli venture capital consists of more than 190 funds (https://www.ivc-online.com/Analytics/VC-Funds-Dashboard, accessed April 15, 2019) and considered the most sophisticated in the world.

To be effective, Yosma relied on three critical programs:

1) ***Inbal*** *(1991)* - a Government owned Insurance company, which gave partial (70%) guarantees to traded VC funds. Four VC companies were established under Inbal regulations. This early VC support program failed to create a VC industry or market.
2) ***Magnet Program*** *(1992-)* - a $60M a year Horizontal Program supporting cooperative, generic R&D involving two or more firms and at least one University.
3) ***Technological Incubators*** *(1992-)* - a program supporting entrepreneurs during the Seed Phase, for a period of 2 years. The incubators are privately owned & managed. Both they and the projects get financial support from the Government.

Source: Based on Teubal and Kuznetsov (2012).

achieved this through the formation of a venture capital program that allowed Taiwanese-born engineers, trained both at home and abroad, to deploy their skills in start-up firms whose activities complemented and facilitated the re-organization of US leaders in the computer and semi-conductor industry. Venture capital—still slowly diffusing within the advanced economies and virtually unknown in developing ones outside of Israel and Taiwan (China)—thus effectively became an instrument for orienting and re-orienting the direction of development of the national economy in rapidly shifting and highly demanding markets. Ireland created an analogous method for identifying and developing growth-enhancing connections from the 1950s: tax exemptions (later reductions) to the corporate profits tax attracted subsidiaries of multinational corporations from promising sectors such as chemicals, pharmaceuticals, and software.

If Taiwan and Israel used venture capital to connect its expatriate engineers and scientists to each other and to world markets, Ireland employed selective FDI. The result in both cases was cumulative capacity-building. In Taiwan and Israel, we saw this in the creation and evolution of firms. In Ireland, we found it principally in the growing responsibilities of managers who rose through the professional networks of particular sectors, at least until the mid-1990s. The chief vehicle of learning—for selecting the most promising collaborators from among those attracted by the incentives, and working with them to ensure incremental improvement of local supply networks, infrastructure, education, and similar areas—was first the Irish Development Authority (IDA) (now called Irish Development Agency), and then, from the late 1980s, as the domestic firms became more important, Enterprise Ireland. These two Schumpeterian development agencies had an explicit mandate to search-by-experiment. The IDA's attention to the systemic or economy-wide implications of its collaboration with groups of firms can be illustrated by two examples: the way it tracked and reacted to indications of possible skill shortages, and the effort directed at supplier development. Thus, between 1977 and 1979 the agency negotiated agreements with electronics firms that, together, would create demand for some 600 electrical engineers per year, about four times the number that Irish universities and regional colleges were then graduating. As it takes between two and five years to educate technicians and engineers, there was a need for a short-term remedy and a plan for a long-term expansion of the education system. The short-term solution was to convert science graduates to electronics qualifications via one-year courses; the longer-term solution was to expand existing courses and add new ones. The rapid response of the Higher Education Authority provided reassurance to subsequent investors that Ireland could provide the skills needed, and contributed to a renewal of the university and technical training systems.

A typical project in a portfolio is a collaborative program which seeks to alleviate specific constraints such as skills shortage or lack of qualified suppliers for electronic firms, as in the case of IDA. A project in the new industrial policy portfolio can be a private firm, incubated in collaboration with private partners. For instance, Fundación Chile, an autonomous private–public agency with a modest endowment, acquired the necessary technology, free of charge, from specialist public agencies in the US in the crisis year of 1982. The Fundación then founded one firm to produce smelts, another to develop hatching and ranching technology for Chilean waters, and a third for smoking fish, creating a foundation for the salmon cluster (Box 16.2 in Section 16.5).

Box 16.2 Fundacion Chile as an Example of SDA

Fundacion Chile is a successful private-public organization triggering productive innovation in a difficult but heterogeneous environment. The Fundación was created as a non-profit corporation by the Chilean government in 1976 with a USD50 million payment by the conglomerate ITT as part of an agreement indemnifying the company for expropriation of its national telephone subsidiary. Only in the aftermath of the economic shock of 1982 did Fundación Chile develop the activities that came to define it. A combination of sharp devaluation, low domestic interest rates and high uncertainty produced a situation favorable to domestic investment but with nationals willing to invest. Seeing an opportunity in salmon farming, the Fundación decided to launch firms itself, hoping the success would lead to imitation and complementary activities. Thus, it acquired the necessary technology, for free, from specialist public agencies in the US Pacific Northwest, and founded one firm to produce smelts, another to develop hatching and ranching technology for Chilean waters, and a third for smoking fish. From these firms grew the Chilean salmon industry, which in 2019 resulted in US$4,660 million in exports.

In the next two decades, the Fundación's model of supporting development was refined in three crucial ways First, it shifted from creating start-ups itself to co-venturing with outside partners. Whereas between 1985 and 1993, 87 percent of the Fundación's start-ups where wholly owned by the Fundación itself (and only one of the joint ventures involved a foreign partner), from 1994 to 2004 only 75 percent of the startups were joint ventures, and 6 of these were with foreign firms. Thus, the foundation went from spinning out projects developed internally to networking with outsiders to create projects. Second, the technological complexity of projects increased, with biotechnology in particular becoming more and more important. Since projects in this area—new vaccines, development of pest-resistant fruit varieties—often required integration of scattered intellectual property and diverse technical tools for genetic manipulation, many of the external partners had to construct networks of their own to serve the specific needs of the emergent companies. Therefore, the Fundación in effect builds networks of search networks linking global knowledge with local capabilities.

Third, the Fundación's own project-selection and review mechanism became more explicitly comparative or competitive: staff members, hired on the basis of demonstrated technical knowledge and familiarity with the markets and business practices in a particular sector, apply for internal grants to develop a case for launching a new venture in some general area. The best of these preliminary plans can be used to apply for a second, longer term grant to develop a business plan for a new venture, typically in partnership with outsiders; and so on until the proto-venture becomes a candidate for seed capital and enters the familiar sequence of venture capital financing. So far, at least, the transparency inherent in the broad and continual benchmarking of projects at every stage has also functioned as an effective governance mechanism, assuring that public funds are indeed directed towards public purposes, as best as these can be defined at any moment.

Source: *author.*

A key problem of a new industrial policy process is the gap between micro innovations and improvements in macro conditions. Incremental changes can lead in principle to wide and abiding transformations: it is easy to start yet much harder to sustain and scale up. Deep constraints can remain binding if *micro changes do not achieve a critical mass*. To lessen the risk of such limited outcomes, NIP programs provide an environment for micro-level changes to continue and scale up. They create coherent portfolios out of unrelated programs and initiatives, that is, they are turning "stand-alone" projects into portfolios. The Taiwanese and Israeli venture capital initiative (Box 16.1 in the following section) are the examples.

By the end of the 1970s, Taiwan had already developed significant R&D capabilities such as the Industrial Technology Research Institute (ITRI) and the Electronic Technology Research Institute (ETRI). Yet transforming technology into new firms proved difficult. The large Hinschu Science Park, opened in 1980, was unable to find tenants despite aggressive efforts to lure multinationals. The program started with the efforts of a minister-without-portfolio and his influential allies, who convinced the ministry of finance to introduce legislation to create, develop, and regulate venture capital in Taiwan, including comprehensive tax incentives and financial assistance. Institutions such as a Seed Fund provided matching capital contributions to private VC funds. Two American-style venture funds, H&Q Asia Pacific and Walden International Investment Group, were created and managed by US-educated Chinese living overseas who received invitations to relocate to Taiwan. Once the first venture funds proved successful, domestic banks and large companies created their own VC funds. As those funds started to pay off, even the conservative family groups decided to invest in VC funds and information technology businesses. By the late 1980s, when companies like Acer and the returnee company Microtek were publicly listed on the Taiwan (China) Stock Exchange, the venture capital industry in Taiwan took off.

A search network is a network of individuals and institutions to identify successive constraints and then people or institutions that can help mitigate these constraints. A search network consisting initially of key, dynamic, and forward-looking members of the Taiwan government and leading overseas Chinese engineers in Silicon Valley was central to the emergence of the VC industry. This network did not have a blueprint, yet it did have a role model (Silicon Valley) and a clear idea of "what to do next." By defining each subsequent step along the road, the network became wider and eventually incorporated skeptics and opponents. Table 16.1 summarizes and juxtaposes three generations of industrial policy: vertical ("picking winners"—second column), horizontal (assuring adequate background conditions or "backing winners", third column), and new (open economy) policy (fourth column).

The theory of change behind new industrial policy is incremental change, which over long time leads to radical transformation. A new private sector, which learns to innovate by connecting to the world economy, and a new public sector capable of providing complementary public inputs for private-sector search develop together: they are two sides of the same collaborative process. This process of the

Table 16.1 Three generations of industrial and innovation policy: vertical, horizontal and new open economy

	Vertical Industrial Policy—*Backward Linkages*	**Horizontal Industrial Policy—*Market Failures***	**New Open Economy Industrial Policy—*Missing Connections***
Motivation for private agents	Rents (infant industry protection)	Subsidies (when private returns are believed to be lower than social returns)	Quasi-rents—rent opportunities which are contingent on one's effort or performance
Focus	*Micro-level* and sectoral ("picking winners")	*National level*: institutional infrastructure ("backing winners")	*Mezzo-level*: connections between agents ("matching winners")
Main conceptual axis	*Government capabilities* enable and monitor firm-level learning	*Background conditions* to mitigate market failures and distortions. Assuring balance of macro aggregations and eliminating the many micro impediments to growth	*Search network*—to identify successive constraints and then people or institutions that help mitigate (in part) the difficulties associated with these constraints
Main problem	State capture: development of capabilities gets subverted by entrenched interests	Absence of a link between macro changes and increase in micro potential	Gap between micro innovations and improvements in macro conditions; deep constraints remain binding; micro changes do not necessarily achieve critical mass
Examples of programs and policies	Infant industry protection	Reduction of regulatory burden; creation of venture capital funds	Supplier development, early stage venture capital and consortia programs

Source: Based on Kuznetsov and Sabel (2011) and Kuznetsov and Sabel (2017).

simultaneous emergence of embryos of Schumpeterian private and public sector begins even if government is overall weak or incoherent, and many firms are rent-seeking because the public and private sectors are highly heterogeneous: there are (nearly always) positive variations of performance—dynamic exceptions from a general (mediocre) rule.[5] In the self-discovery parlance, entrepreneurial self-discovery is predicated on public-sector self-discovery and vice versa. Triggering and, more importantly, sustaining this process of collaborative mutual self-discovery is the key objective of new open economy industrial policy process.

To put it another way, for analytical purposes the self-discovery process can be viewed as two simultaneous and mutually reinforcing processes: Schumpeterian

[5] Often this new private sector develops as exclave—extension of global knowledge economy into national economy in question, as it indeed the case in Israel's high-tech cluster and India IT clusters, the two paragons of innovation. For less well-known examples of the emergence of innovation clusters in rent-seeking environments, see Gonchar, Kuznetsov, and Wade 2017.

creative destruction in the real sector and "creative destruction" in the public sector—the NIP process. It is first the attention to this policy process and second, insistence on its Schumpeterian dimension ("creative destruction") which distinguish NIP from two previous generations of industrial policy. Concepts tools introduced so far—project and program portfolios, search networks, and NIP programs are necessary to describe the NIP process.

Since the process starts from existing positive variations, it takes a long time as it proceeds from micro to mezzo-level (level of clusters, sectors, and industries) and finally to national level. In our Taiwan example this three-stage sequence is the following:

Stage 1: Micro-level: Pilot action which creates positive variation in performance

First private–public venture capital fund is established. Legislation is changed to enable venture capital. Diaspora members relocate to Taiwan to manage the fund.

Stage 2: Mezzo-level: Critical mass effect

Demonstration effect of the success triggers establishment of other venture funds. This stage is critical whether institutional change (emergence of early stage VC in this example) would continue. New industrial policy process is easy to start (no preconditions except some positive variations in performance) but difficult to continue because of the gap between micro innovations and improvements in macro conditions. Deep constraints remain binding and micro changes do not necessarily achieve critical mass (see the last column of Table 16.1 for a summary).

Stage 3: National level: Institutional transformation

Emergence of globally competitive innovation clusters and public R&D effort to support them Massive return of talent ensues.

Such incremental step-by-step institutional transformation has a dual nature: it is humble in the short run (no institutional preconditions are assumed, all that is required is the ability on the part of a policymaker to recognize existing positive variations in performance) and ambitious in the long run (since economy-wide transformation is at stake). Because of this dual nature of the institutional transformation which NIP both triggers and becomes an outcome, a policymaker needs to simultaneously adopt two time horizons: medium-term (how a specific NIP program is conceived, implemented, and discontinues) and long-term (a three-stage evolutionary sequence outlined above). The medium-term outlook—a life cycle of a specific program is directly within control of a policymaker, while the long-term evolutionary process is not. This obviously creates a tension.

This tension—which emerges in Stage 2 of our evolutionary sequence is mediated by a peculiar kind of public-sector agency capable of accountable experimentation—which thus becomes an indispensable part of a long-term evolutionary NIP process. The latter is discussed in more detail in Section 16.5 but we start with our Stage 1—a specific NIP program as a departure from the "business as usual"—a novel positive variation of performance.

16.3 New Innovation Policy Program as a Novel Positive Variation of Public-Sector Performance

NIP programs as positive variations of performance recombine fragments and pieces of existing programs and thus both rely upon and learn from previous private-sector projects and public-sector programs. A key insight here is that new industrial policy programs (e.g., YOSMA in Israel or venture capital programs in Taiwan) follow venture capital logic themselves. Of course, venture capital in itself is a paragon of search networks: it provides a framework to reveal and recombine fragments of companies' technological and technical knowledge, marketing expertise, funding, and financial expertise (Sabel and Saxenian 2008). In rare cases when such recombination succeeds, the result is a so-called "home run"—a highly profitable project, proceeds from which cover accompanying failures. A more vexing outcome, though, is not a failure per se (in that case, it is obvious what to do—just close down the project), but so called "living dead"—a project which barely covers its costs and lingers there for a substantial time before closure. Comparison of new industrial policy programs with venture capital projects is thus not just a metaphor or a simile: it reflects the essential experimental nature of such programs.

Yet experimental venture capital logic contradicts Weberian public sector where failure is not tolerated. One implication of this venture capital logic is that one should not overestimate ex ante design planning of NIP programs, nor the durability of success of these programs. Just like with venture capital projects, even well-designed programs are bound to surprise, and their success is always tentative and provisional.

Box 16.1 on Israeli's Yosma illustrates this venture capital logic of combining pieces of accumulated efforts and experience in experimental fashion. For instance, the success of Yosma is unthinkable without policy learning from Inbal—a venture capital program which preceded Yosma but failed. In the hindsight, the design of Inbal appears bluntly and self-evidently erroneous but it was far from obvious at the time of its design

The demonstrable success of the first generation of new industrial policy programs and agencies in small open economies in the 70s and 80s outlined above, compounded with the success of experimentalist DARPA of USA, leads now to a high demand from politicians to emulate this success. Yet in the developed world, increasing public scrutiny and implementations of tenets of new public management makes experimentalist innovation programs increasingly impractical, unfeasible, or both (Breznitz and Ornston 2018). Hence, we observe two paradoxes: first, this combination of high desirability and impracticality leads to the incidence of "siren call"[6] programs in the developed world. The Smart Specialization Program of the European Union is the most visible paragon of such a "siren call" (see evidence on this for less developed regions of Europe in Morgan 2017). Second, global good practice for the modern-day (second generation) experimentalist programs shifts from high-income to emerging economies characterized by a peculiar blend of weak institutions and sophisticated knowledge capabilities, such as Argentina, India, and Russia (Kunetsov and Sabel 2017).

As a positive variation of performance, NIP programs often emerge at the intersection of the following three factors ("the trinity" of emergence):

- A trigger to depart from "business-as-usual": usually, a "stick" of crisis—and more generally, a sense of urgency to act
- A business opportunity: a "carrot" as a focal point for the action
- Personal agency—policy entrepreneur and her teams who transform "sticks" and "carrots", threats and opportunities, into a project portfolio.

Taken together, those three ingredients create a "space of novelty", an institutional space to experiment in doing new things (Morgan 2017)—which is all the more valuable because it exists amid a stale environment of habitual rent-seeking.

As an illustration of how those three ingredients create a "space of novelty" for second generation NIP programs and agencies, let's consider in more detail a highly unlikely candidate—the Fundación PROARROZ (FPA) in the province of Entre Rios—the "Mesopotamia" of Argentina, north of Buenos Aires.[7] Argentina—country with deeply entrenched corruption and rent-seeking—is an unlikely paragon of institutional innovation, yet this is precisely what happened.

The following circumstances played an important role in the unlikely emergence of this "space of novelty". First, rice yields were declining as the result, largely, of poor quality seed. Growers and grain processors or industrialists were aware of the need to take action to maintain the sector. Second, "extra official" agreements between growers and processors in Argentina (where per capita consumption was then 6kg/year) and importers on the other side of the common border in Brazil abolished tariffs on rice between the two countries and created a de facto common market in rice five years before the Mercosur treaty was signed, in 1995. There was thus reason to think that investments in increased productivity would be well rewarded in the new market for exports. Finally in these years a cohort of capable and well-trained agronomists was returning from post-graduate studies in the US and elsewhere, and finding employment in Argentina. The threat of imminent

[6] Richard Rose (1993, p. 46) coined the notion of a "siren call" program: highly desirable (by politicians, academics, and other stakeholders involved in program design) but impossible or very difficult to implement in practice (In Greek mythology sirens lured sailors to steer in their direction, but the sirens' call actually lured sailors onto the rocks).

[7] Discussion of Fundacion ProArroz draws on Sabel (2012).

decline, the carrot of prosperity, and the team of technical expertise were the three ingredients we introduced.

The alignment of interests was reflected in the formation of our institutional "space of novelty"—an umbrella, rice-promotion organization. The main focus of the umbrella association in these early years was the identification and execution of technically demanding projects of recognized utility to the whole sector (Muller n.d.) By 1994 the umbrella organization was sufficiently established and recognized to incorporate as a foundation, and the FPA came into existence. Throughout this period, the foundation had been financing activities through voluntary contributions by a group of growers and processors, on the one hand, and key suppliers (for seed, fertilizer, and so on) to the sector on the other. One indication of success of FPA is that between 2004 and 2018 three new and highly profitable varieties of rice seed were developed.

Many successful second generation NIP programs are not widely known, they remain tiny and, in the personal experienc, of the author are discovered by accident, or to be more precise by serendipity: we were looking for something else in our operational work in the World Bank and our way stumbled on promising programs which, upon closer inspection, revealed that they were emerging global best practice in NIP (for other examples in this vein, such as India bio-technology programs and World Bank debt management programs see Kuznetsov and Sabel 2017). Accidental discovery, small size, and relative obscurity make such programs "hidden gems"—almost the opposite of "siren calls" (large, widely publicized programs which are "living deads"—continuation of the "business as usual"—under the guise of novel NIP programs) found in the developed world. A procedure for the search for such "hidden gems" and set of measures to make them shine and grow will be discussed in Section 16.5 as part of the NIP process "in the large", but first we shall dwell upon the procedures for a program's revision, error-detection, and correction.

16.4 Key Procedure: Diagnostic (Problem-Solving) Monitoring

Recall our observation that NIP programs recombine pieces of existing institutional fabric and thus resemble venture capital logic. Yet in venture capital, monitoring of the project portfolio is highly pro-active but informal: both project selection and monitoring focus more on entrepreneurs who run them than any formal characteristics of the projects. Tacit experience and the intuition of the VC manager and her team play the central role in making decisions. Such informal logic with a full trust in the tacit knowledge of both the entrepreneur and venture capital fund manager is plainly insufficient when public funding is involved: there is a need for a systematic institutionalized procedure which would make partially tacit knowledge explicit and thus permit combining experimentation with accountability. Such procedure, introduced in the literature by Sabel (2012b) is called *diagnostic or problem-solving monitoring*: the systematic evaluation of the portfolio of projects to detect errors as each of the specific projects evolves, and to correct the problems (including the weeding out of inefficient projects) in light of implementation experience and other new information (see also Kuznetsov and Sabel 2011, 2017).

More specifically, conventional monitoring refers to the determination that a goal has been met or a rule followed and to the distribution of rewards if behavior meets expectations or the imposition of penalties if it does not. The goal of diagnostic monitoring, in contrast, is to determine why goals were not met (or exceeded), or why behavior deviated from the rules. To introduce elements of diagnostic monitoring, one can put in place, for example, *project implementation reviews* which consist of two or three members with an appropriate mixture of expertise. In a two-day site visit, the team would review the documentation of the project and discuss its status with the stakeholders, including not just the relevant firms and service providers, but also actors in a position to judge the performance of both. These actors can be, for instance, selected customers and suppliers to the firms or participants in training and capacity-building programs.

In this procedure, the central governing body is a deliberation council and the focus is on three questions:

- Did the deliberation council initially include all those with the relevant capacities and interests and, if not, was its membership modified so that it eventually did?
- Did the discussion of possible projects canvas plausible alternatives, and was the final choice well motivated?
- Has the project met its milestones and, if not, is there a clear understanding of why that has not happened and a corresponding adjustment of the project's goals and timetable?

For instance, in Fundacion Proarroz, rigorous competitive project selection is complemented by a routinized, meticulous system of monitoring and evaluation that regularly reviews the progress of each undertaking, surfaces problems early, and where possible organizes technical support to overcome them. The core of the system is a set of technical teams operating under a central coordinator. They review projects at least once a month and, in some cases, every two weeks. The task of the teams is to diagnose problems and their likely causes, detect variations across similar projects and suggest remedies for poor performers, and suggest mid-course or, in extreme case, the discontinuation of ongoing initiatives. The FPA's technical teams monitor projects undertaken on the foundation's behalf in universities and other institutions to ensure a comprehensive review of all initiatives according to the same criteria, and to accelerate the cross-fertilization of ideas.

Projects concerned with the genetic development of new seed varieties are under particularly strict and permanent scrutiny. In addition to the routine work of the technical teams, the FPA also assesses progress through "open field" ("campo abierto") tests in various settings. Typically, this means benchmarking trial seed performance on specific dimensions (tolerance to herbicides, generation of organic and non-organic arsenic, and the like) under different agronomic conditions prevailing in different parts of Entre Ríos.

As Table 16.2 makes clear, the "why" of diagnostic monitoring and the "what" of conventional monitoring are best thought of as complementary. They may be procedurally similar, such as using benchmarking, but the meaning of the procedures remains starkly different. In conventional monitoring, benchmarking is a comparison of formal indicators, such as world league tables of performance. However, macro-level indicators and league tables such as, for instance, the competitiveness rankings of countries portray developing economies precisely as what they are not: as homogenous wholes. In diagnostic monitoring, in contrast, the point of benchmarking is to reveal the relevant heterogeneity and the key question is which benchmark is relevant for our portfolio in a given context.

Table 16.2 Diagnostic (problem-solving) vs. conventional (principal agent) monitoring

	Conventional	**Diagnostic**
Key question	What (is the gap between performance target and outcome)?	Why (is there a gap)?
Users who benefit from monitoring	External to the process: e.g., funding agencies	Participants in the process: e.g., project managers
Flow of information and accountability	Vertical: principal–agent problem	Horizontal: extended peer review
Relevant expertise	General (task management)	Specialized expertise: new knowledge is created in the process
Information-gathering procedures	Focus on formal indicators of performance Performance reports	Focus on site visits Technical meetings of diverse experts
Risk management procedure of project and programs	Ex ante (before the project/program begins): through elaborate indicator-based risk rating of projects, both at design and implementation stage	Endogenous: "just in time" error-detection and correction
	Backward-looking: to assign guilt (of bad performance)	Forward-looking: to detect and correct problems
Benchmarking	Of formal indicators (e.g., outcome and output indicators)	Key question is which benchmark is relevant for our portfolio in a given context
Organizational unit which does the monitoring	Weberian bureaucracy: diligent and transparent setting the rules of the game and following them	Schumpeterian development agency: capable of accountable experimentation

Source: adopted from Kuznetsov and Sabel (2017).

16.5 NIP Process "in the Small" (Managerial Sense) and "in the Large" (Evolutionary Sense)

The previous section described how diagnostic monitoring is performed in the course of project or program implementation. Any theory of new industrial policy would be seriously incomplete without a discussion of program/policy life cycle: how do programs/policies emerge, evolve, and eventually die or morph into other programs? Let's discuss the following three stages of the project incubation cycle in which the implementation (stage 2) is preceded by project design (stage 1) and followed by closure or exit (stage 3).

Largely self-explanatory, Table 16.3 juxtaposes these three stages of the incubation cycle in the NIP approach, private-sector domain (early stage VC), and in the New Public Management (NPM) approach (in which funding agency competitively selects projects for funding and does not intervene in their implementation). The private-sector domain—early stage VC (third column of Table 16.3) is mandatory for this chapter because it is the only established institution of experimentalist NIP making choices without "picking winners." The fact that it is in the private sector, rather than in the public-sector domain allows us to highlight crucial contrasts in project monitoring.

The stages of the project cycle: design, implementation, and closure are sharply distinguished only in the hierarchical NPM approach: the project concept is selected in a competitive call for proposals (design stage), then the winning project concept is implemented with no intervention from the funding agency (implementation), and at some point the project is closed when funding is exhausted (exit). In NIP, incremental project adjustment is continuing and recursive and thus the distinction between the three stages of the project cycle is blurred.

As an illustration, consider ARPA-E—an organization established in 2009 to foster radical innovation in the energy sector. ARPA-E follows the practices of DARPA—the agency for radical innovation in the US Department of Defense.[8] As Rodrik and Sabel (2019) note "at every stage in the organization of research—the definition of programs of investigation; selection of a portfolio of projects, advancing the program purpose; and supervision of individual projects in the portfolio—ARPA-E treats goals as provisional, or corrigible in the light of experience". Project design stage consists of two reviews: of concept papers (explaining why a specific research direction is taken) and of full applications (developed out of concept papers selected by program directors). Winning full application receives funding: a typical program consists of ten projects, each awarded three million dollars to be spent over the course of three years (Rodrik and Sabel 2019). The implementation stage is

[8] Defense Advanced Research Project Agency (DARPA)—established in 1958 and with a budget of approximately $3 billion per year—is an intermediary between researchers who create ideas and potential applications which it takes to the point of proof of concept. DARPA then hands these over to specialized actors able to implement them. Established as a response to the Soviet Sputnik, the Agency has a rich 60-year history of successes ranging from the internet stage to GPS and stealth technology (Dahlman and Kuznetsov, 2014).

Table 16.3 First-order monitoring practices: NIP, NPM, and venture capital approaches

	NIP	Venture capital	Conventional (NPM)
1. Generation (design) of a project concept	Active: Iterations of search for project concepts.	Usually passive (entrepreneurs approach VC for funding) and informal (no explicit procedure exists)	Usually passive: applications come in response to call for proposals
2. Implementation	Continuous correction of a project concept through diagnostic monitoring	Informal diagnostic monitoring (no explicit procedure exists)	Accounting monitoring through progress report from the implementor of a project to funding agency
3. Closure	Extension of diagnostic monitoring: gradual phasing out of a problem project through remedial measures	Judgement call. Trivial for failing projects, difficult for "living deads"	Political decision to stop funding a project. Example: program that funds the project runs out of resources

organized on the basis of milestones agreed upon between the program director and research partners. There is a "traffic light" system: if a project misses critical milestones persistently ("red light"), then, as a problem project, it becomes a subject of particular scrutiny. Milestones can be reset to develop an alternative research approach—meaning that the project is back to the design stage. If problems persist, the program director sends "at risk" letter to implementing research team detailing remedial actions including reduction of funding. Problem projects are thus closed gradually and incrementally—through remedial measures—blurring the distinction between implementation and closure: a feature which will recur repeatedly in the NIP incubation cycle. Interaction between the program manager and research teams is intense and includes site visits, conference calls, and consultations with outside researchers. Similar interactions only less intense occur for "yellow light" projects (missed some milestones) and "green lights" (milestones are usually met). Descriptors of the direction of research—the milestones—are not the targets to be achieved but the information to engage with experience-based discussions with research teams. They are meant to be revised frequently rather than met consistently. If the latter happens the approach taken is not novel enough.

ARPA-E is too new to judge its efficacy. We used it as an illustrative example of an NIP project cycle—which provides a sharp contrast to NPM arms-length monitoring practices of other agencies engaged in radical innovation, such as the US National Institute of Health (NIH).

Let us now apply a diagnostic monitoring approach to a portfolio of NIP programs—including promising programs which exist but of which we are not yet aware. By taking this step, attention is turned to the NIP process in a long-term evolutionary sense, which, recall, is not under policymaker control. To put it another way, if institutional experimentation and “hidden gems” programs associated with it are important, then search, scaling-up, and diffusion of the experience of such “hidden gems” becomes one way to construct an effective NIP process. Scanning a portfolio of NIP programs to reveal promising new programs, to revise and adjust designs in light of performance, and to scale down and discontinue programs which are no longer effective is a higher-order monitoring. To be more specific, first-order monitoring is monitoring a portfolio of projects within a single program (recall the example of how ARPA-E monitors its project portfolios), while higher-order monitoring goes one or several levels above by focusing on a portfolio of programs or organizations running these programs.

Table 16.4 introduces the incubation cycle of an experimentalist program in the context of evolutionary process of emergence of promising NIP experiences (NIP

Table 16.4 Detecting and supporting promising practice: Conventional vs. experimental approaches

Stage of policy innovation cycle which is being supported	**Conventional incubation cycle**	**Experimental incubation cycle**
1—Search for relevant “space of novelty” for policy innovation	Assumed that emerging good practice is well known, and thus there is no need for the search. Policymakers decide which programs to fund in a top-down fashion	Active search Serendipitous encounters with novel experiences “ferrets”—individuals and teams who search novel ideas and experiences
2. Support to scale up and diffusion of “hidden gems” and other promising programs	Accounting monitoring	Diagnostic monitoring as problem-solving: continuous identification of problems and their resolution. Determination of relevance of these to others involved in implementation of similar problems
3. Evaluation and lessons-drawing	Monitoring and Evaluation (M&E) is admonished but rarely produces changes in program (re) design. If evaluation shows good results, the program becomes “best practice”	Does not exist as a separate stage: it is part of search (Stage 1), error-correction (Stage 2) and dis-entrenchment/exit (Stage 4) phases
4. Facilitating exit: closure or radical restructuring of the novel program	Results of M&E as empirical ground for the exit. Usually does not occur	Diagnostic monitoring as dis-entrenchment: engaging with vested interests to maintain “space of novelty” and to close non-performing

Source: The author.

process “in the large”),[9] and contrasts it with the incubation cycle of a first-generation industrial policy program. The main contrast lies in the initial and the last stages of the incubation cycle. While in a conventional policy cycle, there is no need to search for promising good practice, the experimental policy cycle does insist on such search: bottom-up institutional innovation may have no incentive to come to light because of the fear of coming to the attention of vested interest, a consideration particularly salient in a rent-seeking institutional environment. In the world of technology start-ups there are two technical terms denoting the need for systematic search for promising good practice: “deal flow” problem (a situation of many good ideas yet few projects ready for venture capital investments) and “ferrets”—venture teams comprising the world of finance (venture capital) and academic world which “ferret out” candidates for VC financing. In the world of policymakers wishing to support NIP programs, a “deal flow” problem is perennial and persistent, yet there are no search institutions similar “ferrets” to look for relevant bottom-up policy innovations.

The problem is even more severe for the final (the fourth) stage of the proposed incubation cycle: closure and turn-around of non-performing programs. Since a program or project running for several years creates its own vested interests, uprooting such vested interests—disentrenchment—is a substantial political economy problem. Suffice it to say that the failure of such disentrenchment is singularly responsible for the failure of vertical industrial policy which proved to be much better in picking (presumed) winners than in closure of clear and obvious losers.

To our knowledge, public-sector procedures to uproot vested interests in innovation programs and organizations have never been studied systematically. To give a gist of the matter, such procedures include a shift from competitive project selection (open call for proposals) to two-stage project generation (in which a governance structure is established to weed out pet projects) or DARPA-style silent competition between several project teams (of which they know nothing), with the resulting closure of all but the winning concept or project. It is often assumed that merely rephrasing policies and programs in experimentalist language will solve the problem of uprooting vested interests: “entrepreneurial discovery” of the EU Smart Specialization is the case in point (there is an evidence that the language is used by the established and the entrenched to continue “business as usual”, Morgan 2017). It appears that ad-hoc mechanisms of exit/closure are surprisingly generic: a system of Max Planck’s Institutes, for instance, has an element of DARPA style solution: it endows a star scientist with a significant infrastructure but automatically dissolves it, making all staff unemployed, once the star reaches a mandatory retirement age.

The only detailed examination of exit mechanisms in the context of innovation programs appears to be Jordan and Koinis (2013). They examined how three types of innovation organizations—venture capital firms, radical innovation agencies

[9] This incubation cycle of NIP program is informed by incubation cycle of technology start-ups (Hodgson and Kuznetsov 2014).

(such as DARPA) and navigating agencies (MITI in Japan, Blue House Secretariat in Korea)—deal with the potential failure of problem projects. They found the following sequence: "1) Bring more information to the surface; 2) add new capabilities; 3) adjust the team or coalition; and a new, equally ambitious goal. 4) Only then exit. Use tools such as the questions: *Can it still be a home run? If yes, what can we do? Whom can we bring?"*.

This four-step sequence means that program closure, if it is unavoidable, occurs through problem-solving monitoring: you restructure the program pro-actively relying on a methodology known to all stakeholders involved, and exit only when all possibilities for error-detection and correction have been exhausted. To put it another way, diagnostic monitoring credibility of exit and closure.

The program of closure and radical restructuring is even more severe for the management units of portfolios of NIP programs—experimentalist innovation organizations. Following the venture logic of NIP process, they must undergo periods of "creative destruction" themselves. For instance, the DARPA in the 2000s shifted its focus from the development of new technology directions to the coordination of existing technology platforms (Fuchs 2010). Yet as Breznitz and Ornston (2018) show, as some programs in the NIP portfolio became widely known "home runs", the agency became too important for politicians to allow autonomous experimentation and they started to watch them closely. They provide a sobering account of how that happened to the two paragons of experimentalist NIP agencies: Israel' OCS and Finnish SITRA. The key question then is what kind of agency is capable of performing diagnostic monitoring of a single program (outlined in Table 16.3) and a portfolio of such programs (Table 16.4).

A type of agency best suited to experiment and perform collaborative search is an *autonomous entity with a mandate to experiment by assembling a portfolio of projects* and carefully monitoring the portfolio, yet remaining accountable for the results of the experimentation. Kuznetsov (2009), coined the term "Schumpeterian Development Agency" (SDA). An SDA which manages such a portfolio tends to have an incentive structure which induces it, or at least permits it, to establish both capabilities and the motivation and discipline to experiment. Examples include project portfolios managed by venture capital funds, DARPA, ARPA-E, OCS in Israel, and Foundation Chile in Chile (Box 16.3).

The key issue of effective NIP agencies is that they emerge as part of an evolutionary process (NIP process "at the large") at the intersection of sense urgency, opportunity, and personal agency (public entrepreneur who takes a risk by organizing new collaborative alliances). By definition, such an NIP process "at the large" is ripe with uncertainty and beyond the control of any single authority.

Experimental NIP agencies appear to proceed through the following stages:

- *Emergence*: Embryonic stage—in response to a sense of urgency and opportunity. Institutionally fragile and dependent on key policy entrepreneurs (Box 16.3)

Box 16.3 Embryonic NIP Agency Fails to Institutionalize and Falls back to 'Business as Usual'

Consider Russia in 2001. An ambitious, charismatic and competent scientist has been transferred from St. Petersburg (an important detail to signal that he has a personal trust of the president of Russia) with a mandate to show skeptical elite and the country at large that 'science matters'. This newly appointed individual is the agent of change—our third ingredient of the three in the recipe to deal with vested interests . The second ingredient—sense of urgency—came from the crisis of confidence in Russian science. Renowned for its past glory, the Russian science establishment was perceived as an ivory tower ruled by aging science elite, a living proof of N. Bohr's adage that science gets renewed 'funeral by funeral'. The third ingredient—opportunity—came as a significant increase in public funding of R&D, the first one after collapse of R&D spending in the 90's. Unwilling to fight the vested interest of science heads-on, our innovation reformer channeled all of increment of the R&D budget into a new initiative called Megaprojects—big (up to $ 10 mln. in public subsidies)—industry-science collaborative endeavors designed to demonstrate that science does matter for growth and poverty reduction. A typical for innovation consortia call for proposals was issued in six priority areas (the usual suspects such as space, information and biotechnology). Many interesting project proposals came outside the priority areas. That was the first surprise. The second surprise was there was nothing new in the proposals: although the initiative was explicitly designed to signal a shift from 'business as usual', the proposals for funding were highly disappointing: both the industry and science were pushing their pet projects.

Not to be deterred, our tenacious reformer formed a group of competent and credible advisors with track record of both in science and industry. The Group (called Monitoring Group) was charged in generating novel collaborative projects on the basis of most promising proposals for funding. The work of the Group was intense: it looked for synergies between related proposals and imposed collaboration on prospective partners. That the collaboration had to be imposed was surely ironic, but what the Group accomplished was to transform promising ideas into projects with credible commitment. Once the project received funding, the collaborative efforts needed to be corrected, so that the Monitoring Group engage also in diagnostic (problem-solving) monitoring—the key procedure of open industrial policy. As the Megaprojects initiative began to show results, our reformer was promoted in 2004 to the position of Minister of Science and Education. With his mandate much broader now, the Megaproject initiative lost its champion and mentor. The Monitoring Group ceased to exist.

Source: *the author.*

- *Institutionalization*: introduction of NIP procedures such as error-detection and correction. This is when the agency flourishes as an experimental organization and most of the examples of this chapter refer to this period of NIP agency life, often quite brief
- *Capture*: the agency loses autonomy for accountable experimentation. Breznitz and Ornston (2018) provide examples of how OCS in Israel and SITRA and Finland have arrived at this stage by becoming victims of their own success.
- *Re-emergence*: avoiding the capture. Usually that means starting this cycle again as a new organization or radically restructured existing organization. Breznitz and Ornston (2018) state that this stage is extremely rare: hence "partial success" in the title of their paper. The logic of a life cycle of experimentalist organization explains why this stage is rare: it emerges in a temporary "space of novelty", and it easier to establish a new organization in a new "space of novelty" than restructure the existing one which is captured by vested interests.

This discussion suggests that the key feature of experimentalist NIP organizations is their institutional fragility: they are likely to remain experimentalist for a limited amount of time. As innovation becomes central to economic development and comes under the radar of politicians, the NIP organizations and programs shift from organizational periphery and the relative obscurity it affords to the close attention and scrutiny of politicians. Relevant programs become too important to fail—and hence to experiment—turning, in venture capital parlance into "living deads": solid programs with modest social return but no possibility of policy breakthrough (example of the latter is Yosma—box 16.1). This is where policy-learning literature provides a useful perspective. From Carpenter's (2001) perspective, the relevant question is not why, say, Israel OCS loses a policy space for accountable experimentation but what prevented it creating a web of political alliances with stakeholders (with a stake in the accountable experimentation: national venture capital association? High tech multinationals? National "born global" high-tech start-ups? Leading national universities?). Without such a web, Carpenter (2001) would argue, NIP would be garbled up by politicians and other established vested interests turning it into "business as usual"—the first generation industrial policy. In other words, both NIP literature (and the experimentalist perspective in general) and the policy-learning literature view any episode of accountable experimentation, a departure from the "business as usual", as rare institutional innovation which is inherently fragile on many counts and which is bound to be captured by vested interests unless protected by a network of alliances maintaining and renewing the relative autonomy of the "space of novelty".

In practical terms, the distinction means that successful and lasting NIP programs and organizations emerge at the intersection of two processes: a short-term NIP process in "the small"—which is under the direct control of policymakers and a long-term evolutionary NIP process in "the large" of which they do not have control. They need to get the process "in the small" right: how to accomplish this is what this chapter is about. But as a background for the NIP process "in the small", policymakers should be aware of entry points (recall the trio of urgency, opportunity, and personal agency in the previous section) and threats (vested interests) as revealed by a longer-term evolutionary NIP process in the large. This is a tall order at national and supra-national level (see, for instance, analysis of Smart Specialization of EU in Radosevic et al. 2017), but more realistic on regional and sectoral levels, in particular in sectors with inherent uncertainty such as biotechnology.

16.6 Conclusion: New Industrial Policy Process is Necessarily Full of Paradoxes

The main point of the chapter is that the NIP process is more important than any individual policies and programs, however well designed. Identifying unavoidable errors and designing remedial measures is a central feature of diagnostic monitoring, just like attention to the management of the program cycle. The distinction is made between NIP process "in the small" as an iterative correction of a specific project or program, and NIP process "in the large": as an evolutionary process of emergence of NIP programs as institutional experiments outside the direct control of policymakers.

The following seven paradoxes of the new industrial policy process provide a summary of the chapter.

First, while the productive sector in both developed and developing economies is actively advancing in experimental entrepreneurial discovery (Toyota-style production and early stage venture capital are two paragons), the role of the public sector in supporting or facilitating this experimental process currently appears to be minimal. If it exists at all, accountable experimentation in the public sector remains an isolated pocket of dynamism and excellence. It is as if public and private-sector learning processes are two separate and barely related trajectories: the public sector remains bureaucratic and hierarchical (Weberian organization) while the private sector is experimental, horizontal, and open. The explanation of this paradox is that a shift to accountable experimentation within the public sector requires simultaneously huge motivation to engage in experimentation (such as a crisis or other sense of urgency) and significant capabilities in the public sector and some, however minimal, institutional space for experimentation. As Breznitz and Ornston (2018) detail, such "spaces of novelty" are increasingly rare in the developed world.

The second paradox is that it was not always the case. From approximately the end of the 1950s to the end of the 1980s, advanced economies have demonstrated a diversity of accountable experimentation in the public sector. DARPA in the US, the Office of Chief Scientist in Israel (supported in its formative years by a World Bank loan), IDA of Ireland, SITRA of Finland, certain innovation programs in Taiwan, and some regional economic development agencies (such as Scottish Enterprise in UK) are the examples. The explanation for this second paradox is that a heightened sense of urgency left no choice but to innovate by creating experimental embryos in the public sector.

The third paradox stems from an observation that new industrial policy programs follow venture capital logic. Of course, venture capital in itself is a paragon of experimental search networks: it provides a framework to reveal and recombine fragments of companies: technological and technical knowledge, marketing expertise, funding and financial expertise. In rare cases when such a recombination succeeds, the result is a so-called "home run"—a highly profitable project, the proceeds from which cover many accompanying failures. A more vexing outcome though is not a failure (in that case, it is obvious what to do—just close down the project), but so called "living dead"—a project which barely covers its costs and lingers there for a substantial time before closure. Yet experimental venture capital logic contradicts the Weberian public sector, where failure is not tolerated. One implication of this venture capital logic is that one should not overestimate the design possibilities of NIP programs, nor the durability of success of these programs. Just like with venture capital projects, well-designed programs are bound to surprise, and their success is always provisional. In other words, there is an important consistency: one cannot pick winners either in real sector domains, or in NIPs supporting them.

Fourth, the demonstratable success of the first generation of NIP programs in small open economies in the 70s and 80s led to huge demand from politicians to emulate this success. Yet in the developed world, increasing public scrutiny and implementation of tenets of new public management makes experimentalist innovation programs increasingly impractical, unfeasible, or both. For instance, many innovation-funding agencies are now prohibited from helping to implement projects by correcting design and implementation problems even in the most innocent form of giving advice to the recipient: the recipients might sue the funding agency if they follow the advice and then fail. This combination of high desirability and impracticality leads to the incidence of "siren call" programs in the developed world. The Smart Specialization Program of the European Union appears to be the most visible example of such a "siren call". In emerging economies, experimentalist "siren calls" are also increasingly common because of the focus to adopt and adapt global good practice. For instance, YOSMA and Fundacion Chile—the two exemplary NIP organizations—are visited and emulated by many middle- and low-income economies, often mediated by international organizations. But the result is disappointing even when the good practice is adapted and adopted to local circumstances rather than plainly emulated. If a well-designed program comes from outside rather than being the outcome of local policy process, its implementation often remains problematic.

The fifth paradox is that that these experimental embryos—spaces of novelty for new industrial policy—are now coming from narrow but important set of countries characterized at once by an efficient rent-seeking state and high knowledge endowments. Departure from the "business-as-usual" habitual rent-seeking creates "spaces of novelty" for NIP at the micro and regional levels (our Argentina example). In this second generation of experimentalist innovation programs we observe the same sense of urgency to innovate and experiment as in the first generation paragons in small open economies. Argentina, India, and Russia are three examples of countries where such experimental embryos emerged and survived for some time, although they remain institutionally fragile and small, remaining "hidden gems" as long as they exist.

The sixth paradox is that the shift of emphasis from individual policies and programs to NIP policy process results in the shift of focus from conventional best practice to what might be called "best of the worst" practice. By the latter we mean creative institutional responses to unfavorable circumstances: that is one point of the detailed accounts of Fundacion Pro-Arroz of Argentina and Fundacion Chile. Just like the Toyota-style system in manufacturing triggers learning by examining the root causes of bottlenecks and "binding constraints", Toyota-style industrial policy (yet another name for NIP) focuses on identifying and removing its own implementation constraints. So examples of how others removed such constraints in (even more) difficult circumstances become central benchmarks in diagnostic monitoring of your own policy process. The need to shift policy attention from borrowing good practice to assuring a good fit between proposed solution and local circumstances ("matching principle") is now a point of consensus (World Bank 1997). While this is an important advance, our point that weakness in local circumstances which "best practice" approach ignored and "matching practice" made endogenous can be a source of strength. For now, however, NIP policy practice proceeds on two parallel tracks: (loud) "siren calls" inspired by "best practice," and (small) discovered by accident "hidden gems".

The seventh paradox stems from the centrality of the "policy-making kitchen" in the NIP process—the ways and means of how programs and policies are designed, implemented, and corrected. Given that relevant policy knowledge is largely, although not completely, tacit, to grasp the NIP process fully, one has to be part of it. Hence the importance of practitioners with a knack for reflection ("thinking doers") and academics with a knack for continuous involvement in the policy-making "kitchens") ("doing thinkers") as sources of knowledge for experimental NIP processes. Outside sources of information: surveys and interviews by academics are not enough. Hence, I rely on personal observation more than it is customary in academic literature.[10]

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[10] In fact, the author fancies himself as such "thinking doer" for whom writing of the chapter was an exercise in diagnostic monitoring of his World Bank portfolio of innovation projects in emerging economies.

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