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Technology adoption and the organization of production. The case of digital production technologies

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DECLARATION

I certify that the thesis I have presented for examination for the PhD degree of the University of Urbino Carlo Bo is solely my own work other than where I have clearly indicated that it is the work of others (in which case the extent of any work carried out jointly by me and any other person is clearly identified in it). The copyright of this thesis rests with the author. Quotation from it is permitted, provided that full acknowledgement is made. This thesis may not be reproduced without my prior consent. I warrant that this authorization does not, to the best of my belief, infringe the rights of any third party.

"Technology does not develop in a unilinear way, there is always a spectrum of possibilities and alternatives that are limited in time—as some are selected and others denied—by social choices of those who have the power to choose; these choices reflect their intents, social position and relations with other within society"

(Noble, 1979)

A Natalina,
per essere stata fedele alla sua anima,
senza dichiarazione da
palcoscenico e abbracci rincorsi.

Per avere scelto il suo destino,
tra possibilità finite e inesatte.

Per il tempo che non è stato abbastanza.

Per la sua penna e la sua amicizia
che saranno, comunque, per sempre.

A Marcello,
per esserci stato.

Abstract

This thesis investigates the determinants for technology adoption and diffusion, with specific reference to the new generation of digital production technologies. A privileged focus is placed on the automotive sector, given its peculiarities as a fertile field for both technology and organizational changes.

As such, this thesis draws from, and aims to contribute to the ongoing debate on the hypothesized rapid adoption of highly transformative technologies. Whilst technological innovations have undoubtedly evolved at exponential rates in the past decades, we here argue that the actual adoption of these technologies depends on a number of elements that pre-exist in the productive structure that intends to adopt them.

In this study, we address the following questions: *what* types of technologies are being adopted in the realm of the alleged Fourth Industrial Revolution (4IR), *why* are they adopted and, eventually, *how* are they used. Business models and institutional features are an essential element to address the direction of technological change and to understand how such changes happen.

This thesis comprises three main contributions. First, we attempt to reframe the theoretical debates related to technological change – to then focus on a narrower aspect of it, that is the adoption of process innovations – and consider the firm as the main unit of analysis to understand how technological change happens. In this framework, our main contribution is the bridge between industrial economics that delves deeper into opportunities and constrains determined at the production process level (material properties, similarities, complementarities), and the Global Value Chains framework, something that contributes to shed further light on the hierarchical dynamics that determine the adoption of specific types of technologies. We developed this synthesis in Essay I and we then empirically discuss its implications in Essay II and Essay III.

Second, a methodological contribution to the field of technological change is our mixed methods research design. We adopted quantitative methods (econometric techniques) to study the diffusion of a specific type of technologies (i.e., industrial robots) using recent and detailed datasets that were able to give a full picture of industrial robots' diffusion, and one of its potential determinants, i.e., Foreign Direct Investment. Then, in the attempt to gather a full picture also of technology adoption, we studied the determinants of it through a pool of more than 35 semi-structured interviews gathered in South Africa with a field work of over four months.

Third, we enrich the empirical literature of our topic by introducing a new framework for the analysis of technology adoption's drivers, which we present at the end of Essay III. Our findings identify three main drivers which, despite looking at the specificities of the production technologies involved, are strongly embedded into, and dependent on, the productive eco-system discussed in Essay II; these drivers are: volume demanded, quality of the product and worker's safety.

Although international constraints and power dynamics may render the picture more complex especially for emerging economies, there is still space to encourage the use of industrial policies for technological upgrade.

This thesis contributes to the growing field of technology adoption determinants by providing the aforementioned framework to study such determinants. It also provides new analytical and methodological lenses to direct the future research in this growing field.

Abstract *(italiano)*

Negli ultimi anni il dibattito sulle nuove tecnologie ha assunto un ruolo centrale, complici le ricadute sociali ed economiche che accompagnano le rivoluzioni tecnologiche ed industriali.

Questa tesi di dottorato indaga le determinanti per l'adozione e la diffusione della tecnologia, con specifico riferimento alla nuova generazione di tecnologie digitali in ambito manifatturiero. In tale contesto, viene effettuato un focus sul settore dell'*automotive*, da sempre considerato terreno fertile per i cambiamenti tecnologici e organizzativi. Il principale contributo al dibattito sull'adozione delle nuove tecnologie, appartenenti alla cosiddetta *fourth industrial revolution* si articola nella proposta di una visione alternativa a quella convenzionalmente accettata. In quest'ultima si presuppone una rapida e omogenea adozione di nuove tecnologie, per il loro semplice fatto di essere a disposizione, ovvero essere inventate. Nonostante l'evoluzione delle innovazioni tecnologiche proceda a ritmi esponenziali da decenni, la mera innovazione è qui dimostrata essere diversa dall'adozione e dipendente da una serie di elementi preesistenti nel tessuto organizzativo e industriale di un determinato contesto.

La tesi affronta le seguenti domande di ricerca: *quali* tipi di tecnologie vengono adottate nell'ambito della quarta rivoluzione industriale (4IR), *perché* vengono adottate e, infine, *come* vengono utilizzate. Nel rispondere a queste domande, viene qui fatto emergere come i modelli manageriali e le caratteristiche istituzionali siano un elemento essenziale per capire e 'direzionare' il cambiamento tecnologico e il modo in cui tali cambiamenti avvengono.

Per arrivare a queste conclusioni viene utilizzato un approccio *mix methods*, che consente di arricchire i risultati della ricerca, sfruttando i vantaggi specifici dell'utilizzo di metodi di ricerca diversi, adatti a specifici elementi delle domande di ricerca.

La tesi si compone di tre contributi principali. In primo luogo, i dibattiti teorici relativi al cambiamento tecnologico sono analizzati con un punto focale sull'adozione di tecnologie innovative di processo. L'impresa viene considerata come l'unità principale di analisi, quella all'interno dei cui processi avviene effettivamente il cambiamento

tecnologico. In questo quadro analitico, il principale contributo del primo essay (Essay I) è il collegamento tra l'economia industriale che approfondisce opportunità e vincoli - determinati a livello del processo produttivo (proprietà dei materiali, somiglianze, complementarità) - e il quadro delle catene globali del valore (Global Value Chains) che permette di analizzare le dinamiche di potere e di gerarchia tecnologica che determinano l'adozione di specifiche tipologie di tecnologie.

In secondo luogo, tramite un'analisi econometrica, si studia la diffusione di un tipo specifico di tecnologie (i.e., robot industriali). I dataset utilizzati sono recenti e dettagliati, e forniscono un quadro completo della diffusione dei robot industriali e di una delle principali potenziali determinanti, quali gli investimenti diretti esteri (Essay II). Seguendo l'approccio *mix methods,* la tesi elabora una serie di ipotesi che successivamente elabora tramite metodi qualitativi, nel tentativo di fornire una risposta maggiormente dettagliata e in grado di cogliere l'eterogeneità dei processi di adozione tecnologica. Vengono quindi riportati i risultati di uno studio sulle determinanti condotto attraverso 35 interviste raccolte in oltre quattro mesi in Sudafrica. Tali interviste guardano a livelli diversi della catena di fornitura, e a imprese che producono diversi tipi di prodotti all'interno del settore *automotive* (Essay III).

In seguito, il terzo e ultimo contributo riguarda l'introduzione di un nuovo quadro analitico per l'analisi delle determinanti per l'adozione tecnologica. I nostri risultati identificano tre determinanti principali che, pur facendo emergere aspetti tecnici delle tecnologie coinvolte e che in un primo momento appaiono slegati da meccanismi di politica economica, danno conferma di quanto queste determinanti dipendano dalle capacità dell'ecosistema produttivo. Tali fattori sono: volume richiesto, qualità del prodotto e sicurezza dei lavoratori.

In conclusione, la tesi discute le possibili implicazioni di politica industriale. Nonostante i vincoli internazionali e le dinamiche di potere all'interno delle imprese multinazionali possano rendere il quadro più complesso, soprattutto per le economie emergenti, c'è ancora spazio per incoraggiare l'uso di politiche industriali per l'adozione di nuove tecnologie.

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If it was not a lonely journey, and it wasn't, it was because of you. Thank you *all*.

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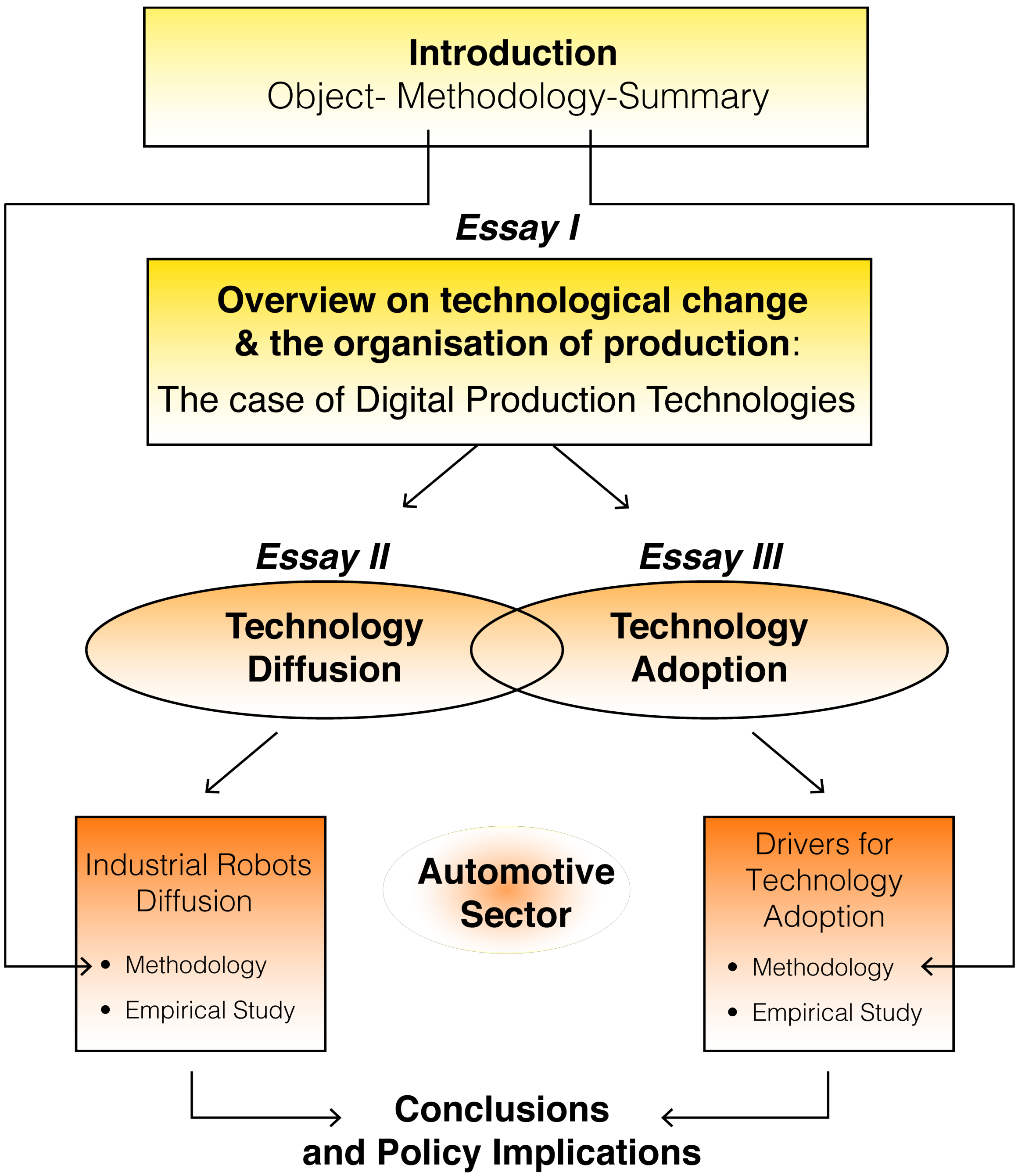

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Introduction

A ride into the realm of digital production technologies

Objective and purpose of the thesis

The research for this PhD started well before the beginning of this journey. I came to economics quite late, after a master's degree in law and a freelance journalist experience. My economic thought was forged in a very unconventional institution[1] where production, technology and capabilities, rather than efficiency, resource allocation and scarcity were at the core of the lectures. This perspective was shaped by the lenses of development, the real pushing force for my economic interests. After I came back from a seven-month research period in Mexico and Central America, one question was incessantly striking me: 'Why are Honduras, Salvador, or even Mexico not as developed as France, Italy or New Zealand?'.

I admit I was never entirely convinced by the principles of comparative advantages, geographic positions, or cultural motivations expressed by the standard economics. After all, during my Master degree, I had spent six months living in Singapore, one of the hottest islands and yet most productive place in the world. Why could Haiti not be so technologically and socially advanced as Singapore?

My PhD represents the natural continuation and further enrichment of this intense, in-depth, and fascinating journey into development and economics, through which the overall picture became more explicit: development is an uneven, complicated and structural process that entails the change of productive structures, through capital accumulation, and of societies. Development emerges from a combination of factors, and when they come together, a process of change – highly dependent on industrialisation and technology transfer – is triggered. Of course, many elements, from the closeness to big markets to the quality of institutions are essential.

[1] SOAS University of London

The process of development often coincides with that of technological change, which impacts societies not only in terms of their industrial structure but in critical social issues, such as… women's liberation, for example. Technological change has been the engine of modern societies, from sophisticated industrial production to the emancipation movement of women, that Rosenberg attributed to more effective technology contraception and the electrification of household chores (Rosenberg, 1979).

As Alice Amsden says in her 'The Rise of the Rest' "*technology transfer was always a necessary condition for late industrialisation but almost never a sufficient one*" (Amsden, 2001). This thesis discusses this necessary, albeit not sufficient, condition that is so complex to achieve.

Technological transfer requires the adoption, diffusion and mastering of sophisticated technologies in capital-intensive manufacturing sectors (Rosenberg, 1979; Dosi, 2000; Rodrik, 2015; Best, 2018; Chang and Andreoni, 2020). Hence, knowledge is the key to economic development, which involves a transformation from wealth-creation centred on primary product-based assets to wealth-creation centred on knowledge-based assets (Amsden, 2001: v). This focus shift motivated an increasing number of economists to study how technological change happens. Such studies increasingly suggest that elements of collective capabilities (primarily organisational and dynamic) are the critical factor underlying the adoption of foreign technologies, the subsequent learning and adaptation to the context and, eventually, the innovation across present and future technological trajectories.

The close relationship between technological change and development is fostered by two main factors: (*i*) technology adoption in collective and individual organisations such as firms and public institutions; and (*ii*) technology diffusion, intended as the intensity of the adoption (i.e., whether the broad productive structure uses specific types of technologies or not). Diffusion plays a fundamental role: a highly advanced island of technological sophistication placed in a developing country cannot be considered development. Unless it links to the productive structure, producing a series of spillovers and linkages to other sectors, in other words… unless it ceases to be an island.

The advent of new technologies thrusts the opportunities that this new wave of technologies may enhance into the limelight. However, it also poses a series of risks, especially those regarding the widening of the technological capabilities gap between a handful of advanced economies and developing countries. This thesis argues for the incremental nature of technological change, where basic capabilities are a necessary pre-condition to engage with more advanced technologies (Andreoni and Anzolin, 2019).

Contextually, the incrementality of technological change is also mirrored by path dependency dynamics. Within a specific context, the relationships embedded in any structure constrain the interactions among economic agents and tend to bring a fixed pattern of aggregate behaviour. There is a strong element of path dependency that characterises different developmental trajectories; in other words, what is feasible in the current period is primarily determined by what has been inherited from a previous period (Baranzini and Scazzieri, 1992; Arthur, 1994). Indeed, technology and the organisation of production are evolving through constant mutual interaction with societies' skills (Malerba and Orsenigo, 2000), embedded in the "capability triad" of production systems, business organisation and skill formation (Best, 2018).

Out of the vast spectrum of questions around technological adoption in relation to what is commonly referred to as the Fourth Industrial Revolution (4IR), this thesis focuses on the determinants (also called drivers throughout the thesis) of technology adoption. A set of research questions was identified, sufficiently narrow to provide theoretical and practical contributions, but also broad enough to be relevant and related to the pressing and challenging questions of our time. The broadest of these research questions, that is explored from different perspectives in each of the essays is: what are the main factors that contribute to technological change (i.e., technology diffusion and technology adoption) in the realm of digital production technologies?

If it is true that every era has its own challenges, the time we live in cannot leave aside technological change, and for a number of reasons. Firstly, as technology progress continues at a fast and unrelenting pace, technologies increasingly appear as luxury for a restricted number of people, firms and countries. In this way, it contributes to enlarge existing inequalities. Secondly, and relatedly, technological change means progress, better lives and less strenuous jobs; or at least, this was what meant for people and countries until the 1970s. Is this still the case? What does it determine who is able to benefit from new technologies? Thirdly, there is an exorbitant power concentration in the hands of few, highly specialised, technological behemoth companies that are becoming solitary masters of data analysis and digital production integration systems. This poses a series of questions for firms and countries that are lagging behind, with the risk of being mere users and importers of hardware and software technologies.

Research on technological change is particularly timely also in a world that seems to slow down from the frantic process of global production disintegration and outsourcing (UNCTAD, 2020), while accelerating on the technological change path. This thesis analyses the advent of the so-called fourth industrial revolution, intended as the recent wave of automated and highly connected process of technology adoption. By unravelling the past and present technological paradigm, we observe that real changes are about digitalisation, rather than automation – that has been characterising industrial processes for a long time. Yet most of the countries are still in the process of automating, and the digitalisation of entire production systems appear to have a much slower pace.

Within this scenario, recent proposals about developing countries possibly leapfrogging towards the promises of social and economic upgrade offered by the fourth industrial revolution have become attractive. Nonetheless, evidence from successful experiences of leapfrogging is rare and anecdotal at best[2]. Furthermore, leapfrogging opportunities mainly concern those technologies that offer an alternative to costly infrastructure, which can be seldom bypassed in the path towards industrialisation. This thesis argues

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[2] For example, rapid technological change and cost reduction in ICT contributed to the bypassing of fixed landline infrastructure, while reaching high level of mobile subscription in countries such as Cambodia, Gambia, Ghana, Mali among others (UNCTAD, 2018).

that industrialisation, and all the capabilities' acquisition process attached to development, are a fundamental step for the acquisition of more advanced technologies.

Once the importance and the challenges of new technologies' adoption have been acknowledged (Essay I), this thesis will investigate the determinants of technology diffusion (Essay II with reference to industrial robots' diffusion in 35 countries) and the determinants of technology adoption (Essay III through a series of case studies collected in South Africa)[3]. Both studies refer to the automotive sector. Finally, we will briefly review which space is still available for industrial policy[4] with a clear-cut perspective on emerging economies (Conclusions and Policy Implications section). Although industrial policy has reappeared in the policy and academic debate in the past two decades, it seldom changed the standard tools of approaching industrial development processes.

Methodological considerations

This section is dedicated to exploring the methodological aspects that guided this research. Although Essay II and Essay III present and discuss in depth the respective methodological strategies, this section adopts a different angle presenting the reasons that induced me to use a mixed method approach. Different research questions generally demand for different methodologies, which can either be quantitative, qualitative or a mix of them. Methodologies are a sore point in economics. Shaped by tools and methods borrowed from mathematics and other hard sciences, most importantly statistical physics, economics is nowadays mainly explored through sophisticated regression techniques whereas qualitative studies seldom appear in the best academic journals – they tend to be considered not as good as quantitative tools because they are less generalisable. The main difference between these two methods, is the close-end

[3] According to Kee (2017), adoption and diffusion differ in the following way. Adoption is the decision and the subsequent implementation, discontinuance, modification by an individual/organisation. It is an individual or organisational process that leads to diffusion as a systemic process. Diffusion is the commercialisation process through which an innovation travels or spreads through certain channels from a person, an organisation or any unit of adoption.

[4] In this thesis, the term industrial policy is used with regard to technology and innovation related industrial policies.

approach of the quantitative methods versus the open-end approach of qualitative methods. In standard quantitative research, pre-determined sets of information are collected, and they constitute the research instrument, therefore assuming *a priori* that the researcher knows the specific informational items that played a central role in subject's behaviours and decisions (Starr, 2012).

Aiming for a holistic description of technological change, the mixed methods approach used in this thesis relies on the more and more widespread idea that there are limitations, as well as advantages in both techniques, and that quantitative and qualitative methods complement each other. Although mixed methods approach are generally longer-term projects and undertaken by interdisciplinary teams, this thesis presents a mixed method approach which is the result of a three-year project based on an initial quantitative study on technology diffusion, whose results were then explored with the use of qualitative data. The domain of this thesis is industrial organisation, a subject area where mixed methods have been used since the 1990s (Helper, 1995; Ichniowski et al., 1997; Cockburn and Henderson, 1996 on the pharmaceutical industry; Sloan Foundation program, see NBER/Sloan, 2000).

Given the specific characteristics of this topic, the exclusive use of conventional econometric analysis could be problematic for two reasons. Firstly, regression analysis requires the availability of appropriate dataset, often longitudinal and generally collected at the national level (Jefferson et al., 2014). Data for this type of research about technology adoption are scarce, often due to non-availability, and often – but not always - because we are at the beginning of a new phenomenon such as the adoption of digital production technologies. Sometimes these datasets are entirely or partially available; one of the newest datasets on the diffusion of a specific production technology, i.e., industrial robots (International Federation of Robotics), is used in this thesis (Essay II). Relatedly, the majority of econometric studies focus mainly on fitting parameters, sometimes overlooking the limited relevance that the available data might have to the phenomenon of interest (Blaikie, 1993; Downward and Mearman, 2007).

Secondly, results are generally interpreted by focusing on sign and magnitude of statistically significant fitted parameters, as evidence of a causal link between dependent and independent variables. Within this methodology, specific strategies have been developed to control for heterogeneity. For example, random and fixed effects panel models have been introduced to reduce the impact of unobserved heterogeneity in estimating regression coefficients (Jefferson et al., 2014)[5]. As such, standard econometric techniques are better off at estimating correlations that hold on average within relatively narrow confidence intervals, but they have hard times when the variables that one wants to explain, as well as their co-variates, are subject to extreme variability.

While this can be consistent with different types of research questions, technology adoption necessitates a strong focus on heterogeneity. Essay I delves deeper into the crucial role of heterogeneity, being it at the technology, firm, sector and country level. Crucially, homogenous trajectories of technological change are seldom found across different countries, and it is hard to find them across different sectors and firms.

Furthermore, another more general limitation of conventional econometric analysis derives from the neglected role of agency-structure mutual influences, intended as the socially and institutionally embedded nature of individual and collective decisions (Delbridge and Edwards, 2013). For instance, an ideal study of technology adoption and diffusion would require longitudinal data on industrial policies in place. If we consider industrial policies that foster technology adoption and diffusion, they are a crucial aspect for countries' trajectories of technology upgrade. Unfortunately, this dataset is not currently available and unlikely available in the future, being extremely time and cost demanding to build.

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[5] They point out that statistical significance simply indicates the likelihood that, given limitations in the sample size, a statistical proposition about a relationship between two particular variables is reasonable. However, statistical significance does not imply economic significance, which is about the practical consequences of particular relationships between economic variables. They emphasise that economists should be concerned with economic significance, rather than statistical significance (Ziliak and McCloskey, 2004)

Therefore, we use a quantitative approach to define the space of our research for the determinants of technology adoption, and successively to formulate hypotheses that are tested through a qualitative approach of semi-structured interviews. In this way, mixed methods approach enables a more holistic picture, and more finely grained understandings of complex causal relationships in the identification of emergent issues (Jefferson et al., 2014). Hence, we integrated different forms of data and analyses in parallel or sequential phases (Tashakkori and Teddlie, 2003; Creswell, 2009).

By adopting econometric analysis this research aims to produce patterns of occurrences through generalisable results. Such results enable building a series of robust hypotheses that are further explored through the method of semi-structured interviews. In this sense, qualitative data help to reveal the importance of countervailing influences because such focusses on the unit of analysis, i.e., the firm, embedded within specific social and institutional settings.

Mixed methods approach affords a more careful and robust analysis of the more diverse set of information that may lead to technology adoption, by drawing on a broader set of information and being "exploratory" in nature. Namely, attempting to identify the complex links between specific collective and contextual characteristics of technology adoption in which firms' decision to adopt technologies are embedded.

The mixed method approach adopted in this research was designed with the idea that technological change has to be studied through the study of diffusion, intended as historical and qualitative type of analysis that puts technology at the centre of the story. In the words of Nathan Rosenberg:

Technological change is a study about adoption and diffusion, as Nathan Rosenberg states:

"*Although we are still a very long way from being able to assess the exact role of technological change […], it is, I think, clear that the contribution of technological change itself will have to be established through the study of diffusion. Only in this way can we develop a closer understanding of the rate at which new techniques, once* *invented, have been translated into events of economic significance*" (Rosenberg, 1976: 189).

We envisioned the study of diffusion through the use of mixed methods in the following hierarchy. First, in Essay II we performed quantitative analysis by drawing on two rare and recent sources of data compiled across countries and sectors with extensive useful information. Specifically, we explore the extent to which foreign direct investments (i.e., an international type of determinant) drive the adoption of industrial robots by using a model to study the determinants of industrial robots' adoption in the automotive sector, along two segments of the automotive value chain. Herein, we also inserted additional variables to proxy the local ecosystem. Patents and exports disaggregated for our two segments of the automotive value chain, which respectively indicate the ability to innovate in that sector and its competitiveness, constitute our level of the industrial ecosystem. Having observed that foreign direct investment explains only one aspect of the story, i.e., the adoption of industrial robots at the final assemblers (i.e., the OEMs), we formulated a number of hypotheses in order to study what are the dynamics at the local ecosystem level and how they affect technology adoption.

The qualitative work that we performed in South Africa is widely described and discussed in Essay III, section 4 on Methodology. We aimed at considering a series of elements that are very hard to proxy by means of econometric techniques. It is well acknowledged that technology is adopted on the basis of institutions, in terms of the policy adopted, the coordination mechanisms in place for technology transfer, the engagement mechanisms of MNCs with local actors, and so on. Also, technologies are adopted and used on the basis of different business strategies (Teece, 2010), which may change not only from one country to another but, and especially, from one firm – for instance a German automotive firm – to another – for instance a Japanese firm. Decisions concerning the adoption of new technologies involve a complex series of elements, many of which are production specific, in the sense that they regard the product that is manufactured, the specific production process that is in place, as well as more standard aspects such as productivity, volume and the overall cost structure of the firm. The thirty-five interviews conducted in South Africa along different stages of the value chain, thus involving OEMs and suppliers gave the possibility and opportunity to shed further light on these aspects.

As mentioned above, the topic of technological adoption is characterised by high heterogeneity on multiple levels: technologies, sectors, countries, and firms. Heterogeneity is so deeply embedded in this field of research that patterns of technology adoption applicable to different countries and different sectors can hardly be found. This was one of the main elements that pushed for the selection of a limited bulk of technologies, and a specific sector. This thesis focuses on digital production technologies, which are technologies usually adopted in the process towards complete automation and digitalisation. In agreement with other recent studies, our analysis convenes that the so-called fourth industrial revolution (4IR) technologies focus more on digitalisation than automation. The latter is an old, incremental and slow process that started decades ago and that did not see a particular increase recently – in manufacturing-related processes. Instead, the full potential of 4IR would be released by connectivity and the (slow) shift towards the Cyber Physical System.

This thesis focusses on the manufacturing sector (generally in Essay I), and specifically on the automotive industry (in Essay II and Essay III), for a number of reasons. The automotive sector enhances a series of direct and indirect spillovers to the rest of the economy, in terms of both productive capabilities and employment. It also constitutes the bulk of digital production technologies. Recently, technologies have emerged at a rapid pace through digitalisation, thereby revolutionising the automotive industry (Christensen, 2006). Furthermore, automotive industry establishment at the national level has been one of the main policies to foster development such as in Germany, United Kingdom, United States, Japan, South Korea, Argentina, Brazil, India, China.

We chose South Africa as the reference country in our qualitative analysis and we conducted there a research over a period of four months. South Africa is an emerging economy that has a longstanding tradition in the automotive sector, which has been capturing the attention of policy makers for decades. In the South African context, automotive production started before the institution of the apartheid regime and continued until 1995; after this year, the sector was transformed through a more export-oriented strategy, with the aim to link the country to automotive global value chain and to develop the local supply chain.

Summary of the chapters

The thesis is organised in three Essays that can be read as self-standing papers, as well as part of a red thread that guides the reader through this research work. Part I presents the conceptual framework of the research. Essay I, ***Technology and organisational change. Implications for digital production technologies*** sets the theoretical framework that is used to inform about compelling challenges regarding the fourth industrial revolution, and throughout the thesis constitutes the theoretical framework for each piece of the work. This Essay aims at bridging two strands of the literature (i.e., technical change and the organisation of production – using tools both from industrial economics and the economics of innovation) in order to unveil the challenges faced during the adoption of digital production technologies, within firms and across international borders.

On the one hand, technical change and industrial economics concentrate on the firm as the central unit of analysis. By adopting this perspective, it delves deeper into the role that similarities and complementarities at different levels of the productive structure have in the incremental pattern of technology adoption. On the other hand, analysing the reorganisation of production along Global Value Chains sheds further light on the hierarchical dynamics and on the context specific factors that determine the adoption of specific technologies. Firms are increasingly segmented into different countries, activities and tasks with effects on institutions, countries' space to adopt new policy instruments and overall production and trade flows.

This essay paves the way for a discussion around the existing relationship between technology and the organisation of production, and the different ways in which they interchange mutual influence. Hence, we conclude this essay by addressing the main challenges for digital production technologies adoption, thus trying to redefine the incremental nature of such technologies, and the different issues that firms and countries face at different stages of development. Such challenges regard both different capabilities at the shop floor level and the reconfiguration of the power dynamics along the value chains.

Part II of the thesis empirically examines technology diffusion and adoption by applying different methodologies and adopting different units of analysis. Having defined the set of research and the analytical tools that are used to address the questions, the two subsequent essays present and discuss empirical findings, and use them to further enrich the conceptual framework. Essay II - ***What is driving robotisation in the automotive value chain? Empirical evidence on the role of FDIs and domestic capabilities in technology adoption*** – considers a country level dimension to explore how the international determinant par excellence, i.e., foreign direct investment, influences the adoption of industrial robots in the automotive sector. The focus on industrial robots is motivated by two main elements: on the one hand, we could work within this first dataset that collects all industrial robots' application across sectors and countries. On the other hand, the narrowing down to a specific technology allows to examine closer the technology heterogeneity.

Therefore, with a focus on a key production technology of the fourth industrial revolution, the essay looks at the role played by inward foreign direct investments and other host-country-specific factors in the adoption of industrial robots along two main segments of the automotive value chain. The argument concludes that FDIs *per se* do not have a significant impact on the adoption of industrial robots in the host country, but they become significant when interacted with proxies of host countries' innovation capabilities.

By using disaggregated data on robotisation and controlling for endogeneity, the analysis finds that the combination of FDIs and local innovation capacity impacts robot adoption only in the case of the automotive assembly segment. Instead, host-country-specific factors that characterise the local industrial eco-system drive robotisation in the components supply segment of the automotive value chain more than in its assembly segment. Such findings not only confirm the importance of domestic productive capabilities development in the process of manufacturing automation, but they also reveal that remarkable heterogeneity exists within the automotive sectoral value chain in terms of drivers of technology adoption. To conclude, we formulate a series of hypotheses from the econometric results, around the country specific factors that influence industrial robots' adoption.

In Essay III - **Opening the black box of technology adoption: a study on the drivers of automation in the automotive sector** - these hypotheses are tested through the collection of industry-based interviews, thus adopting qualitative methods to explore our analysis further. In this Essay, we analyse specific drivers that lead to technology adoption in the automotive sector. Herein, the firm is adopted as the privileged unit of analysis to observe technical change, thereby looking inside productive organisations and down to the production floor.

This analysis explores the drivers underpinning the introduction of digital production technologies, and thus reveals three main drivers: volume, quality of the final product and ergonomics. These drivers that are related to production processes, tasks and materials constitute part of the ecosystem at the core of our hypotheses in Essay III; for example, "volume" factors that influence the adoption of robots are affected by size and capabilities of countries where adoption is undertaken. The unique set of information that are presented in this Essay draws on an extensive period of fieldwork in South Africa (between April and September 2019), where more than thirty-five interviews were collected across twenty-eight different types of organisations and along different stages of the automotive value chain (e.g., OEM, suppliers, system integrators, institutions).

To conclude, in the last section, ***Conclusion and Policy Implications: what is the way forward?*** we summarise the contributions to both theoretical, methodological and empirical issues, and expose a series of policy implications. For instance, targeting digitalisation means to design industrial policy for technology transfer and for direct investments in technological infrastructure, and to induce MNCs to transfer large shares of their value addition locally. Although some limitations are acknowledged, an additional effort is made to address sector-specific and technology-specific determinants of technology adoption, and to understand how production-based dynamics play a crucial role for the use of new technologies. Whilst international dynamics of power do matter, firm-level capabilities seem to be the single most crucial factor for productive and additionalities-generating use of present, and future, technologies.

Essay I

Technology and organisational change. Challenges for digital production technologies[6]

1. Introduction

Technological change has been continuously redefining the structure and dynamics of production organisations. Despite the substantial heterogeneity of technology adoption across countries, sectors and industrial actors, it is well-established that technological change is a crucial factor for growth and development.

The complex relation between technology and organisation has been deeply transforming in the last years, both within firms and along their international structure of production. More specifically, the mechanisms of outsourcing and fragmentation of production that characterised the last decades of international production organisation deeply reshaped the dynamics in which R&D, innovation and technology adoption occur and are organised (Baldwin, 2017; Sturgeon, 2019; Papanastassiou et al., 2020). The relation between new technologies' adoption and organisational changes is of mutual influence and interaction, yet it is rarely examined under the micro dynamics that evolve both at the firm and at the international level, and that are embedded in GVCs (Global Value Chains).

This essay attempts to fill this gap, by looking at dynamics at the microlevel, that are influenced not only by typical GVC structures, but also by a finer organisational element -where modularization and features of the production process are crucial - that highly matters when considering technology adoption. The essay does that unpacking such relation between technology and organisation and exploring how this has been evolving with a focus on the adoption of digital production technologies. With the latter term we

[6] The last part of this Essay I (section 5) elaborates from the UNIDO Working Paper Series N. 07/2019 produced with Professor Antonio Andreoni. The paper is cited in this essay as Andreoni and Anzolin, 2019.

intend those technologies that are applied in the manufacturing realm with the aim to digitalise and automate production processes (e.g., industrial robots, ERP systems, sensors, predictive maintenance software, etc. see section 5). Understanding the determinants of technological change is an essential step to recognise the dynamics of capitalist development (Schumpeter, 1934; Lazonick, 1990; Dosi et al., 1994). Technologies are in a constant state of change, and they are characterised by heterogenous micro dynamics that depend on the structure of the production process. These dynamics are related to two complementary spheres: firms' internal dynamics and GVC external – or international – dynamics. This essay looks at each sphere with reference to technology and organisational related changes.

On the one hand, by delving deep into past strands of industrial economics (Nelson and Winter, 1982, Lundvall, 1992, Dosi et al., 2000 for the evolutionary school; Scazzieri, 1981, Landesmann and Scazzieri, 1996, Morroni, 1990 for the structuralist school), the essay brings the attention back to the firm as the main unit of analysis with a specific focus on to the role that similarities, complementarities and materials' properties have for the adoption of new technologies. The focus on the firm is important also because it considers the organization at the shopfloor level as a crucial element for firm's efficiency and prosperity, thus allowing a type of analysis where technological change is at the core.

On the other hand, the international fragmentation of production and the recent literature on Global Value Chains (GVC), assists us in shedding further light on the hierarchical dynamics that influence the adoption of specific types of technologies, and in specific geographical locations (Gereffi et al., 2005; Morrison et al., 2008; Andreoni, 2019). As firms are increasingly broken down into different countries, activities and tasks, firm's internal and external dynamics are strongly influenced and shaped by international production patterns.

This essay considers the firm as the main unit of analysis, emphasising it as the privileged place where technological change actually happens. It is the organisation and structure of the shopfloor level, its flexibility and adaptiveness, that highly determine whether a technology will be adopted or not. This contribution considers the so-called Marxian forces of production (e.g., materials, costs, productivity), their interrelation and mutual causality unfolding on every level of the organization, and of the groups that inhabit it (Lazonick, 1990; Noble, 2011); it then goes beyond it, considering the firm as the *Penrosian* pool of resources, where technological and organisational changes are the result of tacit knowledge and long term investments, and where heuristics, rather than codified knowledge are likely to determine different businesses' trajectories (Penrose, 1959; Dosi et al., 2000; Andreoni, 2014; Teece, 2019).

In the journey around structural changes and firms' dynamics, we build a framework that gives a revisited perspective to examine challenges for the adoption of digital production technologies[7]. The focus of our attention is mainly on production technologies[8], as they played a key role in driving productive transformation since the first industrial revolution (Rosenberg, 1969; Andreoni and Scazzieri, 2014; Andreoni, 2014).

Although new technologies may have a series of disruptive impacts in the way in which people work, consume, and live, we claim that a more careful consideration of why and how technological change happens is relevant to understand the determinants of technology adoption, the incentives for a rapid increase in new technologies' use and eventually the impact they may have on societies. For this type of process, which we argue to be incremental and much slower than what some observers have discussed, we intend to limit our analysis to the determinants of technology adoption and to what is happening and may happen in the near future, rather than considering futuristic trends.

This essay is structured as follows. Section 2 reviews the main elements regarding the role of technology and, especially, technological change in economic growth. Structuralist and evolutionary theories are thus revisited to provide useful insights for

[7] Fourth industrial revolution technologies entail several types of technologies of which digital production technologies are only a subgroup. Other technology clusters include advanced materials, biotechnologies and quantum technologies, just to mention a few. (OECD, 2017)
[8] Production technologies are defined – in the simplest sense – as any type of machinery that creates a tangible physical product.

technological change in the realm of digital production technologies. The combined study of technology and organisation, further explored by these meso and microeconomic theories, allowed for a better understanding of the technological black box "content", and a consequent redefinition of what really matters to enable technological change and, especially, technological adoption. Section 3 addresses the importance of the firm, as the place where new forms of technologies and organisation co-evolve, together with the development of suitable capabilities. It is, indeed, the consequences at the level of the organization, how it can adjust over time and along different technological trajectories, e.g., its flexibility, that are crucial in determining technology adoption and its level of efficiency. Section 4 explores the determinants of technology adoption both from the firm and the Global Value Chain perspectives. The latter provides international lenses to better understand hierarchies and power and how they influence the adoption of technologies within firms and along value chains. Section 5 adopts the framework presented in the theoretical part and it discusses the main challenges for technological change with reference to digital production technologies, exploring the heterogeneity of these challenges at different levels of development. Section 6 concludes putting forward some policy implications.

2. Technology and economic growth.

The analysis of technological change in economics is born with the discipline itself. Although the role of technological change for economic growth has been neglected for a long time, precisely with the advent of the marginalist revolution, in the last decades technology has been integrated into more recent strands of neoclassical economics, however in a very different – and somehow limited - manner from classical political economist and the schools of taught that are discussed below.

This section explores two main sets of issues. First, section 2.1 starts with an introduction into the history of economic thought about technology – and technological change – in the economic discipline. It is not a complete analysis, which is something beyond the scope of this essay and this thesis, rather it is an overview on how three main schools of thought looked at technology.

The section begins with a historical perspective, considering the classical economists, from Adam Smith task reorganization, to the Ricardian comparative advantage, and to the Malthusian obsession for scarcity over technological progress; the very founders of the discipline were all concerned with economic growth, and thus with the links between technological change and economics. Notwithstanding, it is probably with Marx and his theory of capitalist development that we have the first systematic study on technological change, with a precise and detailed effort in the definition of the role of technological change in shaping the structural characteristics and dynamics of productive organisations.

Thereafter, the three schools briefly considered are: the neoclassical, the structuralist and the evolutionary schools. For a long time, the neoclassical marginalist theories have long intended technical change as something exogenous that leads to a shift outbound in the function of production. The strict Walrasian assumptions prevented to include technological change, e.g., increasing returns, into the standard mathematical analysis. Although these theories dominated the debate for decades, there were some attempts to shed further light on the important role that technology plays for economic growth (Young, 1928; Sraffa, 1926; Verdoorn, 1949; Kaldor, 1966)[9]. Among the most relevant attempts to study the role of technology there are: the development theories of the 1960s (Hirschman, 1958; Gerschenkron, 1962), the resources-based theories of the firm (Penrose, 1959; Chandler, 1990), and the late Schumpeter – the so-called Mark II Schumpeter – further explored by evolutionary theories. Moreover, starting from the 1980s two new strands of the literature emerged to shed further light on the black box of technological change. Specifically, evolutionary and structuralist theories – the other two theories discussed in this section - paid great attention to the microlevel dynamics in the attempt to understand technological change and to study processes of uneven and non-proportional economic growth (Scazzieri, 2017).

[9] Some of these authors contributed to the discussion in the Economic Journal in the 1920s and 1930s contributing to maintain the debate alive in that time.

Section 2.2 focusses on the importance of heterogeneity in the discussion of technological change. There is no 'one size fits all' argument because technologies are different, they adapt differently, and they diffuse and are adopted in different ways and respond to different incentives that are firm and sector specific. As this essay looks at diffusion and adoption mechanisms, heterogeneity is a crucial feature of such mechanisms and it presents a series of characteristics, which we try to unpack and discuss.

2.1 Technology, from a neglected to a glorified ingredient of growth

It would not be fair to say that technology has not been given the just amount of attention in the economic debate. Rather, the critique is that the attention has been discontinuous and often subject to the mantra of the neoclassical theories.

If a glimpse to the past is taken, the role of technology adoption and economic structural change was intertwined with the one of increasing returns to scale, that were in fact allowed by technological change and the reorganisation of production. Classical economists acknowledged this dynamic aspect of production. The initial theory of increasing returns to production formulated by Smith, and the almost exclusive importance he gave to producibility, revolved around the extent of the market – and the consequent division of labour represented by the Smithian example of the pin factory – and structural opportunities about learning and invention that the reorganization of production brings about (see Scazzieri, 2014). An important contribution on the structural opportunities emerging in the production process is Babbage's study of increasing returns with his formulation of the law of multiples that introduced a criterion of proportionality. This intuition is still relevant today: as we present and discuss in Essay III, reaching a minimum process scale is a necessary condition for the adoption of more productive technologies (Babbage, 1835; Andreoni and Scazzieri, 2014).

Among classical economists, one of the most important contributions in terms of the depth and breadth of the analysis on technological change is Marx's theory, centred around the role of technology as a continuous and dynamic engine of growth of the capitalist system. Marx's theory of the firm roots the analysis of capitalism, much more than previous attempts, in the operations of the production process, with an emphasis on the dynamic interaction between technology and organization – what Marx calls the forces and relations of production that determine the level of productivity (Lazonick, 1990).

In the view of classical economists, increasing returns were associated with two essential and complementary elements: the supply side with the prominent role of technology and the demand side with the size of the market. The latter opens for a series of opportunities in which organization could be restructured through different combinations of its factors of production, revealing that there is no real distinction between technological change and factor substitution (Rosenberg, 1979). The optimistic Smithian view left space for the more pessimistic concept of *scarcity à la* Malthus and the decreasing marginal returns that entered the economic debate with Ricardo, subsequently glorified by the marginalist revolution. In both Ricardo and Malthus's thinking, the law of diminishing returns played an important role (Krautkraemer, 2005) in shaping the future direction of economic thinking.

Decreasing – and constant – returns to scale soon became an important cornerstone of general equilibrium models, despite being very distant from the Ricardian focus on the 'antagonism coexistence' between producibility and scarcities (Scazzieri et al., 2015), where scarcity is observed as a relative element rather than an absolute one. It is interesting to recall here how the law of decreasing returns, was not intended by Ricardo as an application to all economic sectors, rather he referred it to the exclusive corn and agricultural sectors, in a similar way to Petty (1690) [10].

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[10] Although decreasing returns proved incorrect by historical trajectories of technological change in the agricultural sector, the Ricardian example was transferred to the entire realm of economic sectors by the Marginalists (Pasinetti, 2015). Afar as the law of decreasing returns is concerned, Sraffa (1925) highlighted that the decreasing productivity was always dealt with by classical economists in relation to the rent of land and was included in the theory of distribution, while increasing returns were discussed in relation to the division of labour and therefore in the analysis of production. The neoclassical economists unified these two tendencies in one single law of non-proportional productivity, as a basis of the theory of price. This is the central idea of Sraffa's article (Sraffa, 1925, in Pasinetti ed. 1998, pp. 324-325).

Despite the rich studies of the classical economists in analysing production processes through the lenses of development (Pasinetti, 2007), the idea that technology does not change and, if it does, it is not strong enough to overcome diminishing marginal returns, shaped economic theory for a long time. History proved that the predictions about unavoidable scarcities[11] and their consequent limitations for economic growth were wrong (Tahvonen, 2000), but meanwhile the technical change and innovation were disregarded from economic analysis as they could not enter the mainstream model of economic growth (Kaldor, 1960; Pasinetti, 2015).

In fact, increasing returns were problematic for two reasons: on the one hand, it is difficult to integrate them into static economic models under mathematical control (Arthur, 1994; Marshall, 1890); on the other hand, they present a series of disturbing implications for equilibrium and market efficiency (i.e., competition). As such, increasing returns have been seen as deviant from standard economic theory (Buchanan and Yoon, 1994) that shifted its focus from the study of economic growth, where increasing returns could happen, to the one of resource allocation and scarcity.

A static view of technology dynamics and a production process characterized by decreasing marginal returns better conciliated with the dominant neoclassical view that technology is freely available. This view reinforces the perfect competition assumption and that returns are always constant or diminishing; differently, increasing returns would prevent the stability of the equilibrium process and leading to a situation of monopoly. As such, technology was studied as a sort of black box that could be transferred through a series of blueprints and codified information.

Solow (1957) named technological change the residual of our *ignorance*, while Abramowitz studied it as a wider "proximate cause", that embedded an even larger share

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[11] The natural resources sector is particularly interesting as following the theory of comparative advantage and (some) historical experiences, this sector became to be considered a curse (Auty, 1993). A wide strand of literature and empirical evidence, whose initial most relevant contribution is probably the Making the Most of Commodities Programme (Morris et al. 2012) flipped this theory demonstrating that in fact it was technological change and the increasing space for *in situ* innovation and technology adaptation that contributed to shed further light on the sector.

area of *ignorance*, where social and cultural dynamics are hard to separate (Abramovitz, 1993: 219); or to put it in Rosenberg words "*it is […] an extremely complicated methodological matter to separate out the contribution of technological change from other changes in human behaviour*" (Rosenberg, 1979:25).

The 'black box' conciliated better with the neoclassical methodological inability to provide an explanation beyond quantitative mathematical aspects, largely insufficient to explain technological change. In the words of Morroni:

"*The analysis of the economic aspects of technical change involves almost all difficulties excluded from the standard analysis of competitive equilibrium, e.g., non-convexities, scale economies, indivisibility, externalities, public goods, uncertainty and price competition*" in (Morroni, 1992: 18).

Decades later from the marginalist revolution of the XIX century, a closer examination of production processes was rediscovered as the principal *loci* of structural economics where the transformation of production structures through opportunities and constrained trajectories takes place (Hagemann et al., 2003; Andreoni and Scazzieri, 2014). Structuralist and evolutionary theories appeared from two works written in the 1980s that addressed uneven, unbalanced, and non-proportional processes of structural growth (Scazzieri, 2017), and they provided further understanding on how and why technology plays differently in different contexts. These two works are Pasinetti's *Structural Change and Economic Growth. A Theoretical Essay on the Dynamics of the Wealth of Nations* (Pasinetti, 1981) and Nelson's and Winter's *An Evolutionary Theory of Economic Change* (Nelson and Winter, 1982).

Structuralist theories focus on intermediate levels of aggregation, where asymmetries between short and long processes of production may generate a sequence of temporally connected transformations. This attention to interdependencies had the merit to bring the element of time into the discussion, starting from Hicks (1965) studies on the relationship between development and historical elements, to Georgescu-Roegen's effort to go beyond the static function of production through the proposal of a fund-flow models to study production processes. Structuralism sees the continuous change in technology and in the size of the market (Pasinetti, 1993) as the main triggers of structural change[12], with an important role played by sectoral decomposition, both vertically and horizontally. Differences in speed and mismatches between different elements of a given production system impose to study system unbalances, indivisibilities and the raise of complementarities that characterise the way in which productive structure changes.

Structuralism anticipated and, at the same time, went beyond new growth theories[13] in the sense that it not only gave a prominent role to technology, but it also acknowledged the role of organisational changes, thus allowing the opening of the black box. While new growth theories incorporated technology in their model at the cost of rendering it freely available as a standard public good (Freeman, 2019), structuralists allow the process of structural change to be probabilistic, rather than deterministic, and constrained by path dependency and consistent coordination mechanisms, where technological change is progressive and propagates itself in a cumulative way (Young, 1928). Nonetheless, in order to complete the shift in methodological terms, the persistent state of equilibrium remained problematic. Some signs of change were introduced with the concept of Hicksian traverses, intended as different phases in which structural change processes endogenously take place (Morroni, 1992; Landesmann and Scazzieri, 1996). This is an important step towards the acknowledgement of disequilibrium, yet it remains uncompleted since traverses are conceived as the transition between two equilibria (Nguyen-Huu and Pottier, 2020).

The emergence of the evolutionary theory, based on Nelson and Winter's (1982) contribution, completed the methodological shift towards a dynamic framework to study economic growth. Revolving around the concept of dynamism and cycles, with a clear

[12] Structural change is a process that can be described in the form of directionality (impulse, technological change, demand shift, environment), stage structure (there can be a particular sequence), irreversibility (the process cannot be undone, patterns of coordination become interlocked) (Landesmann and Scazzieri, 1996).
[13] According to Dosi (2000), new growth theories made innovation endogenous but at the very high price of inserting it in the production function and inside the optimal allocation of resources.

perception of the time component as in the case of structuralists, evolutionary economists put forwards the idea that there are technological paradigms and then technical change unfolds in an uneven and Rosenbergian incremental way along these paradigms, while radical changes imply a shift to a new paradigm (Dosi, 1982). Digging into the microeconomic level of technical change, evolutionary authors emphasized the existence of complementarities that emerge from history, where interlocking elements of pre-existing structures, developed in a path dependent way, which lead to asymmetric responses to trigger technological change[14]. A further contribution of this strand of literature is the crucial role of technologies that are acknowledged to be the main driver of economic growth and structural change (Nelson, 2005). This aspect is dependent on the development of collective capabilities (see section 3). Capabilities emerge from what agents do in their activities characterised by bounded rationality and a high degree of heterogeneity (Dosi, 1997).

Nowadays there are little doubts on the fact that the mastering of specific technologies is a precondition for sustained economic growth. When referring to successful experiences of economic growth and development, whether far back in time such as British, American and Japanese experiences or the more recent South Korean and Chinese ones, these are all associated with industry-related technology developments[15]. In these cases, technologies were often mastered by companies that received subsidies and rents to reach specific technological goals, to enable linkages to the rest of the economy, and to expand in the international markets with a renewed, and dynamic, comparative advantage (Chang and Lin, 2009).

The aforementioned old and recent experiences of development were built through the strengthening of the manufacturing sector, that due to its technological spillovers, to its wide applicability and to its positive socio-economic effects, is still considered a crucial sector for economic growth (Haraguchi et al., 2017). Industrialisation also leads to the

[14] This paragraph builds on during Professor Scazzieri seminar at SOAS University of London in February 2017.

[15] Alice Amsden book Asia Next's giant (1989) refers to the fundamental process towards heavy industries, with a developmental trajectory that goes from light to heavy industries, which are those where machine tools are more sophisticated and more heavily used.

acquisition of unusual skills in problem-solving activities that are crucial to create the capacity to flourish (Rosenberg, 1969).

2.2 Technology and structural change, how does it happen? Some technologies **diffuse** *more than others.*

This section considers the high degree of heterogeneity that characterises technologies and their dynamics of adoption. After the overview presented above on the concept of technology in general, we now use the term with a narrower scope, by intending it as technology adoption and diffusion. To demonstrate how technologies differ and how differently they may play within an economic system, this section begins by providing the example of production technologies. Then, we focus on the drivers for technology adoption and on their heterogeneity. Here, heterogeneity even among drivers is the crucial element to understand productive systems features.

If it is widely accepted that technologies matter, it is also true that not all technologies are the same. Across different sectors, the superiority of some specific technologies gives a strong competitive advantage to countries that become users and innovators of such technologies.

Production technologies are such type of superior technology, they are called 'mother machines' as, due to their wide range of applications, they enable the production of all other machines and equipment (Rosenberg, 1963). Production technologies encompass a wide range of machine tools, tooling and complementary equipment that operate in a coordinated and synchronized manner to execute a set of tasks to produce goods at the required volumes and quality.

Nowadays, these machine tools range from simple hand-held tools, lathe machines, grinders, and injection moulding machines to highly flexible and complex industrial robots with programmable software to handle changes in the task, volume and quality performed. Production technologies can be used in different ways, following different manufacturing methods, from casting, forging, welding, soldering, moulding, up to the most recent additive processes and laser technologies. Furthermore, they have been increasing their level of sophistication, and they still play a crucial role as it is clearly demonstrated today by countries that either produce complex machines like industrial robots (e.g., Switzerland with ABB, Germany with Kuka, Japan with Fanuc and Yaskawa, just to name a few) or that master complex system integration technologies (e.g., the German company Siemens). These countries have crucial advantages over the rest of the world, both in terms of technological capabilities and path dependence type of advantage, and from a more macroeconomic perspective of the trade balance surplus, as exports of these digital production technologies and services is destined to increase.

These technologies do not come out of the blue, nor are they taken off the shelves. There are in fact specific mechanisms and dynamic forces in action that foster the adoption of new technologies. Not all technologies are equal; building on Nathan Rosenberg legacy, we discuss that production technologies become important when adopted, and they diffuse throughout different production systems. Here, we try to unpack and analyse the mechanisms of technological diffusion.

Evolutionary and Schumpeterian theoretical analysis, together with economic history and history of technological change, seem to indicate a framework to analyse and understand if and how technologies diffuse, becoming economically and technologically relevant.

Before analysing such contributions, it is worth recalling that some other strands of the literature studied the mechanisms of technology diffusion, building theoretical models to assess it. In 1986 Davies introduced the Technology Acceptance Model (TAM) to study the reasons for adoption and use of computer systems, which delineated the causal linkages between two key elements: the perceived usefulness and the perceived ease of use. The former may refer to either organisation or individuals; in the case of organisations, utility stands for economic benefits which may derive from (i) increase in productivity, (ii) enhancement of product quality, (iii) cost savings, (iv) improvement in market shares (Calantone and Di Benedetto, 1990; Philipps et al., 1994). This approach despite providing useful tools for the understanding of adoption, avoids unpacking the characteristics at the production process level, thus leaving the black box of technological change untouched. Two other models to study diffusion are Roger's diffusion of innovation model based on the S-shaped logistic diffusion curve (Roger, 1995) and the technology, organisation and environment framework elaborated by De Pietro et al. (1990). We now consider two approaches that observe technology adoption from the invention and innovation dynamics perspective, whose contributions and limits are used to build a synthesis over the importance of drivers' heterogeneity across production systems.

A first approach of the literature focuses on industrial growth and economic development models, such as the ones developed by Schumpeter, with a strong focus on the role of the entrepreneur. Schumpeter's work has been further enriched by the work of Freeman and Nelson (1982) with their focus on the diffusion of knowledge and learning, whose collective essence is at the core of the way in which we know technologies. A second approach of the literature relies on the effort of economic historians such as Nathan Rosenberg, whose writings are crucial in trying to open the black box of technological change. In this latter approach there is great attention on industrial microlevel dynamics, with a particular emphasis on the role of complementarities, similarities and microlevel processes of industrial dynamics.

Schumpeter is one of the first authors who attempted to conceptualise innovation as a process characterised by sequential actions. He gave insightful explanations on the process of technological innovation, although relying very much on the description of a linear and static mechanism of innovation. Invention, innovation and imitation are, according to Schumpeter, linked through a linear sequence, which has been dominating the study on technical change (Silverberg, 1991).

Moreover, he tended to highlight the important role of the initial invention and the circumstances surrounding and influencing the single act of innovation. This innovation is presented as an exogenous process, very much connected to the exaltation of the heroic entrepreneur (Schumpeter, 1934; Rosenberg, 1976; Smiles, 1984; Dosi et al., 1988). In one of Schumpeter's first books *The Theory of Economic Development* (1911), he characterises the heroic entrepreneur coming along with new inventions starting from scrap, getting rid of the incumbent, in the transient making more money and therefore departing from the need of bringing further innovation and eventually going back to the zero-profit condition equilibrium once the innovation diffused. The first Schumpeter – the so-called Mark I – in the *Theory of Economic Development* (1911) was subjected and fascinated by the Walrasian general equilibrium, although broken by the unexpected arrival of the heroic entrepreneur and his innovations. Notwithstanding, the focus of the Schumpeterian alternative on the role of the entrepreneur has been insufficient in explaining how technological change happens, as he overlooked the importance of *ex post* innovation within new technologies, whose process has never been one of mere replication (Rosenberg,1970:551). This limitation is partially resolved by Schumpeter himself with his latest work *Capitalism, Socialism and Development* (1942) – the so-called Mark II – where the attention and the devotion for the entrepreneur is substituted to the one for large firms, and their R&D facilities, which in fact allow firms' prosperity, thus revealing also the importance of cumulativeness effects and alluding to collective capabilities.

The innovation system is much broader than what happens in a single firm and by a single man, especially considering that important parts of the process happen through a collective process where adaptation and feedback mechanisms are crucial. Despite providing important insights for economic theory, the work of Schumpeter did not examine the entire innovation process. The overestimated role of innovation, and the underestimated role of learning, are also evident in relation to late industrialisers, where innovation is conspicuously absent, and the interlink between adoption and learning takes the central role (Amsden, 1989).

The very specific features, such as time, space, constraints and opportunities that are crucial for innovation and imitation stages, as discussed above in the structuralist contributions, have been poorly analysed in the Schumpeterian analysis where technology resembles a disruptive, rather than incremental, process. The unidirectional movement within the *invention-innovation-imitation* dynamics overlooks the evolution of dominant economic factors and the forces and actors that characterise each step of the Schumpeterian series of separated steps, "*as if technology remains the same just passing through the pipeline*" (Silverberg, 1991).

Although the literature on diffusion tended to remain around the work of the first Schumpeter (Silverberg, 1991), there are some important exceptions. Among these, the acknowledgement that technical characteristics of specific innovations develop simultaneously to diffusion (Rosenberg, 1963; Sahal, 1983), has been crucial for the understanding of how the spread of new technologies among specific types of organisation happen. This is because the process of incremental innovation which can be much more relevant than the original '*act of innovation'*, tends more towards a collective invention (Allen, 1983; Freeman, 1982).

It is important to understand the mechanisms behind technological adoption and diffusion, as history has plenty of miraculous inventions that remained on the shelf for years (when not forever), for technical or economic obstacles. Rosenberg and Kline (1986), among others, acknowledge that technological process is much more incremental and driven by complementarities and induced mechanisms, where technological and engineering alterations and adaptations are crucial (Rosenberg, 1970)[16]. The role of complementarities, which can shift the development or lack of development towards one technology, determines the opportunity to foster or the reason to prevent developments in other technologies (Dosi, 1982: Morroni, 1992). Structural

[16] Among different authors, Rosenberg put a great amount of emphasis on incremental technological changes. In his rich anectodical case studies, he mentioned Hollander study of the Du Pont rayon plants. The findings of this case study show that the cumulative effect of minor technical change on cost reduction was actually greater than the effect of major technical changes (Rosenberg, 1979).

change is in fact characterised by a sequence of complementarities, both at the sectoral level - the Dahmenian developmental blocks, that are characterised by sectoral interdependencies (Dahmen, 1988) - and at the firm and task level (Morroni, 1992; Dosi and Marengo, 1995; Andreoni, 2014).

Moreover, most innovations "*passed through many hands and strange byways before they attained the final shape and design by which we know them*" (Silverberg, 1991). Therefore, it is thus crucial to

"*break with this one-way concept of innovation causality and advance the hypothesis that imitation, copying, and diffusion themselves contribute significantly to the further technological maturation of the original innovative idea through a complicated, two-way process of interaction and collective exploration*" (Silverberg, 1991:70).

It is not a mere process of imitation from early to later adopters, rather a process in which technology evolves, changes and adapts to different conditions and needs (Geroski, 2000). Technological change's effectiveness depends on how the organisation of production and resources, within the firm, evolve and respond to different *stimuli*. Technological change and organisational changes are deeply interrelated: as it will be mentioned in this thesis the reorganisation of production both within the firm and at the sectoral level had important influences in the technologies developed. Those sector specific technological and organisational changes that happen at the micro-level will set the rate of change of different economic sectors (Andreoni et al., 2017).

Of course, in the presence of technological change, the way in which an organisation adapts says much about its level of flexibility, capabilities and ultimately efficiency. The organization that is more flexible adapts better to changes, and the literature agrees that more flexibility comes from firms' resources that developed a wider set of individual skills and collective capabilities with a series of consequences at the level of productive organisations (Lazonick, 1990). In this process, which is collective in nature and which responds to internal compulsions and pressures, it is fundamental to understand the role of organisations and of infra sectoral and intra sectoral interdependencies.

3. Organisation of production, a resource-based theory of the firm to endogenise technology adoption

Technological change is a crucial factor in determining industry organisation, intended as the way in which firms organise their production processes and engage with other actors along the value chain. Technical change is thus interrelated with several innovation processes that can lead to the transformation of the "organisational economy" (Simon, 1991). These interrelations and evolving systems, over the long run, trigger broader changes in the fabric of society, shaping its institutional and political configurations, and explaining much of the distribution of power among organisations and states (Amsden, 1991; Andreoni and Chang, 2019).

This section will review the different units of analysis to look at organization, at the theoretical level, and why specific types of organizations, and of organisational capabilities, matter as triggers for technological change and innovation. This process is characterised by *Knightian uncertainty* and *Rosenbergian expectations* regarding technological change, political factors, and unforeseen economic interactions (Knight, 1921; Rosenberg, 1976; Teece, 2019).

Technology and organizational changes are deeply interconnected. Indeed, an analysis of technical change must consider both technology and organisation, as well as their mutual influences. Productivity comes from cooperation between capital and labour, giving rise to a series of interdependencies at the shopfloor level, between labour and capital, skills and properties of the machines (Lazonick, 1990). Within the firm, Lazonick's analysis at the shopfloor level illustrates that investment in effort saving technologies activate cooperative relations between workers and managers, and it is within these relations that lies the ability of businesses to generate value by utilising the productivity potential of past investments in organisation and technology, as alternative to undertake costly investment required to develop the productive potential of new effort saving technologies (Lazonick, 1990; also Penrose, 1959).

Along these processes, firms are characterised by both a dynamic element associated with the transformation of the material (e.g., the task and processes), and a persistent (rigid) element associated with the productive apparatus and with the organizational set up (skills and capabilities) (Landesmann and Scazzieri, 1996). Such dynamic and rigid elements play a fundamental role in shaping the interplay between capability, transaction and scale-scope aspects, which in turn determine the rate and ways in which firms grow (Morroni, 2006).

It is within the capitalist firm, and the necessary interconnection between reorganization of labour and technology, that innovation happens. In the words of Lazonick:

"*as the products that the capitalist enterprise generates become more 'innovative', and hence as capitalism becomes more 'advanced', the need to motivate workers to generate productivity and to share the productivity gains with them becomes all the more important as a fundamental principle of the development of the economy*" (Lazonick, 2016:85).

Although the analysis carried out in this *essay* enters the machines-workers relationship only partially, the power that workers have to shape an existing organisation is crucial to acknowledge, as an important factor to explain why technologies may be used in different ways. This section introduces different levels to examine technical change (section 3.1), with a focus on the firm as the preferred unit of analysis to understand induced mechanisms of change, and the capabilities (section 3.2) that enable further technical change following specific - and partially pre-determined - directions.

3.1 The firm as the preferred unit of analysis. Different units of the analysis entail different methodologies to look at organization

The mechanisms of diffusion and adaptation depend also on the organisational level at which technological change occur. Following the structuralist theories, technological change can occur at three levels, which corresponds to different ways to look at production (Landersmann and Scazzieri, 1996).

1) The *task* level, that corresponds to the Smithian approach and that privileges technological change at the level of the operations or task in which a process may be decomposed.
2) The level of the *sector*, known also as Lowe's approach that focuses on the singular interdependencies of the economic system (see Gehrke and Hageman, 1996).
3) The *agent* level that focuses on the agents' capabilities that interact with the subdivision of a process into tasks and sets of tasks, with the emergence of a series of complementarities.

These levels are not mutually exclusive, rather they are interdependent,

"*the implementation of technological innovations which take place at one level of the productive process is always constrained by the technological feasibility at the other levels, the ability to respond to new task arrangement is a function of the stage of technological knowledge*" (Landersmann and Scazzieri, 1996:308).

Despite the high level of abstraction of these three ways in which production and technological change can be observed, they provide interesting elements that, once combined, give rise to the firm as the result of the limited set of feasible combinations, given by existing technologies, and feasible tasks assigned to productive agents, that corresponds to the organisation.

There are a series of interdependencies between the three levels aforementioned and they make the process of technological and structural change unbalanced, and non-linear by definition (Morroni, 1992). Relatedly, bottlenecks and opportunities associated with complementarities among components of the production process, that could arise at the level of the task, of the sector, and of the agents, have a degree of influence in the direction of technological change, which is also bounded within the space of what is structurally feasible (Marengo and Scazzieri, 2014) and structurally invariant.

The firm is the place where these three levels, task, sector and agents' dynamics, interrelate. It is the centre of technological change and organisational capabilities; its essence, as argued by Edith Penrose, goes well beyond reducing transaction costs, being it often the best option for the creation and development of capabilities, and not only on the basis of transaction costs. It is in fact, the pool of resources (of workers and production processes) that are organised and managed within a specific framework, that create additionalities through a non-linear process of error and trial (Penrose, 1959; Richardson, 1972).

The firm is, to put it in Rosenberg terms, "*the centre for the transmission of relevant knowledge and techniques*" (Rosenberg, 1970:553). Crucial to the structuralist and evolutionary theories, production and technological change analysis within the firm are characterised by an element that is often overlooked in standard economic theories of production. This element is time, and as production unfolds in historical time, it needs to be incorporated in the theory of production. Moreover, time is crucial as different elements belonging to existing structures change at different speed (Landesmann and Scazzieri, 1996). If time is not part of the analysis, two major problems arise. First, the main feature of technological change, that is incrementality, is taken out of the analysis. Second, fund idleness inefficiencies are not considered and the only inefficiencies that may arise are due to underutilisation of non-perfectly divisible funds.

One of the main authors in acknowledging the role of time within production is Georgescu-Roegen[17] using a function to describe at any time the cumulative quantity of output, going beyond the static linear model of production through his flow-fund model[18]. The consideration of time when looking at the firm organisation is fundamental for two main reasons, both coming from Georgescu-Roegen model. First, if we consider the analysis of the production line, it is clear that the existence of efficient scale of production and of possible efficiency reversals over certain ranges of increases in production levels derives not only from the presence of indivisibilities or from scale dependent nature of the elementary process, but also from the particular distribution of fund utilization times in relation to production process duration (Marzetti and Morroni, 2020).

Second, the analysis of the degree of flexibility requires a model that accounts for the time dimension of production processes. The flow-fund inputs model shows how the degree of flexibility is linked to short set up times of machines and large warehouses, whose reductions is key element for enhancing flexibility (Morroni, 1992 and 2014)[19]. "*The analysis of the degree of flexibility requires a model that accounts for the time dimension of production process*" (Morroni and Marzetti, 2020). In parallel production processes present also a series of rigidities due to limited substitutability between different technologies, and other types of bottlenecks on the supply side (Quadrio Curzio and Pellizzari, 1991).

[17] In their review of time within the theories of production, Morroni and Marzetti (2020) considers Georgescu-Roegen fund-flow model and Winston optimal utilization model as the two main theories, one that complements the other, in the study of production that embeds time.
[18] The model distinguished fund and flow factors. Fund factors are elements that are part of the production process both as input and as output, that are connected among themselves through identity or quantitative equality, they are characterized by economic invariability (e.g., a needle). Flow factors are elements that are present in the production process either as input or as output (e.g., textile, clothes). Georgescu-Roegen, 1969, chapter 4 of *The Economics of Production*.
[19] This element will come back throughout this thesis, and specifically in reference to the Japanese capabilities of production in a flexible environment where set up times and warehouses are reduced to minimum (Essay III) (Lazonick, 1990; Dosi, 2000).

As such, the firm is also the place where, thanks to cumulative learning and individual and collective capabilities, structural coordination failure such as bottlenecks and rigidities can be overcome. There are no predetermined ways in which the economic system may evolve, rather it is open to a variety of outcomes, that are influenced by specific characteristics of the organisation, such as productive structures' resilience and adjustment process that the organisation undertakes over time (Andreoni, 2013). In other words, the organisation process of technological change depends on its capabilities, which in the process of the growth of the firm – when capabilities need to adapt and co-evolve - are influenced by the managerial abilities to limit possible negative effects (Morroni, 2006; Teece, 2019).

3.2 Organisational capabilities and learning

Capabilities are crucial, "*one cannot adequately explain the wealth of either firms or nations without a theory of capabilities*" (Teece 2019)[20]. One of the few attempts to consider capabilities by the standard economic theory is Arrow (1962) who placed great attention to the Smithian effect of practise, focussing on how specialisation leads to learning, that in turn leads to an increase in experience, reinforcing the specialisation loop. Nonetheless, and probably due to the fact that capabilities do not enter the standard production function, as they are untethered from specific products, their role for economic growth has been overlooked for a long time, emerging only recently as a critical organisational feature which may interact with the subdivision of a process into tasks and sets of tasks (Babbage 1835; Georgescu-Roegen 1969). This is a crucial point, as it seems that economic theories progressively lost their way to assess reality, forgetting to address those firm level critical questions that managers struggle with every day. These questions are essentially related to how firms build and maintain competitive advantage, to their unique organisational and managerial capabilities, and especially to those related to innovation and change (Teece, 2019).

[20] *They are so important that Sutton (2012:8) in his book writes that* "the proximate cause [of differences in the wealth of nations] lies, for the most part, in the capabilities of firms".

Nor the profit maximising machine of neoclassical economists, nor the careful analysis of minimising transaction costs[21] go at the core of what firms are: a bundle of individual and collective capabilities that evolve over time, and where institutions, sectors and history play a crucial role for their development (Penrose, 1959; Morroni, 2006). If we want to understand the allocation of resources and the mechanisms through which these resources develop within the firm, the minimisation of Williamsonian transaction costs has little relevance to this; it is rather the bundle of each firm's capabilities that matter.

"*The basic argument is that firms differentiate themselves through learning, entrepreneurship, innovation, and astute decision making; in short, firms are differentiated by their capabilities, especially their capabilities to decide, to innovate, and to change*" (Teece, 2019:3).

The resource-based theory of the firm emerged to explain firm level heterogeneity, analysing firms as organisations where capabilities and skills are continuously growing, adapting and exploring, due to a continuous tension between structure and agency, and through the internal compulsion created by technology (Penrose, 1959; Barney, 1991). Penrose was one of the first in providing an explanation for interfirm variation through the relation between firms' resources and services extracted from them. This perspective was followed by Richardson (1972:888) who took the idea forward, intending capabilities "*as the firm's 'knowledge, experience and skills', as the driver of, and constraint on, the activities of the firm".* Demsetz (1976, p. 373) pointed to the 'inherent capabilities of producers' as a possible socially benign explanation for large market shares.

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[21] Teece classifies make, buy or rent choices (Teece 2019). The 'rent' option can be a powerful accelerator for capability development. It involves using consultants to jump-start the establishment of a capability at a high (best practice) level in order to produce good results fairly quickly. A barrier to the success of renting can be resistance from the existing organization. The option requires conscious direction from senior leaders to endorse the direction being given by the outside firm as part of a strategic vision and set expectations for the behaviour change.

Core to the capabilities approach is the recognition of the business enterprise as an organization with capabilities and strategies, that develop through individual and cumulative processes of learning and take decades to develop. These capabilities are not just a mere collection of blueprints, they rather involve a high degree of tacit knowledge that is difficult to transmit. The way in which tacit knowledge happens to be transmitted is hard to codify by definition. Again, technological learning involves a series of elements beyond invention, discovering and patenting, which stem from a cumulative and self-generating process (Rosenberg, 1969). Crucial activities that help in the diffusion of technologies are imitation, reverse engineering, adoption of capital-embodied innovations, learning by doing and learning by using (Freeman 1982; Dosi 1988). These processes all critically depend on cumulativeness and pre-existing capabilities, thus minimising opportunities and space for leapfrogging (Soete, 1985; UNCTAD, 2018).

The resource-based theory and similar approaches were fundamental in opening up the right type of questions yet leaving unresolved other important issues such as the specific technologies, standards and criteria that allowed some firms to remain competitive across different technology and production cycles. Evolutionary economic and especially the dynamic capabilities framework has been trying to answer some of these questions (Teece, 2007; Teece, Pisano, & Shuen, 1997; Andreoni, 2014). Such framework emphasizes the role that business strategies and management have for the productivity and long-term success of firms. The capabilities and subjective components of managerial choices molds the firm's evolutionary path conducing to a large variety of outcomes (Morroni, 2006).

"The capabilities view of the firm to be outlined below looks beyond 'factors of production' and production functions to recognize the importance of the choices managers make to render resources more productive and to meet customer demand. It also recognizes that technology and know-how do not fall like manna from heaven but rather result from search, R&D, and investment." (Teece, 2019:7).

At the management level, an important focus is in fact placed on capabilities, how they develop, how they cumulate and become a strong long-term asset for business firms. Capabilities are not developed equally along different units of the firm, nor they are developed in a same way across different firms (see Essay III on how American and Japanese firms' priorities differ over the accumulation of capabilities). The way in which different firms prioritise capabilities' development has a series of positive effects deriving from long term interaction between different parts of the structure (Lazonick, 1990).

Capabilities can be either individual or collective, and despite the firm is composed by both, collective capabilities are more important in order to study how firms differentiate and develop strategic advantages.

"Many capabilities become embedded in routines, and some reside with the top management team. Organizational capabilities can usefully be thought of as falling into one of two interconnected (but analytically separable) categories: ordinary capabilities and dynamic capabilities. Ordinary capabilities are to a large extent operational whereas dynamic capabilities[22,23] *are generally strategic in nature"* (Teece, 2019:7).

These capabilities interact and are the result of firms' activities. Within firms, it is useful to distinguish between capabilities and competencies. The former involves organised activities, where routines as well as individual skills are building blocks of such capabilities. The latter refers to the fact that a firm, an organisation, tends to be good at some specific thing, i.e., it has that specific competence. As mentioned by Dosi et al.,

[22] Dynamic capabilities seek to explain long-run growth and firm survival (or failure) by detailing how firms can create, extend, integrate, modify, and deploy their resources while simultaneously managing competitive threats and effectuating necessary transformations (Teece, 2010).

[23] Dynamic capabilities can be classified in: (1) identification and assessment of threats, opportunities, and customer needs (sensing); (2) mobilization of resources to address fresh opportunities while capturing value from doing so (seizing); and (3) ongoing organizational renewal (transforming). Engagement in continuous or semicontinuous sensing, seizing, and transforming is essential if the firm is to sustain itself as customers, competitors, and technologies change (Teece, 2007).

(2000), "*the concepts of 'core competence' and 'dynamic capabilities' point in the same direction, being broadly concerned with the firm's ability to carry off the balancing act between continuity and change in its capabilities, and to do so in a competitively effective fashion*" (Dosi et al., 2000:6). The ability to reconfigure internal and external competences, especially those crucial technical competences, and to adapt to a different environment, enters in the definition of dynamic capabilities.

Both competencies and capabilities depend on learning trajectories that emerge at the level of the firm. Structural learning is defined as process through which structural constraints in production named bottlenecks, incompatibilities and technical imbalances are transformed into learning opportunities (Andreoni, 2014). As aforementioned, technology is far from the deterministic process of the entrepreneurial hero, it rather resembles a cumulative and self-generating process that happens within an organization. It is the organisation itself that determines what is feasible and what is not on the basis of pre-existing capabilities and the existing technological paradigm.

When analysing technological change and the specific capabilities that matter for the adoption of new technologies, it is important to note that technological change often happens in a retrofitting manner, which means that there is a gradual shift towards new technologies with an increase in the situations where older and newer technologies coexist in the shopfloor. This entails a specific set of capabilities that are more developed in certain type of organisations over others, depending on the priorities that organisations have.

For example, the different degree of autonomy and decision-making lead to different degree of innovation and retrofitting capabilities[24].

This is evident in the comparison between United States and Japan ways of organising the shopfloor level. While the former tended to take the skills off the shopfloor, the latter have been always keen on upskilling the blue collars and to make them feeling part of

[24] As mentioned in Essay III, retrofitting is intended both as an introduction of a new machine into an existing line and as modifications regarding a single device such as to allow it to perform new tasks.

the organisation. This different approach has consequences on their level of flexibility and the ability to change from one to another type of technology[25].

In addition, capabilities can be observed from a firm perspective, but also from an ecosystem perspective. In fact, there is a further crucial set of capabilities that are those characterising the industrial ecosystem, intended as the firms' space underlying the structural interdependencies and the co-evolving dynamics at the core of the production innovation nexus (Andreoni, 2018). Within the industrial ecosystems, crucial activities that help in the diffusion of technologies are imitation, reverse engineering, adoption of capital-embodied innovations, learning by doing and learning by using (Freeman 1982; Dosi 1988). The level and degree of specificities of these capabilities determine the so-called "production space", which is full of opportunities and constraints, and that is characterised by a level of readiness to change. There may be structural holes that undermine the readiness to change; for instance, absent or limited skills in ICT (Information Communication and Technology) would undermine the system in the transition towards new digital production technologies, whose functions depend on ICT technologies (Andreoni, 2018).

4. How technology and organisation shape the direction of productive systems: firm-level and global value chain level determinants

In a different way from scientists, economists are generally not interested in technology *per se*, but rather in those technologies that are economically significant and potentially impacting societies, while redefining existing production systems. Differently from the organisational type of *innovation*, the scientific invention requires other, complementary, elements to become of industrial interest.

[25] See Essay III for a further discussion on this topic in relation to the automotive sector.

In his writings, Rosenberg recalled that "*a very high fraction of new inventions, new products, new processes, once conceived are of no economic relevance until the capital goods industries have successfully solved the technical and mechanical problems to develop the new machines which the inventions require*" (Rosenberg, 1976:175). In this process, the machine tool industry is an example about the crucial role of complementary innovations.

As discussed in the previous sections, the firm-level perspective adopted in this *essay* is indispensable to analyse the microeconomic determinants, which stem from the interrelation of different elements of the productive structure. At the same time, these microeconomic determinants need to be complemented by those emerging from the international organisation of production approach. Such a perspective acknowledges and discusses the importance of power distribution and hierarchies in shaping technology adoption along different value chains.

There have been numerous attempts to bridge the GVC literature to firm-level approaches, such as the corporate make or buy dilemma, the technology value creation analysis and the institutions centred approach (see Sako and Zylberberg, 2019). Among others, the linking of GVC with innovation systems is one of the most recent attempts. The authors here created a framework to embed governance, power, learning institutions and the co-evolution of suppliers and buyers in the analysis (Rabellotti and Pietrobelli, 2010; Jurowetzki et al., 2018).

This essay contributes to this ongoing research and provides an alternative perspective. Namely, this work aims to bridge the micro-level processes of technological change discussed in the previous sections with the dynamics involved in the fragmentation of production within GVCs. We suggest that the mechanisms for technology adoption and diffusion cannot be entirely understood if firm-related determinants, such as the goods produced, and their material and process related innovations are not considered alongside with business strategies and power relations that shape the operations of MNCs and local companies that are integrated into GVCs.

4.1 A renewed microeconomic perspective: firm-level determinants of technology adoption

The analysis presented in the previous sections clarified that the standard theory of microeconomics fails in delivering answers to compelling firm-level issues. The reality is more dynamic, more uncertain, less linear, more time-dependent and less subjected to convexities and profit maximisation, than what the standard theory predicts.

"*[…] economists have been silent for too long on critical managerial issues such as: (i) how firms innovate (beyond just spending money on R&D); (ii) why firms have capabilities that transcend the sum of individual skills of their employees and contractors; (iii) how individual firms evolve to build and sustain competitive advantage over rivals.*" (Teece, 2019:4).

The standard theory mainly focuses on price-guided decisions and largely – although not always - disregards management-guided resource allocation (Demsetz, 1997). However, prices explain little of what happens within firms when they face innovation based competition, while capabilities play a crucial role in technological change and thus in the adoption of new technologies.

Capabilities determine how a specific technology is used, whether it is adopted or not, and what are the possibilities for structural change along similar technological trajectories since the "*development or lack of development in one technology might foster or prevent developments in other technologies*" (Rosenberg, 1982)

The adoption of a specific technology depends on a broad and diverse range of factors, and profitability is a critical one. Soete (1985) discusses two main forces determining profitability. On the one hand, there are those factors emphasised in the standard diffusion model, such as the investment required (cost) and the expected profitability (return on investment) deriving from the innovation. On the other hand, there are income levels, technology supply markets - a point well explored in Rosenberg (1970) when comparing the different roles of machine tools producers in the UK and the US - and the maturity of the technology being diffused. The latter aspect links technology adoption with the concept of technological gap, i.e., how technologically far is a specific country or sector from the frontier of new technologies. Such concept has been widely explored in the literature, and there is a general agreement that it is a discriminant for rapid economic growth (Findlay, 1978; Kokko, 1994; Glass and Saggi, 2002)[26].

Diffusion mechanisms tend to be relatively incremental and influenced by the problems that need to be solved, on which technicians are likely to concentrate. Charles Babbage invented the first computer in the attempt to solve a problem that "bored" him. In 1820s he was working with John Herschel checking astronomical log tables for ship navigation, which he considered dull work. As the tables were full of mistakes, he started to think how they could be computed by steam. In this process of error and trial, problem-solving and search for complementarities, some technologies emerged on top of others, precisely because they are more economically relevant (Rosenberg, 1970). This can be associated with multiple factors, such as the possibility to utilise some innovations in numerous sectors, the complementarity (and resistance) of old technologies, that are subjected to a "selective rejection", the availability of specific materials that trigger a series of complementarities in existing mechanisms. The development of the transistor, for example, awaited the availability of high purity germanium and, later, silicon (Rosenberg, 1979); different industrial layers move at different speeds and respond to different dynamics, whose interactions are fundamental to establish technological feasibility.

Different mechanisms and incentives underlie the adoption of new technologies, ranging from merely economic incentives such as cost and return on investment to more

[26] See Essay II for a more compelte analysis on the relation between technological upgrade, FDIs and technological gap.

structural elements such as the status of the technology supply market, as well as learning and absorptive capabilities. The literature agrees that costs are essential, as the final incentives are economic in nature, and they encompass both direct costs (e.g., the purchase of the equipment) and indirect costs (e.g., organisational[27] and human[28] integration and implementation costs) (Irani et al., 1997).

Notwithstanding, costs do not fully capture the particular sequence and time of innovation activities, which are more related to the analysis of supply push forces and the crucial role is played by key technologies. The latter determine the technological paradigm and the technical changes that are feasible in that paradigm. The feasibility of such changes is also determined by the *ex-post* role of the market, which acts through demand-pull forces (Rosenberg, 1969; Dosi, 1997).

Firstly, when considering technology-push forces, we observe that innovations are not isolated but rather tend to develop in an incremental way, highly dependent on past investment in well-established technologies. In fact, previous investments in physical capital and human skills could slow the diffusion of new innovation (Soete, 1985), as old technologies *die slowly* (Rosenberg, 1976). As an example, Rosenberg (1976) observed how the introduction of steam-powered machines was significantly postponed and delayed by a series of (attempted) improvements to the existing waterpower technologies. Therefore, the nature of scientific inputs and R&D render innovation a long-term process for firms, where there is no God scientist or heroic entrepreneur, but instead a collective process with a complex structure of feedbacks at different levels of the economic environment (Dosi, 2000).

Secondly, demand-pull factors mainly rely on the role of the market as the force for technical change that acts as a selecting mechanism between readily available

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[27] Organisational costs arise due to changes in the existing practice to support the integration and assimilation of the new technology (Hollenstein and Woerter, 2008; Irani et al, 1997).

[28] Human costs can be attributed to individuals and result from on-the-job training (Ryan and Harrison, 2000), management time and resistance to the new technology (Hollenstein and Woerter, 2008).

technological possibilities (Dosi, 1982). However, this demand-pull perspective is problematic when considered in isolation as it tends to observe technology as a freely available black box, failing to describe what happens between each need and the final outcome. In other words, market needs are not prime movers but rather selectors, which pick readily available technologies when these have already emerged from structural processes on the supply side.

In the process of technological change, many difficulties hinder the adoption of new technologies (Rosenberg, 1970). The compulsions that play an essential role in technology diffusion and adoption, whether they are demand or supply triggered, depend on structural conditions of the firm and the environment where the firm acts. The possibility to overcome such obstacles depends on two interrelated factors, which are path dependency technology adoption and absorptive capacity.

It is by now widely acknowledged that technologies are not just blueprints or collection of artefacts[29], and technological change is never a random phenomenon (Rosenberg, 1970). Complementary skills, tacit and codifiable know-how, built upon the pre-existing of industrial capabilities, are crucial in determining the type of technology adopted and how they are adopted (Nelson and Winter, 1982; Silverberg, 1991; Dosi et al., 2000; Andreoni, 2014). Similarly, decision and value creation at the firm level are mechanisms

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[29] Codifiable knowledge is a crucial aspect of technology as it is linked to the challenges around appropriability and intellectual property rights (IPRs). Although IPRs have become more robust and sophisticated, especially in advanced economies, some authors argue that their extent overtook the point of causing hinders to technological progress (Sahal, 1983; Teece response to Nelson, 2018). An interesting passage for this argument is the following:
"Appropriability is a fascinating issue for the economist because it is an example of an externality, and thus poses a challenge to the optimum welfare implications of those styles of general equilibrium analysis that, at least in theory, fully reconcile individual and social interests. This has led to a sophisticated literature on whether too much or too little R&D will be done compared to some posited social optimum, due to either the inadequate private incentive or the danger of redundancy and duplication of research efforts. From the perspective of this paper, I think that these questions are somewhat beside the point. As I shall try to demonstrate in the following, both externalities and (near) duplication can be very useful, perhaps even necessary, components of technical change when seen as a collective evolutionary process. The key concept in this regard is learning, which can take place within the individual, the organisation, and collectively through a network of feedbacks unfolding over time between both cooperative and competitive agents" (Silverberg, 1991:70).

induced and triggered by the industrial ecosystem, characterised by learning activities and a degree of resilience that allows productive structures and processes to be adjusted over time (Andreoni, 2018).

The building up of technological knowledge is thus linked to previous investments and existing capabilities to integrate new technologies in an existing environment. The latter is highly influenced by an organisation's absorptive capacity, which determines the ability to learn new knowledge (Cohen and Levinthal, 1990)[30]. It is widely recognised that countries' absorptive capacity is crucial, as it determines the extent to which organisations can rapidly and efficiently introduce foreign technologies into their economy (Soete, 1985), through a fundamental mechanism of local adaptation (Hausmann and Rodrik, 2002).

To conclude, there is a specific type of determinants that influence the adoption of technologies at the level of the organisation: the organisations' retrofitting capabilities, which can be considered part of the absorptive capacity element discussed above. The large majority of companies do not adopt new technologies all at once, but gradually and having old and new technologies coexisting, so that the capabilities to integrate these different levels of machines is fundamental, as a lot of the innovation process depends *"on employees taking initiative and applying all their skills and knowledge to advance and achievement of the organisation's objectives"* (Simon, 1991).

4.2 GVC power and global ties: why do they matter for technological change?

Firms are not only bundles of capabilities, as discussed above, but also actors in globally-dispersed value chains, which is something that gave emerging economies significant opportunities to link up to international competition, standards and products. The exposure of firms to GVCs may act as one of the channels for spillovers and linkage creation for a larger set of opportunities for learning and capability development (Morrison et al., 2008; Saliola and Zanfei, 2009). Firms active in GVCs have been found

[30] See also Essay II of this thesis for an elaboration on absorptive capacity.

to be more likely to adopt new technologies, be it in the form of new equipment, production standards, or management practices (Baldwin and Yan, 2014; De Marchi et al., 2018).

Nonetheless, GVC access around the world is particularly uneven across countries and regions (Lema et al., 2018; World Bank, 2017). Furthermore, the outcome from value chain integration is far from being unanimous. Despite the opportunities generated by GVCs, the nature of interfirm relationships along GVCs remains unclear at best, with heterogeneous impact on learning that varies significantly according to countries' stages of development and local institutions (Giuliani et al., 2005; Pietrobelli and Rabellotti, 2011). The experience of East Asian countries such as South Korea and China indicates that local innovation systems are crucial to overcoming capability failures and thus climbing up the developmental ladder from export-led industrialisation, towards sustained knowledge-based competitiveness (Fu, 2015; Lee, 2013).

Concerning new technologies, numerous studies suggest that firms participating in value chains are more likely to adopt advanced technologies (see Delera et al., 2020 for a case on fourth industrial revolution technologies). Different learning mechanisms unfold within GVCs: far from an automatic process, learning is subjected to different configurations of power distribution along the value chain (Morrison et al., 2008). Crucially, even when the right set of power configuration is put in place[31], thus leaving space for technology adoption, learning is subjected to organisational capabilities across multi-firms supply chains.

Differently, when space related to the power configuration is too narrow, value chain relationships are not necessarily beneficial for domestic firms, as asymmetric power relationships may prevent them from upgrading their capabilities, with possible adverse effects (Delera et al., 2020). For instance, considering Africa, its link to GVCs has led many African countries to a process of dramatic deindustrialisation, import penetration

[31] See Khan 2013 for a detailed example on Bangladesh and how the configuration of power matter for development and technological change.

and competition from emerging countries such as India and China (Edwards and Jenkins, 2015; Torreggiani and Andreoni, 2019).

To avoid such situations and to capture high-value niches, companies have to develop multiple sets of complementarity production capabilities across the value chain, which rarely stem from the mere integration to GVC but are instead the result of institutional efforts at the local level (Andreoni, 2019). The upgrading coming from the integration to GVC will only reach developing countries if this is combined with a process of technology transfer (Stewart, 1977). Such transfer relies on adaptation, and it is supported by technical assistance, which could potentially conflict with the notion of technology appropriability. Appropriability issues have been leading many MNCs to restrict the access to their know-how (i.e., kept inside the headquarters and very few subsidiaries), resulting in a limited number of manufacturing miracles happened in developing countries.

The GVC framework aims at clarifying the relationship between international participation and various forms of governance and upgrading (Gereffi, 2014; Humphrey and Schmitz, 2002). The latter are generally not equal, as they imply different spillovers to the rest of the economy. In this context, the literature focused on learning mechanisms and investigated their circumstances. For instance, those resulting from compliance needs with international standards or those fostered by value-chain leaders that involved the suppliers directly. When actors along the value chain have complementary competencies, learning mechanisms can also be mutual, based on intense face-to-face interactions. Notwithstanding, here, the main element for technological change relies on local suppliers' capacity to absorb, master and adapt knowledge and capabilities that leading firms can transfer to them. In turn, this stems from local suppliers' availability of complementary sources of knowledge from outside the GVC – for example from international trade, foreign direct investment, human capital mobility, and international research collaboration – as well as in the level of maturity of the local innovation systems (Morrison et al., 2008).

Acknowledging that GVC insertion is more of a "demanding stairway", rather than a "benign escalator" (Humphrey and Schmitz, 2002: 1020), and that GVC insertion success depends on countries' and firms' capabilities, imposes a reconsideration of the type of analysis needed to assess the GVC impact. While considerations about the end of GVC golden era (Humphrey and Schmitz, 2000; Gereffi et al., 2005; Gereffi and Fernandez-Stark, 2011) could be premature, the GVC perspective will have to face challenges related to the advent of new technologies, their role in changing existing cross-border dynamics, and the fact that the mere linking to GVC is likely to be even less sufficient to upgrade.

Since decisions about location, technology adoption and firm boundaries are made by companies, GVC would benefit from a more systematic firm centric strategy analysis (Sako and Zylberberg, 2019; Pardi, 2018). Various studies combine innovation systems and GVC, providing a more precise understanding of the benefits obtained by countries upon linking up to GVC (Coveri and Zanfei, 2020). The innovation system approach makes an important effort, as it includes all market and non-market networks that foster the creation, transfer, adoption, adaptation, and diffusion of knowledge through individual, collective, and organisational learning processes (Nelson, 1993; Lundvall et al., 2009; Lema et al., 2018).

Herein, we attempted to bridge and combine an industrial economics type of perspective with the GVC one, thus going inside the black box of technology adoption and linking these micro-level processes with dynamics at the GVC level (Pardi, 2019). Such a framework will not only allow us to understand better the challenges posed by 4IR technologies (in the next section) but also to consider multi-tiered organisational structure, thus overcoming the sector as the central unit of analysis, replacing it with the task and the chain-network one (Andreoni, 2018).

Moreover, such GVC approach shed further light on the role that big MNCs have in different types of GVC whose configuration may determine the way in which downstream actors evolve, both from an organisational and technological point of view

(Saliola and Zanfei, 2009; Kano, 2017). Complementing the GVC approach with the more micro level industrial economic approach could help to characterise in more analytical terms the actual and potential linkages between various forms of economic upgrading and social upgrading promoted by MNEs' strategies in emerging countries.

The fourth industrial revolution relies on a combination of business and manufacturing processes which, due to the implementation of digital technologies, should allow the integration of all actors in a company's value chain (Rojko 2017; Gracel and Łebkowski 2018). Nonetheless this integration process requires capabilities, both financial and productive, and the tools and technologies to fully become part of an integrated value chain. Also, it is very unlikely that given costs involved in purchasing, setting up and absorbing new technologies, firms in both developed and developing countries would choose to digitalise all their operations at once with the result that different generations of production technologies coexist within firms and local (and global) ecosystem[32] (Delera et al., 2020; Andreoni and Anzolin, 2019; Fu, 2020).

This would determine that some tasks, intended as applications performed inside the firm, may be upgraded with the adoption of a new sophisticated type of technology, thus triggering a series of mechanisms interrelated with different units of the firm, and the network of firms[33].

The next section will provide a dive into the realm of new digital production technologies, discussing the nature of the so-called fourth industrial revolution

[32] Delera et al., 2020 found a high degree of heterogeneity in their study on fourth industrial revolution technology adoption in Vietnam, Ghana and Thailand. On one end of this spectrum, there are many firms producing goods and services through traditional production processes, without the use of any digital technology; on the other extreme, few firms for which advanced digitalisation is an essential part of the business strategy.

[33] For example, the adoption of a new laser welding industrial robot in a South African based subsidiary of a global MNC, happens in a shopfloor that is characterised by both old self standing machines and new online machines, with the presence of both highly skilled and unskilled labour. This new application connects aluminium suppliers for the laser welding robots, with technology providers back in Italy and Germany and with a series of actors, both within and across different levels of the organisations involved (see Essay III for the detailed case study).

technologies. The section will also address the main challenges for countries adoption and diffusion of these technologies, both in relation to firm level and GVC level constraints and opportunities.

5. Are firms ready for the 4IR (re) evolution? From line system to cyberphysical systems in manufacturing.

The theoretical part discussed at the beginning of this essay intends to prepare the discussion the specific dynamics and challenges associated with Fourth Industrial Revolution (4IR) technological change.

Industry 4.0 is understood as a new industrial stage in which there is an integration between manufacturing operations systems and information communication technologies (e.g., IoT) giving rise to the so called Cyber Physical System (Wang et al., 2015, Jeschke et al., 2017; Dalenogare et al., 2018). This connectivity element is a key feature of the most advanced developments in manufacturing systems, although it is far from being diffused across both developed and emerging economies.

Despite the incremental nature of most technological change, as Keynes put it *"it will all happen gradually, not as a catastrophe"* (Keynes, 1930), there is an undeniable difference between the present and previous waves of innovation. While the first and the second industrial revolutions experienced technological advances in parallel with productivity levels, the technology-productivity nexus appears to have lost momentum. There is empirical evidence that suggests an upper tail of a small number of firms that are actively engaging at the technological frontier, and a long tail of firms lagging behind and lacking the necessary capabilities to adopt new technologies.

The former, productivity leaders, are moving even further out from slow productivity firms, thus indicating that technological diffusion from leaders to laggards have slowed, and perhaps even stalled (Dosi, 2000; Andrews et al., 2015; Haldene, 2017). Poor productivity trends and the inequality between firms' capacity to innovate and the use of technologies, hide ongoing dynamics of technological diffusion mechanisms and investment in technology adoption. This section elaborates on the main features of digital production technologies, providing an analysis of the major challenges for their adoption by countries at different stages of development.

The issues raised in the previous sections of this Essay will be recalled and examined in the following section on digital production technologies. In section 5.1 we discuss the incremental nature of 4IR technologies, which in fact stem from technologies, infrastructure and capabilities developed during the Information Computer and Technology (ICT) revolution, i.e., the third industrial revolution. This connects to, and further qualifies, what discussed in sections 3 and 4, illustrating how technological change is constrained by the capabilities and previous technological achievements of specific firms, countries and sectors. In section 5.2, we discuss a series of challenges that countries at different stages of development face when attempting to make the leap forwards new technologies. These challenges highlight the role played by drivers of technology diffusion and adoption at the firm level and at the GVC level, which we claim ought to be considered in parallel.

5.1 The 4IR hype is out of control, but is it real? Incremental **versus** *disruptive*

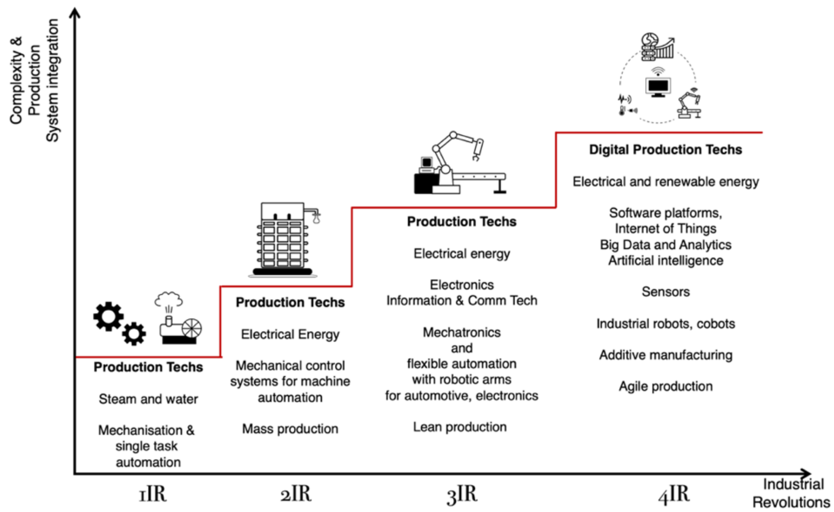
The so-called Fourth Industrial Revolution (4IR) encompasses different types of technologies that are altering production and service activities within and across sectoral value chains. In some cases, these technologies combine and merge the physical and digital realms. For example, advances in fields such as robotization and additive manufacturing as well as related data analytics and systems (Internet of Things), are unlocking new opportunities to accelerate innovation and increase the value-added content of production, especially across manufacturing processes and industries (OECD, 2017; WEF, 2017).

In engaging with these new technologies, countries encounter a series of challenges due to their existing productive structures, their capabilities, their ability to change and react from existing methods to new technologies and ways of organising production. The evolution of technologies and new organisational models indicate that we are witnessing an 'evolutionary process' (rather than a 'revolutionary disruption') in which companies are still sizing up many of the opportunities that new technologies offer, and face major challenges, especially in terms of effective adoption and retrofitting of their legacy systems[34].

Figure 1 illustrates the evolution in production technologies since the first industrial revolution, also indicating the source of energy for production and the dominant co-evolving organizational model of production – from mass production to lean and agile manufacturing.

[34] With this expression we intend the fact that older technologies – that cannot be replaced for different reasons – coexist with new technologies that, once adopted, would have to be adapted and integrated into existing systems.

Figure 1. Revolutions and evolution in production technologies[35].



Source: Andreoni and Anzolin, 2019.

These technological processes are constituted by layers of capabilities that are necessary for the adoption of the next set of productive technologies. In this sense, path dependency contributes to create lock in effects for companies that are not aware of the advantages they may have, nor they have the tools to overcome the gaps. This is the reason why it appears at best very complicated to skip from one step to the next one, without having completed the industrialisation process and having acquired the necessary capabilities.

These are indeed all technologies whose evolution started a long time ago. Automated technologies like, for example, robots and data collection have been at the core of production technologies for a long time. For instance, despite the prevailing idea that robots are a new technology, automation dates back to the 18th century, and the first

[35] In the work by Kupfer et al.(2019), they propose a classification of technological generations: (i) first generation of analogue production (no digital technologies); (ii) second generation (rigid production), limited to the use of specific purpose in a specific function (e.g. CAD on product development); (iii) third generation, where digital technologies involve and connect different functions and activities within the firm (e.g. use of CAD-CAM) through basic automation processes; (iv) fourth generation, with integrated and smart production through fully integrated activities with information flows in real time.

robotic arms deployed in industrial production goes back to the 1960s. Since then, automation technologies have evolved and found applications in almost all industries. More recently, industrial automation has allowed the replacement of manual operations of workers with logical programming commands and the use of mechanized equipment.

For what concerns data, the availability of more and higher quality data lies at the core of today's digital production technologies. Productivity improvements have been achieved through the availability of better and more reliable data since the 2IR. From Taylorism in the 20th century and Japanese lean production to the present 4IR, operation management and system engineering have always been based on data collection and use, which come from the bedrock of ICTs and data infrastructure within and across companies in the form of the internet (OECD, 2017; Sturgeon, 2017; Dosi and Virgillito, 2019).

There are different stages of digital maturity, Drahokoupil (2020) describes five of them: (*i*) automation with the use of older generation of fenced off robots; (*ii*) more advanced but isolated and co-existing with legacy machinery; (*iii*) value adding components are connected for the purpose of digital monitoring; (*iv*) production controlled through cyber physical systems; (*v*) production is completely automated. The dynamics around 4IR regarding the increase connectivity between production processes is taking place between (*iii*) and (*iv*).

It is indeed the availability of data and the consequent possibilities that they open at the business level that gives rise to the 4IR, intended as a bundle of different technical developments, whose core is found in the monitoring and maintenance of production processes with planning, optimization, and development activities (Butollo et al., 2018)[36].

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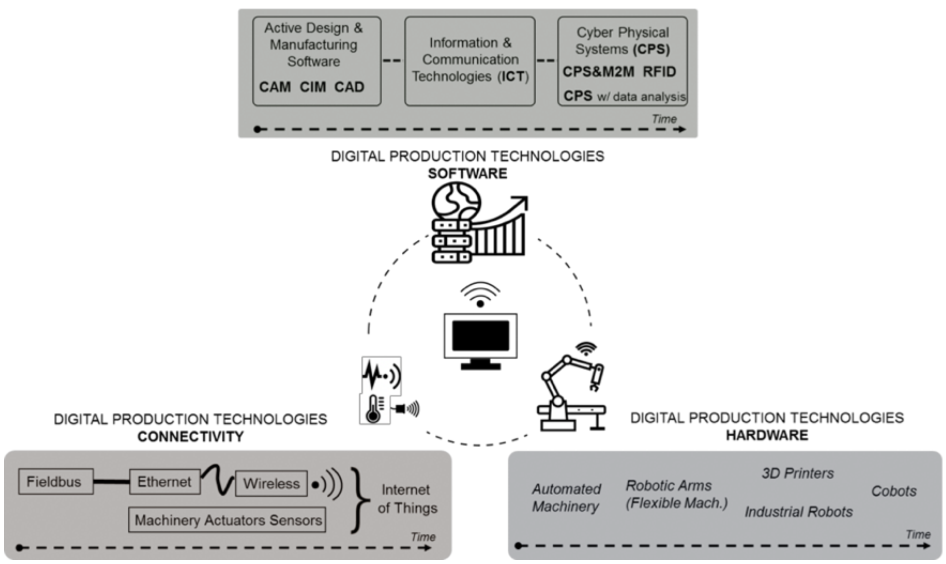
[36] Industry 4.0 combines the digitalisation of the manufacturing processes with real time data acquisition, processed and analysed via server and edge (cloud) computing as a means of optimising industrial processes (Alcerman, 2018). The different nodes of the network (products, machinery and controllers) exchange info through technologies developed through IoT (Gaddi, 2020).

Digital production technologies are the result of the integration of hardware, software and connectivity into an integrated production system. This integration is both technological and organizational and often requires retrofitting of existing production plants. The challenges companies face in integrating 4IR technologies and retrofitting their existing production systems can be better understood if we look at three main structural components of digital production technologies (Figure 2).

Figure 2. Digital production technologies



Source: Andreoni and Anzolin, 2019

First, there are hardware components that are made of the tools and complementary equipment of modern industrial robots and intelligent automated systems, that are largely similar to their predecessors in the 3IR (despite functional improvements, even 3D printers and robotic arms of the 1990s have remained largely the same).

Second, what makes these machines different is their connectivity. The ‘sensorization’ of digital production technologies through Ethernet and wireless systems can potentially open the way to a paradigm shift where the product is able to communicate with different machines (i.e., Internet of Things).

Third, software technologies are the enablers to make 4IR technologies fully digital, allowing big data analytics, and creating the conditions for cyber physical system (CPS). These are smart networked systems, relying on a multidisciplinary concept regarding the knowledge of mechatronics, cybernetics, and design, with embedded sensors, processors and actuators (Suh et al., 2014)[37].

For example, in the automotive industry, such technology integration and automation processes allow linking the product, process and data by defining which component should be manufactured based on which production steps (Schmidgall et al., 2005). This process enables suppliers located in different parts of the world to track the inventory levels of OEMs and when materials or components run low, they receive an automatic order to prepare the next shipment.

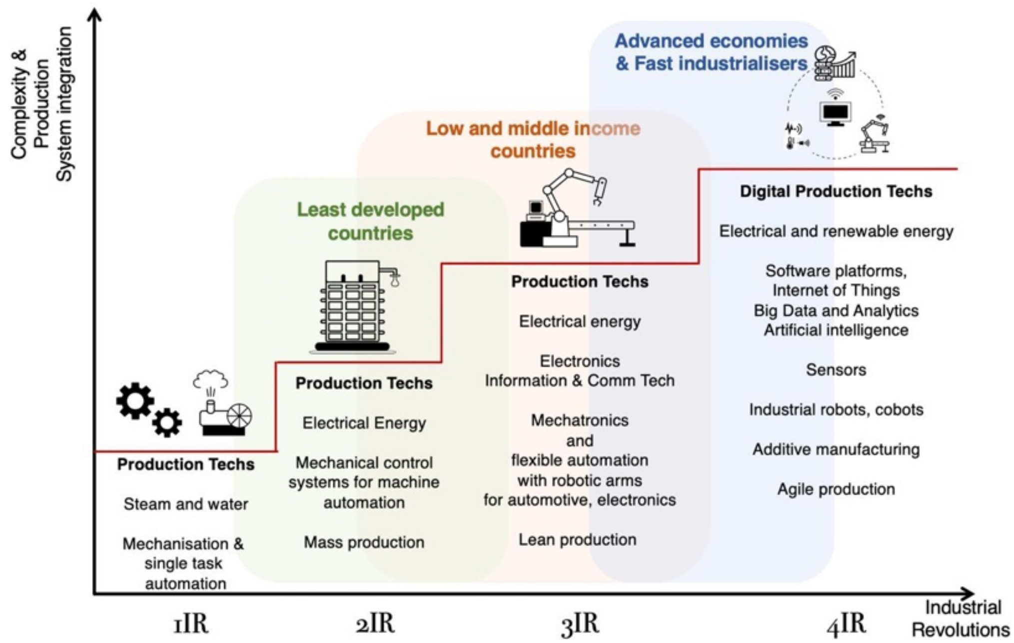
5.2 Challenges in engaging with 4IR: developed and developing countries

Capabilities and incentives to adopt new technologies are not equally distributed across sectors and countries, and they rely extensively on the set of pre-existing capabilities at the firm, sector and country level. In fact, industry 4.0 was born in developed countries - and precisely in Germany as a way to foster the manufacturing sector (Zhong et al., 2017). In these countries, prior industrial stages regarding automation and ICT usage, two concepts of the third industrial revolution that converge in the Industry 4.0 (Kagermann et al., 2013), are already mature. For these reasons, further explained in this section, emerging countries may face an important gap for the Industry 4.0 adoption due to the low maturity of prior industrial stages (Krawczyński et al., 2016; Guan et al., 2006).

[37] Frank et al., 2019 adopted a four-level classification with the following technologies: IoT, cloud, big data and analytics. They are characterized by different levels of capabilities; IoT aims to solve communication issues among all objects and systems in a factory, while cloud services provide easy access to information and services. Big data and analytics are considered key enablers to advanced applications of industry 4.0, since the intelligence of the system depends on the large amount of data accumulated and the ability to analyse them with advanced techniques.

The co-existence among different types of digital production technologies and in different countries is represented in Figure 3. It gives a sense of how 3IR technologies coexist side by side with some initial 4IR technology applications in both developing and most advanced countries. Companies in developing countries are still largely using 3IR technologies, often with a lack of command of these technologies (e.g., automation and ICTs) that makes it difficult to fully exploit the opportunities of the 4IR. Interestingly, and despite sensationalistic announcements of an ongoing disruptive revolution, even among advanced economies and fast industrializers, only a few companies are incrementally engaging with 4IR technologies. Recent studies on the applications of 4IR technologies among SMEs in Germany and the Republic of Korea suggest that only around 20% of the companies have engaged with 4IR technologies (Yu, 2018; Sommer 2015). In a study on SMEs from Italy, United States, Thailand and Austria a series of barriers were individuated as crucial obstacles for the adoption of new technologies: economic and financial, cultural, competence and resources, legal, technology/technical and implementation processes (Orzes et al., 2019). This stems from the fact that the majority of these technologies are developed for, or by, large MNCs, and different studies on SMEs adoption of digital production technologies, even in developed economies, found that firms are prevented from adopting 4IR due to financial and knowledge constraints (Masood and Sonntag, 2020).

Figure 3. Industrial revolutions across countries at different stages of development



Source: Andreoni and Anzolin, 2019

In addition, this interrelation represented in Figure 3 points to the importance of determining how 4IR technologies can be gradually integrated within existing 3IR production systems, and in what specific areas companies need to retrofit their production plants to make such integration possible. For example, capturing the opportunities offered by additive manufacturing in areas such as rapid prototyping (that is, making product design faster and more effective) or tooling (i.e., savings on expensive tools or retooling) cannot occur without an effective re-structuring of production operations, scaling up of technology and organizational processes. Against the backdrop of 4IR opportunities, technological and organizational integration (and thus retrofitting) are key challenges for firms.

Another example concerns the reason behind the slow diffusion of industrial robots, that are powerful but highly demanding technologies. To deliver productivity gains, automated machinery and robots require significant capital investments and reliable power generation infrastructure. Robotized production, in particular, is only economical and cost-effective under very specific conditions, which are often not present in developing countries. As such, given the dramatic shortage of affordable electricity across developing countries, many companies have to rely on manual and semi-automated technologies, alongside second-hand automated machineries from the 1980s.

These processes are taking place across international borders, and GVC reconfigurations are already happening. Notwithstanding, the process of outsourcing, mainly initiated due to cost reduction, has been often changing over time with interconnectedness and interdependencies growing between sites (Meil, 2020). This is the reason why considering GVCs determinants for technology adoption – as presented in section 4.2 – is indispensable in the present scenario of global international production.

This could have both positive and negative aspects; on the one hand, the value created in decades of international relationship may decrease the attractiveness of reshoring dynamics, on the other hand, and under a more pessimistic scenario, the maintenance of the *status quo* could impact negatively suppliers that may found themselves in a lock in situation, unable to upgrade their position. The readiness and space to change depends on sectoral value chains and technology platforms present in the ecosystem in a certain point in time, composed by one or more key technology system. Need to go beyond the sector as the main unit of analysis, replaced by task and chain/network. Task specialization requires the identification of complementarity sets of capabilities which constitute the technology platform underpinning task specialization.

Five critical challenges are likely to determine whether companies would adopt digital production technologies or not. First, as discussed in section 3 organisational and productive capabilities are required to absorb and effectively deploy new technologies. These capabilities are both basic, intermediate and advanced (see Andreoni and Anzolin, 2019), because 4IR is about the ‘fusion of existing and new technologies’ into complex integrated technology systems (Andreoni et al., 2021). These basic and intermediate capabilities are crucial for creating the micro-efficiency and reliability conditions required to effectively deploy new digital production technologies, as well as to embark on a learning journey of technology absorption and adaptation. These capabilities of the ecosystem are often embedded in several institutions and result in a certain level of "social capability"[38].

Second, retrofitting capabilities are at the core of firms' ability to deploy new technologies. As discussed in the previous sections, firms are likely to slowly adopt new technologies thus allowing different level of technologies, some self-standing and some connected through internet, to operate in the same production line. Very often, the commitments are of an organizational nature and they entail the specialization of individuals in developing specific skills. If we intend firms as organisations with capabilities and strategies, in firms and countries where these capabilities are more developed changes are likely to happen more smoothly.

Third, 4IR technologies require the adequate level of basic and digital infrastructure to be effectively used. Some developing countries face considerable challenges in the provision of affordable and reliable electricity, as well as decent connectivity. Infrastructures are thus a pre-condition to engage with new technologies; for instance, IoT would not be feasible without prior development of coding and standardization capabilities as well as access to reliable connectivity infrastructure. Similarly, the widespread diffusion of data depends on the availability of a different set of enabling technologies, such as the internet and standardised protocols.

The last two challenges are directly related to the dynamics at the GVC level. Fourth, developing countries are often characterised by 4IR islands, typically belonging to some kind of international activity, in a desert of technological backwardness that prevents

[38] Chang and Andreoni (2019b) propose an institutional taxonomy including six types of institutions that determine social capability: (i) institutions of production, (ii) institutions of productive capabilities development, (iii) institutions of corporate governance, (iv) institutions of industrial financing, (v) institutions of industrial change and restructuring, and (vi) institutions of macroeconomic management for industrialization. These general institutions are not included in the matrix as they can assume different forms in different contexts, and the same institutional functions can be performed by different institutional forms.

local firms to exploit knowledge spillovers and to learn international standards from such 4IR islands (Andreoni, 2019). This makes it extremely difficult for the leading companies—say an OEM—to link backward and nurture their supply chains. In addition, while the use of digital production technologies is speeding up, these technologies are still concentrated in a few sectors only (and in a few companies and supply chains within them), especially those that received targeted industrial policies in the form of the developmental state[39], and the full automation of "routinized tasks" is far from diffused as many observers seem to suggest.

Fifth, digital production technologies are complex and controlled by a limited number of advanced countries and their leading companies. Developing countries heavily rely on the importation of such technologies from advanced economies, and in many cases, even when they are able to mobilize significant resources to access them, they are tied to their buyers with respect to both the hardware and software components. In this sense, the importance of using common protocols and software platforms for the deployment of digital production technologies bears the risk of verticalization and concentration of power, with the development of:

"*nested modules and platforms based on both de jure and de facto standards, stretching from discrete functional elements (technology platforms) to higher- mechanical systems, level tools, hardware systems, and software environments (core platforms) upon which developers*" (Sturgeon, 2017:8)[40].

[39] As an example, Thailand put in place manufacturing policies directed to specific sectors, among which automotive and plastics, for the upgrade of the industrial structures (Pollio and Rubini, 2018; Black et al., 2018)

[40] The 4IR presents elements of networked openness and elements of power concentration. However, we are also increasingly realizing that this openness is not for everyone. Digital technologies will intensify value chain modularity and disintegration, but these technologies are at the same time integrated through protocols, software and machines that are mainly, when not exclusively, invented and produced in developed economies. Interconnectivity also means that hardware producers, for instance, require customers to purchase proprietary design software by the hardware supplier (Berman, 2012).

This is even more evident as these technologies are not “plug and play”, i.e., the acquisition of hardware goes hand in hand with the need for expensive technology services and royalties for the use of related software (Sturgeon, 2017; Piva and Vivarelli, 2017).

To conclude, companies in advanced countries are better positioned to capture 4IR opportunities, precisely because they have spent decades absorbing, improving and deploying 3IR technologies in manufacturing production, which are preconditions for 4IR technologies. For example, for a big final assembler in a developed country, it is relatively less challenging to introduce a new digital production technology as its local suppliers operate with similar software and hardware systems and are thus aligned in terms of their production standards and use the same connectivity infrastructure.

6. Conclusions

The complexity of structural change and technological upgrade are increased by the sector and product specificities of such processes, characterised by continuous transformation that redefine the boundaries across sectors and the emergence of new ones. Furthermore, companies need a sufficient bundle of capabilities to make the absorption and effective deployment of these technologies possible (Andreoni, 2020), and these capabilities are the result of layers of investments and learning journeys that require time to unfold.

The theoretical part discussed at the beginning of this essay intends to prepare the discussion for 4IR technological change. The policy urgency of this type of research stems from the fact that, despite the sophistication of recent technological advances, productivity is continuously lagging behind, with a widening gap between leaders and laggards.

For these reasons, 4IR opportunities are not equally distributed as companies and countries face different challenges. Effective adoption of these new technologies presupposes the existence of productive organizations endowed with basic and intermediate production capabilities, supported by enabling infrastructures such as reliable electricity, standardization and connectivity. These conditions, however, are largely missing in the majority of developing countries, as well as in many regions of emerging countries and mature industrial economies. Instead, "*industrial societies have acquired unusual skills in problem solving activities*" (Rosenberg, 1979: 108), and these are the steppingstone of present and future achievements.

To conclude, this analysis points in the direction that, once technological change is understood as the critical, unbalanced, interconnected and highly agency dependent process (i.e., depending on the capabilities present at the collective and organisational level) we attempted to describe, the direction of policies and space for international integration, technology adoption and GVC upgrading should be redefined accordingly.

Instead of concentrating on cutting edge 4IR technologies, the promotion of digital production technologies in developing countries should begin by identifying the specific set of basic and intermediate capabilities that must be developed to reduce the digital capability gap across firms in the supply chains in specific regions.

The ride into the realm of digital production technologies continues with the analysis of 4IR technologies diffusion and adoption mechanisms. The next Part II is the empirical section that will presents two studies on the diffusion of 4IR technologies in the automotive sector.

PART II

Essay II

What is driving robotisation in the automotive value chain? Empirical evidence on the role of FDIs and domestic capabilities in technology adoption[41]

1. Introduction

During the last decade, interest towards the so-called 'fourth industrial revolution' (4IR) has exploded (Schwab, 2016; OECD, 2017; Hallward-Driemeier M. and Nayyar G., 2018; Sturgeon, 2019; UNIDO, 2020). An increasing number of interconnected digital technologies is expected to have a profound impact on different sectoral value chains, possibly reshaping the main channels through which technologies are adopted and diffused across advanced and emerging economies. Despite this mounting interest, empirical evidence on specific factors driving adoption of digital technologies remains limited. This essay contributes to filling this gap by providing new empirical evidence on the role that inward Foreign Direct Investments (FDIs) and other host-country's specific factors play in the adoption of industrial robots – one of the key production technologies of the 4IR – and with a specific focus on the global automotive value chain spreading across 34 countries.

Traditionally FDIs have been considered a crucial channel for technology adoption (Cantwell 1989; see Papanastassiou et al., 2020 for a recent and comprehensive review), less is known about their role in the new 4IR scenario. Understanding the extent to which FDIs are driving robotisation is particularly relevant for emerging countries. They have been large recipients of FDIs over the last decades, and the adoption of

[41] Part of this Essay II elaborates on the following published paper: "Robot adoption and FDI driven transformation in the automotive industry" International Journal of Automotive Technology and Management, Vol. 20, Issue 2, pp. 215-237, co-authored with Antonio Andreoni and Antonello Zanfei and it is cited as Anzolin et al., 2020.

foreign production technologies has been key in driving their industrialisation (Verspagen and Kaltenberg, 2015).
With this contribution we analyse: (i) the role that FDIs have vis a vis other country and sectoral specific variables for the adoption of industrial robots in the automotive sectoral value chain; (ii) whether the dynamics observed in the automotive sector as a whole tend to differ across two chain segments, namely Automotive Assembly and Automotive Components, thus capturing also the heterogeneity within the same sector. We built an ad hoc dataset covering 34 countries across 11 years. In our empirical analysis we define the dependent variable as the operational stock of industrial robots within the automotive sector, and a series of independent variables, i.e. inward FDIs and a series of country and sector specific variables to proxy the readiness of the host-country's ecosystem (e.g. its innovativeness, and export competitiveness, and its level of industrial development). We use standard OLS estimations with fixed effects to study the main relationships between our dependent and independent variables. To control for endogeneity, that could arise from both reverse causality and omitted variables, we develop and deploy a new instrumental variable for the estimation of our model. The 2SLS approach to estimate our IV confirms our results.

This analysis is innovative in two main ways. First, by focusing on a specific sectoral value chain – i.e., automotive – and a specific technology – i.e. industrial robots – we are able to study specific drivers of technology adoption; we disentangle global and country-specific factors as well as their interactions, and we explore how these factors play a different role along different segments of the sectoral value chain. This approach allows to capture the high degree of heterogeneity in technology adoption, even within the same sector. To the best of our knowledge, this is the first time that such a study on different drivers of technology adoption is performed with a focus on industrial robots.

Second, in performing this analysis we combine several data at a high level of disaggregation. In particular, for the first time, we combine two datasets which have never been integrated to study technology adoption. These are: the International

Federation of Robotics (IFR) dataset, a worldwide unique source on all robots adopted across countries and sectors, and fDi Markets, an online database issued by a specialised division of Financial Times Ltd, that provides detailed information on all greenfield investments projects across countries and sectors. By combining these data-sources we are able to account for the main drivers of technology adoption with reference to a precise technological domain (robots) and with an appropriate level of disaggregation of a specific sectoral value chain (i.e. specific segments of the Automotive industry).

Considering the cross-country heterogeneity in the patterns of robot adoption and the importance of domestic/regional value chains for technology diffusion, this essay explores a series of hypothesis around the role of FDIs and additional country-specific factors that could act as drivers for robotisation. Special attention will be given to the potential role played in different countries by their domestic industrial ecosystem.

This essay is structured as follows. Section 2 presents a review of the literature on the role of FDIs and the role played by other host-country specific factors in technology adoption. From this perspective, we consider different strands of the literature on the impacts of FDIs on receiving countries, with a specific focus on the role played by absorptive capacity and local capabilities in host countries. Being a sector and technology specific analysis, section 3 introduces the main features of the automotive industry and of industrial robot technology. Section 4 presents the sources of our data, some descriptive statistics and the main hypothesis of our econometric model. Section 5 presents the empirical strategy and our main econometric results. Section 6 discusses our main results and Section 7 concludes.

2. FDI and technological change

Technological innovation and development are costly, especially when we look at new digital technologies. As a result, they tend to be concentrated among large or specialised enterprises that have enough financial capabilities to invest (Gestrin and Staudt, 2018).

Thus, it is common to associate technological upgrading of countries and industries with the presence of large MNCs (Søreide, 2001), and to look at FDIs as one of the main channels through which technology diffuses internationally and is adopted by firms in emerging and developing countries (Crespo and Fontoura, 2007; Glass and Saggi, 2008; Narula and Driffield, 2012; Amighini and Sanfilippo, 2014).

2.1 Technology adoption mechanisms: the special role of FDIs

The links between FDIs, technology adoption and development have long received attention in economic literature (Cantwell, 1989; Caves, 1996; Lall, 2000). This link has received mounting attention over the past three decades mainly as a result of two increasingly acknowledged facts. First, the experiences of some developing countries especially in East Asia proved that if well managed FDIs could act as a trigger for industrialisation (Amsden, 1991; Chang, 1994; Lee, 2013; Walheer and He, 2020 for a recent contribution on China). Second, it has become apparent that MNCs are key spenders in R&D, decentralising a relatively large and increasing fraction of their R&D outside their home countries, and contributing to a high and growing share of R&D carried out in recipient countries, including emerging economies (UNCTAD, 2005; Dachs et al 2014). In spite of this growing evidence and of the attention of scholars to these phenomena, attempts to explore the mechanisms through which FDIs actually contribute to the dissemination and adoption of technology has largely led to mixed and inconclusive results (Lall, 2000; Gorg and Greenway, 2004; Castellani et al., 2015).

The literature has traditionally addressed the technological impact of FDIs in terms of direct and indirect effects of MNCs on the efficiency of host economies (Barba Navaretti and Venables, 2004; Castellani et al., 2015). Direct effects are mainly observed in terms of overall productivity increases and employment creation. There is a general agreement that productivity increases with FDIs through MNCs' operations because their endowment with new technology as well as their managerial efficiency is superior (Torlak, 2004; Proença et al., 2006; Sur and Nandy, 2018).

In this sense, a substantial body of literature found a positive direct effect of inward FDIs on the host economies mainly in terms of: (*i*) changes in the composition of industry, as FDIs bring in bundles of competencies and knowledge assets that increase the overall productivity level of the recipient economy (Dunning, 1993; Barba Navaretti and Venables, 2004; Criscuolo and Martin, 2009; Castellani et al., 2015; Denisia, 2010); (*ii*) employment creation, especially when MNCs contribute to import substitution and to the expansion of a country's export capacity (Ncunu, 2011; Chaudhuri and Banerjee, 2010 for FDI in agriculture).

With specific reference to low- and middle-income countries as recipient economies, Vacaflores (2011) studied the relationship between FDIs and employment in 12 Latin American countries and found a positive and significant effect. Latin American countries were among the highest recipients of FDIs starting from the 1980s but, once compared to other regions like South East Asia or Eastern Europe, the impact of FDI was much weaker in terms of employment growth and other parameters of industrial upgrading and competitiveness (Zhang, 2001). In contrast to these fast industrialisers, countries like Mexico did not engage strategically with MNCs, on the contrary their approach was one of "*passive open-door policy with limited policy interventions and no industrial policy*" (Lall, 1995). As a result, if we look at Mexico as an example, while the development of the auto cluster was impressive – export grew 18% a year over 1994-2002 – the country grew at a modest 3% and the expected automotive multiplier did not materialise (Mortimore and Vargara, 2004).

Indirect effects occur through the change in local firms' behaviour. The standard assumption is that MNCs can be a crucial pushing factor for technological upgrading due to their ability to inject substantial human and fixed capital, hence inducing technological change and knowledge spillovers (Hymer, 1976; Blomstrom and Kokko, 1996). The standard assumption is that FDIs will determine some kind of either technological externalities, contributing to shifts in the local firms' production function, or pecuniary externalities, determining shifts in the local firms' profit function (Blalock and Gertler, 2008; Newman et al., 2014; Santos and Khan, 2018). Empirical evidence on these impacts is more controversial. Some studies found evidence of technological upgrading at a general level, where local firms learnt from MNCs by observing technologies employed by international actors and attracting employees trained by the same actors (Borensztein et al., 1998; Blomström and Sjöholm, 1999 for a study on Indonesia; Meyer, 2004). While the results based on cross-sector analysis revealed a positive impact of FDIs (see for example Makki and Somwaru, 2004; Aykut and Sayek, 2007), due to the fact that international activities take place in better performing countries, the availability of longitudinal firm level data has led to explore spillovers effects of multinational presence across and within industries, leading to less clear-cut results. In fact, a number of studies have found null or even negative impact of FDIs on the performance of host economies (Gorg and Greenaway 2004).

Extant literature has identified the following main channels though which knowledge spillovers accrue to local firms: demonstration/imitation effects, training of local workforce, improved competition, reinforced export, backward and forward linkages with domestic firms (Kinoshita, 1998; Crespo and Fontoura, 2007; Wang and Blomstrom, 1992; Markusen and Venables, 1999). Barrios and Strobl (2002) suggested that the relevance of demonstration-imitation effects increases with the similarity of the goods produced by the two types of firms when considering spillovers related to product and process technology. Moreover, the imposition of higher standards to suppliers as an important indirect way to improve productivity, has long been emphasised in the literature on the impact of MNC activity on host economies, since the seminal studies on linkages carried out by Hirschmann (1958).

This aspect is quite relevant for our analysis on the automotive sector where increasing standards (e.g., in health and safety) have important cascade effects on suppliers' productivity and overall performance (Bisztray, 2016 for an example of AUDI in Hungary). As for the training of local workforce, Kinoshita (1998) highlights the importance of developing absorption capacity for technological spillovers to materialise. In her work on China, she demonstrated how the arrival, through MNCs, of new technologies alone cannot create the positive results expected unless the labour force has the corresponding skills. Accordingly, "*the catch-up effect is important but not as much as the firm's costly effort to build a skill base for greater absorptive capacity, it is indispensable to create the corresponding skills*" (Kinoshita, 1998). These are not general skills but specific to the technology and they imply an adoption cost which is represented by the cost of training (Zanfei, 2012) and by the effort of building up the firm-level capabilities in the host-country.

2.2 Absorptive capacity and technological readiness: the role of the host-country's ecosystem

Empirical evidence shows a positive correlation between FDIs and sectors' technology upgrading and productivity when the host-country is a developed one (Caves, 1974 on Australia; Globerman, 1979 on Canada; Pain and Hubert, 2000 on the United Kingdom; Castellani and Zanfei, 2003 on Italy, Spain and France). However, the picture becomes less clear when studies refer to developing countries exhibiting a weaker ecosystem of organisations, capabilities, and institutions. Xu (2000) carried out a study on more than 40 countries to find positive FDI-driven technology diffusion and adoption in developed countries but not in developing countries. Similarly, positive impact of FDIs on manufacturing firms' technology adoption were found in the United States but not in Mexico and Venezuela (Aitken et al., 1996).

Reflecting these empirical findings, several studies have attempted to explain why FDIs are not beneficial *per se* and pointed to a number of other host-country specific factors responsible for technology diffusion and adoption. These factors include local firms' absorptive capacity (Cohen and Levinthal, 1990; Kokko 1994; Kemeny, 2010; Li, 2011), technological gaps separating foreign and local firms as a source of technological opportunities (Findlay 1978; Blomstrom and Wolff 1997), catching up potential and innovation systems of the host-country (Meyer and Sinani, 2009; Lee, 2019).

A substantial literature has also identified exporting capacities of local firms as an additional feature of host economies which can contribute to explaining technology adoption. In fact, while there is a long tradition of studies reporting that best performing firms are likely to self-select as exporters (Bernard and Jensen, 1999; Clerides et. al., 1998, Wagner 2012), there is growing attention in extant literature to the likely positive impact of exports on firms' efficiency, by inducing new technology adoption and learning (see Girma et al., 2005 on the UK; Head and Ries, 2003 on Japan).
The consideration of these host-country specific factors points to the importance of host-country ecosystems, that can be at least partially captured by the technological capabilities and export competitiveness of local firms and institutions (Lall, 1992; Meyer, 2001; Andreoni and Chang, 2017). It thus appears that technologically advanced investment projects and investors from abroad need to combine with local capacities in order to yield technological spillover effects (Castellani and Zanfei 2003).

This line of argument connects to at least two main developments in extant literature, which are demanding for more empirical analysis.

First, the literature on technology gaps. Findlay (1978) introduced this concept and emphasized that the greater the technological gap, the higher the possibility of potential spillovers. In contrast, Glass and Saggi (2002) and Kokko et al. (2001) considered technological gap as absorptive capacity and hypothesized that the greater the gap the lower the possibility of spillovers. In a previous contribution, Kokko (1994) stresses the idea that the gap does not have to be neither too small nor too big. In the former case there would not be any tangible benefits, while in the latter benefits would not materialise because of no automaticity (Kinoshita, 2001; Buckley et al., 2007). Differently, Liu et al. (2011) conclude that less productive firms, thus with a bigger gap, benefit more from foreign technologies.

Second, a series of studies acknowledges that in order to be able to efficiently take advantage of technological expertise of foreign MNCs, policies are needed to upgrade human skills and the development of productive capabilities (Lall, 2000; Cimoli et al., 2009). Rather than merely attracting foreign capital by means of standard promotion policies, such as tax benefits and the creation of export promoting zones, FDI recipient countries governments should accumulate location-specific assets (Nordas, 2000) and address impediments to technology transfer more directly (Klein, 2019). The level of absorptive capacity is fundamental as local actors can take advantage from MNCs' operations only if they are ready to do so, both in terms of 'social capability' and 'technological congruence' (Abramovitz, 1986; Fagerberg et al., 1994). The former concept relates to the capabilities to engage in innovation and organisational processes, while the latter refers to the technological frontier which determines the capabilities to use and adapt new sources of knowledge.

The presence of absorptive capacities and specific production capabilities can be interpreted as a sign of the so-called technological readiness of firms, sector or countries to adopt new technologies (WEF, 2018; UNCTAD, 2019; UNIDO, 2020). The level of structural readiness of specific industrial ecosystems stems from both technological capabilities and sectoral value chain (Andreoni, 2018). On the one hand, the readiness is influenced by technological and organisational path dependencies, determined by previous investment patterns, by collective organisational learning, and by sector specific characteristics (Hallward-Driemeier and Nayyar, 2018).

2.3 From GVC linkages to horizontal clusters: the role of policy in building up domestic capabilities

Each country's ecosystem is the result of processes that often tend to involve one form or another of industrial policy. Although it is hard to find datasets that collect public and industrial policies – as they are difficult to grasp especially under the time dimension – industrial policies, particularly those that aim at creating linkages from GVC's participation to the rest of the economy, are of strategic importance for technology diffusion among different players of the ecosystem. We briefly discuss these concepts below.

In the last two decades, the impact of FDIs on hosting countries has been increasingly studied through the analytical lenses of global value chains (GVCs). The GVCs literature points at the existence of two critical factors mediating the relationship between FDIs and technology diffusion, i.e., governance and upgrading within and along value chains (Gereffi 1994, 1999 and 2018; Gereffi and Lee, 2016; Ponte et al., 2019; Sturgeon, 2009). First, different types of GVC governance systems determine the ways in which MNCs manage, organize and orchestrate their suppliers on a 'glo-cal' scale and potentially result in 'endogenous asymmetries' (Milberg and Winkler, 2013). Second, upgrading – understood as a positive shift in the competitive position of a firm within and along value chains – depends on several institutional and economic actors in the process of local productive capabilities and linkages development (Gereffi and Lee, 2016; Andreoni, 2019; Dallas et al., 2019).

Despite the importance that this approach gives to understanding the interrelations at a global level, the sectoral characteristics are still important for many reasons. The ability of countries to link up through backward linkages, and then either add value forward or remain upstream, is strongly related to the specific sectors, the types of FDIs that a country is able to attract and the types of linkages that develop from and around the FDIs (Andreoni, 2019). Value creation and spaces for learning and development are distributed unevenly across value chains in different sectors (Andreoni and Chang, 2017), most often involving a fine-slicing of production and R&D activities also within sectors (Mudambi 2009, Papanastassiou et al. 2020).

The Local Production System (LPS) framework (Andreoni, 2019) points to the importance of looking at different types of linkages in a developing country's production system, how they develop both vertically along the FDI-driven global value chain and horizontally in the local economy at the intersection of several sectoral value chains and other actors (including public ones such as industrial research intermediate institutions and services providers).

The local production system is made of multiple types of production, technological, consumption and fiscal linkages which are based on the existence of specific set of capabilities. This framework points to the importance of focusing on the productive, technological and organisational capabilities of local firms, linkages development across industries, institutions and political economy factors (Hirschman, 1958; Amsden, 1989; Chang, 1994; Lall, 2000; Andreoni, 2019; Andreoni and Chang, 2019) as well as the nature of investment projects and the technological level of investors (Castellani and Zanfei 2003, 2006).

Considering the multiple factors suggested within the GVCs and LPS, technology spillovers may not accrue when host economies have a weak industrial base – therefore, FDIs might trigger low or no technological upgrading effects (in our specific case, robotisation) when occurring in local environments that are not responsive to the stimuli of foreign capital injections. In this sense, capability creation, absorptive capacity and production linkages are a key concern when considering spillovers to the rest of the economy (Jindra et al., 2009; Saliola and Zanfei, 2009; Meyer and Sinani, 2009) and different types of value chain integration (Ponte and Gereffi, 2019; Andreoni, 2019).

3. Automotive industry and Industrial robots

This section presents an overview of the automotive sector (3.1) and of the technology at the core of the study here presented (3.2 on industrial robots).

3.1 The globalization of the automotive industry: few final assemblers and the rise of mega suppliers

When studying the relationship between FDIs and robotisation, a focus on the automotive sector is particularly relevant due to three specific structural characteristics of this industry. These characteristics are: automotive GVC structure and concentration, the geographical distribution of its activities, and its early adoption of robots. This section explores the first two aspects.

First, the fragmentation of production and the huge amount of FDIs resulting from both outsourcing and concentration trends, deeply reshaped the industry and contributed to the 'producer-driven' definition of the automotive GVC (Gereffi, 1994). The automotive GVC has been among the first in undertaking important measures of outsourcing and deverticalisation of its productive structure, benefitting from both globalisation and competition between different auto producers and within the same sector, what Baldwin (2016) calls the second globalisation.

The automotive GVC is characterised by a small set of final assemblers with relatively high market power, an increasingly exclusive club of Tier 1 suppliers, which are also becoming closer to the final OEMs (Wong, 2017), and a series of Tier 2 and Tier 3 suppliers which are more dispersed despite being increasingly controlled by OEMs. The last decades have witnessed a consolidation in the automaker markets around sixteen major players. In 2015, ten OEMs accounted for three quarters of global production with the top five accounting for 50% of total production (International Organization of Motor Vehicle Manufacturers, 2015)[42]. Global firm leaders focus on the design part of vehicles that is where an important share of the value-added lies (Sjoestedt, 1987). Pre-production and engineering activities, "*where conceptual designs are translated into the parts and sub-systems that can be assembled into a drivable vehicle, remain centralized in or near the design clusters that have arisen near the headquarters of lead firms*" (Sturgeon et al., 2008: 8).

In terms of concentration trends, over the past decades the global automotive industry has undergone important oligopolistic trends (Nolan, 2012). The result is that few global players divide the lion's share and the challenge for new entrants is increasingly bigger (Datamonitor, 2011). This is well known at the OEM level, but it has been accompanied by the rise of first tier mega suppliers. Over the past four decades component

[42] The forecast of production engineered by the leading OEM (less than 10) is 83% of global output in light vehicles (IHS Markit, 2018)

manufacturers dropped from 40.000 in 1970 to less than 3000 in 2015 (Wong, 2017). Hence, fewer larger first-tier suppliers have survived and consolidated while, at the same time, they have developed close relationship with big OEMs. In this emerging configuration of the automotive value chain, OEMs still control and manage the entire supply chain.

However, since OEMs are the mere final assembler of the product à la Foxconn (McGee, 2016), they put pressure on their suppliers, especially Tier 1, and have forced them to take increasing responsibilities in investments and supply chain management. Indeed, given the small number of global automotive firms and their strong purchasing power, suppliers can be forced towards the adoption of specific standards, information systems and even production technologies. As pointed out by Sturgeon et al. (2009), "*with consolidation, we must question the staying power of smaller, lower tier, local suppliers*" and thus the increasing "endogenous asymmetries" along the value chain in different countries (Milberg and Winkler, 2013). Indeed, the relationship between OEMs and suppliers appear to follow similar global benchmarks but can also develop differently in different country contexts.

The high competition influences also firms already in the sector, that need to rapidly adapt their business models and technologies, in order to maintain their position in the industry (Christensen and Raynor, 2003). On a purely technological point of view, the automotive sector has always been a fertile field for manufacturing automation advances due to its high-volume production, standardisation, and production and product modularisation. This characterisation stems from the degree of transnational dispersion of production in automotive industry (Birkinshaw. et al., 2016; Winroth and Bennett, 2017; Serfati and Sauviat, 2019), which provides an effective illustration of the possibility that companies can create and well manage long-distance business relationships (Sturgeon and Lee, 2005). These aspects require firms already in the industry to develop dynamic capabilities, and to quickly adapt to the fast-paced changes in the industry (Teece et al., 1997).

On the geographical distribution of its activities, the automotive sector is characterised by sectoral and market dynamics resulting in a specific spatial organisation and distribution of production. The fragmentation of automotive production is based on networks that tend to organise regionally, much more than globally (Jetin, 2018). Regionalisation was favoured by the widespread adoption of modularisation in the 1990s (Sako, 2003) and by the importance to be 'next-door' to car assemblers, especially for Tier 1 suppliers that are located close to (when not fully integrated with) assembly plants, in order to better synchronise just-in-time-delivery of complex modular units (Frigant and Lung, 2002; Berger, 2006). In this process, big multinational final assemblers' choices affect the characteristics of the automotive industry and its geographical distribution, considering also their key role in determining the level of industrial concentration, as well as to technology diffusion[43] and to the geographic dispersion of production.

The last features, i.e., the role played by FDIs in robot adoption in the automotive sector is explored in the next section.

3.2 Automotive sector and industrial robots

The automotive sector has always been the bedrock for manufacturing automation and industrial robots make no exception, as the sector has been characterised by the early adoption of industrial robots, since its first introduction in the automotive sector by Ford in the 1960s (Mehrabi et al, 2000; Michalos et al., 2010). The automotive sector has also been a fertile field for many improvements in production technologies, being characterised by intensive economies of scale and by the use of automated machines since the 1970s (Sjoestedt, 1987). The use of industrial robots, despite not being recent, experienced a growth due to improvements in technologies, the consequent increase in productivity and, to a certain extent, flexibility.

[43] In this sense, since OEMs are the leading actor for organisational and technological innovation, they also have the power and ability to manage the modular production and the mastering of new technologies both at the plant level and along the supply chain (Jacobides et al., 2015).

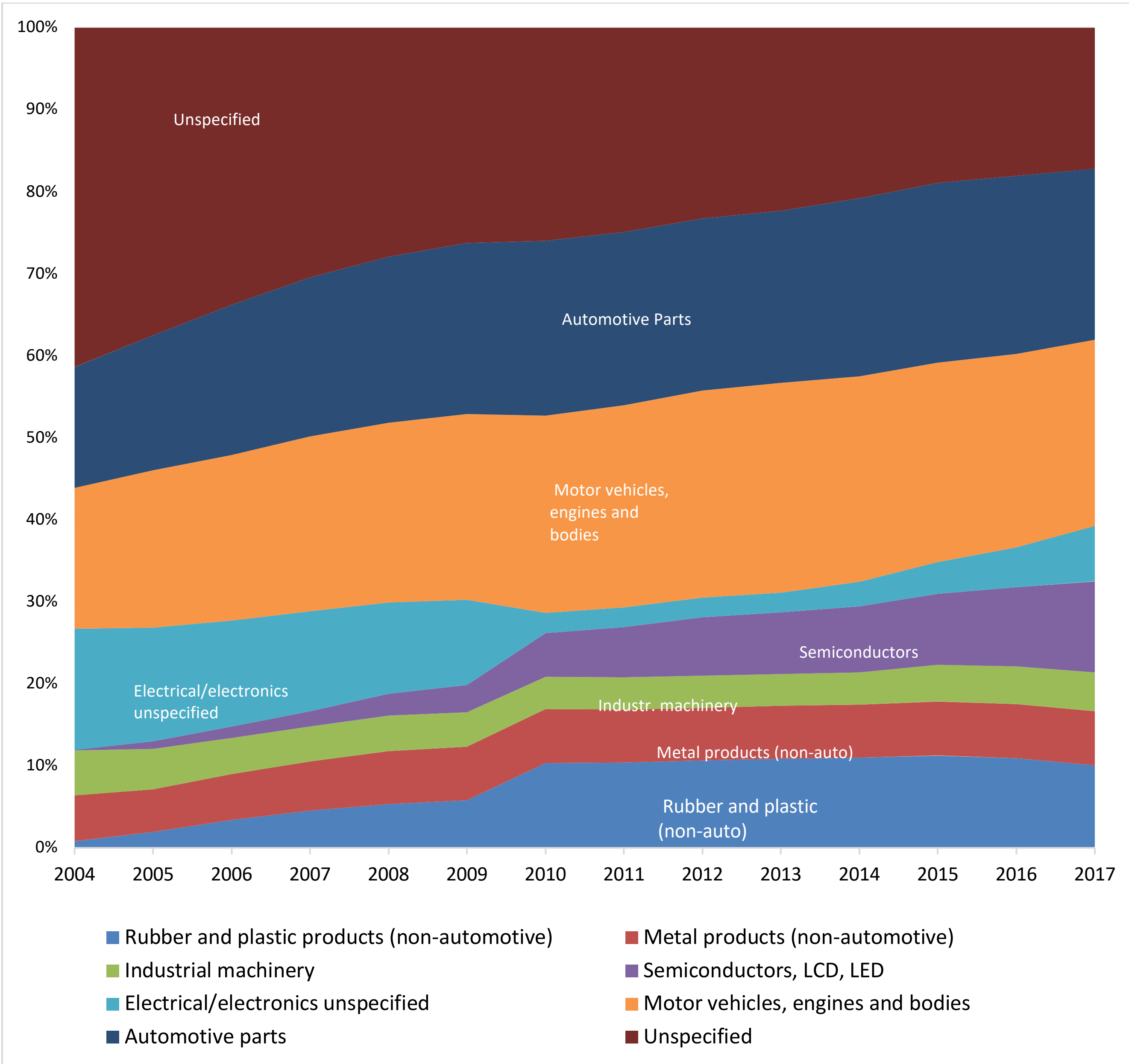
Industrial robots have evolved significantly, and they are one of the key digital production technologies of the 4IR (Andreoni and Anzolin, 2020). They are today defined according to ISO 8373:2012 as

"*an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications*".

Technological innovation in industrial robots has been mainly about increasing their ability to perform precision engineering complex tasks, connecting them into cyber-physical systems and use of industrial data for product and process improvements.

According to the International Federation of Robotics (IFR) dataset, there is a high sectoral concentration of industrial robots. A striking 99% of industrial robots are used in the manufacturing sector and, within manufacturing, the automotive sector makes up for more than 36% of total industrial robots, making it the first sector for industrial robots' adoption (IFR, 2018). The automotive sector, which is at the core of this study, has always been the bedrock of manufacturing automation advances due to its high-volume production, standardisation and modularisation that allow the production of different parts to be assembled. Indeed, it is within downstream assembly operations, led by large OEMs specialising in final assembly, that the majority of robots can be found. Figure 1 shows industrial robots' distribution among manufacturing sub sectors, including sub-sectors of the automotive sectoral value chain.

Figure 1. Industrial robots' distribution in the manufacturing industries (operational stock, 2004-2018)

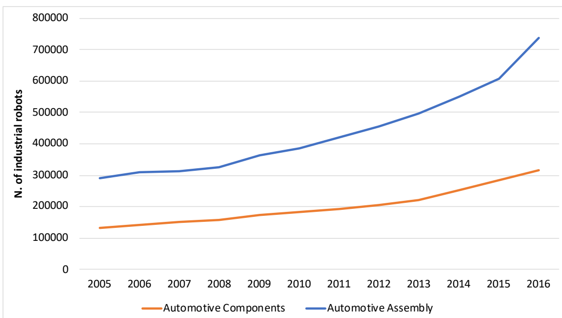


Source: Authors based on IFR

The deployment of these sophisticated, highly expensive and asset specific technologies is associated to the increasing concentration of market power, technological and financial capabilities of final assembly OEMs that act at the global level and produce high number of vehicles.

Figure 2 and 3 show the trend of FDI inflows and industrial robots' adoption for our two categories of Suppliers of Automotive Components and OEM[44] Automotive Assembly, aggregating the whole set of countries used for this analysis.

Industrial robots in the automotive sector 2005-2016



FDIs in the automotive sector (2005-2016)

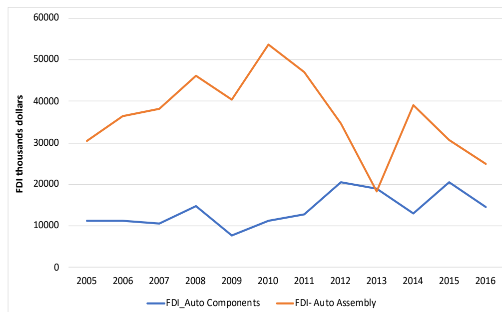


Figure 2 and 3. Source: Authors based on IFR and fDi Markets dataset

Looking at the success of the most recent experiences, both in terms of technology adoption and expansion of automotive national production, such as in Eastern European countries or Thailand (see Barnes et al., 2017 for Thailand; O'Shaughnessy 2007, for Czech Republic) it is evident how the importance of attracting big MNCs investments runs in parallel with the urgency of developing local suppliers with the capabilities to deal with, and respond to, final assembly OEMs requirements (Anzolin et al., 2020).

4. Data and Research Methods

This section provides information on (*i*) the two main datasets (*ii*) the key variables used in our analysis and some descriptive statistics

[44] In fDi market dataset Automotive OEMs is intended to be Automotive final assembly OEMs.

4.1 Sources of data

We used two main sources of data, the International Federation of Robotics (IFR) and fDi Markets. The former collects data on industrial robots, precisely it reports the number of industrial robots' applications from nearly all industrial robots' suppliers in the world (IFR, 2018). The IFR dataset provides insights on the number of robots per industry, country and year. The two main pieces of information provided by IFR are: (*i*) the number of robots (both in operational stock and in market delivery value) by sector and segment (i.e., further classification within the sector) up to three digits in ISIC rev. 4 classification; (*ii*) the type of application and sub-application (e.g., in the welding category there are laser welding, arc welding, spot welding, etc.). We will use the details offered by the first set of information on the automotive sector. This new dataset is the only available source about industrial robots, and it has been recently used in a number of publications, mainly focusing on the impact of robots on labour and at a higher level of sectoral aggregation (Acemoglu and Rastrepo, 2019; Graetz and Michaels, 2017).

fDi Markets is an online dataset built and maintained by the Intelligent Unit of the Financial Times. It compiles data on cross-border investment projects covering all sectors, specified in NAICS 07 classification[45], and countries worldwide. Out of more than 142000 observations of investment projects registered in 2003-2016, we use investments in the automotive sector, considering the two industry sectors Automotive OEM and Automotive Components. Among the numerous pieces of information that fDi Markets offers, we use destination_country, year, business_activity (intended as the functional activity) and sub_sector. Out of all business activities we used only Manufacturing, in order to provide further consistency with the first dataset where there are – by definition- only industrial robots applied in manufacturing activities.

The rich information on business_activities (including also R&D, Design Development and Testing, Sales and Marketing; see below for full array of functional activities used) is further used to build the instrumental variable technique in order to correct for

[45] https://www.fdimarkets.com/faqs/

endogeneity as explained below. The fDi market dataset has been used by UNCTAD to compile data on greenfield FDIs in the World Investment Report series and in a number of academic publications (Castellani et al. 2013, Crescenzi et al., 2014; Amoroso et Müller, 2017).

We focus on two specific segments (sub-sectors) of the automotive sectoral value chain. Through a matching table[46], we were able to combine data on robot adoption and inward FDIs in 34 countries with reference to the following two sectoral classes:
(*i*) Automotive Assembly which matches Motor Vehicle (291 in IFR) and Automotive OEM (in the fDi Markets dataset). We refer to this as **class 2910**.

(*ii*) Automotive Components which matches Auto parts (293 in IFR) and Automotive Components (in the fDi Markets dataset). We refer to this as **class 2930**.

We restrict our analysis to countries that have more than 500 industrial robots within their entire automotive sector for a total of 34 countries. See table A1 and A2 for a list of the countries included in our sample. We built a unique country level panel dataset on the automotive sector by matching our sources of data, covering the period from 2005 to 2016 for which data are available. The time span for data on robot adoption thus largely overlaps with the coverage of FDI data (2003-2017). Lags between the two data series will be utilised to reduce endogeneity problems (which are further dealt with by introducing an appropriate instrumental variable as specified below).

Although the two datasets are extremely rich in detailed information, they present some limitations. First, within the automotive classification of IFR data on industrial robots there are two unspecified classes, which are Unspecified AutoParts (class 2999) and Automotive Unspecified (class 299)[47]. While we were able to insert the former in our

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[46] ht*tps://www.census.gov › naics › concordances › 2007_NAICS_to_ISIC_4*
[47] We triangulated our information interviewing people responsible for the IFR in Germany. According to what they mentioned, we decided that the choice most pertinent to the data was not to include the 299 class in our specifications.

Automotive Components final class, the latter remains excluded from our model because we are not able to check if they belong to Auto Components or Auto Assembly[48].

A second limitation is due to the fact that up until 2010 the United States, Mexico and Canada were classified together as a single geographic aggregate by the IFR database, therefore in order to have an 11-year panel we used aggregate data for North America, thus encompassing the three countries for the entire period. Accordingly, our final sample is of 32 countries[49]. A third limitation refers to the nature of FDI data. On the one hand, fDiMarkets collects data on FDI projects monitored through press information and company reports. A possible source of bias is that a fraction of announced FDI projects may not take place. This drawback is partially dealt with by means of periodic checks by the FT unit in charge of double-checking the information provided and of removing information on projects that are not realised. On the other hand, as said, the dataset reports only greenfield investment projects, hence it does not monitor international investment operations that take the form of Mergers and Acquisitions.

4.2 Variables

The purpose of this paper is twofold. First, we intend to observe whether, and to what extent, FDIs drive the adoption of industrial robots in the automotive sectoral value chain with a focus on its two main segments. Our observations include the number of robots adopted by each country in the relevant sectors in each year of our panel, and the FDI flow measured in million dollars[50]. Second, we want to provide further information on other possible drivers that lead to industrial robots' adoption and that are related to other sectoral and country level characteristics that lead to the adoption of industrial robots. In this sense we use the following variables to proxy the readiness level of adopting industrial robots across different countries:

[48] We opted for this approach after an email correspondence with IFR personnel in Germany.
[49] 32 countries excluding Mexico, US, Canada and including North America.
[50] UNCTAD uses the same dataset and the same unit of measure (UNCTAD, 2019)

Patents. We use patents as a proxy for the innovativeness level of the destination country. Although patents could present some criticalities (Arundel and Kabla, 1998; OECD, 2009) they are widely used in the literature as a proxy for innovation (Acs et al., 2002; Dosi et al., 2015). Our source of data in this respect is the OECD Patent Statistics (Science Technology and Patents section) and the method used to link IPC[51] classes on the basis of an 'Algorithmic Links with Probabilities' approach developed by Lybbert and Zolas (2014). With the use of table concordances, we were able to match patents classification with our two industrial classes, Automotive Assembly and Automotive Components.

Export data. We use UN Comtrade dataset, which provides detailed information about exports following HS classification. We used data on export to proxy countries' competitiveness in the automotive sector (Doner et al., 2006; Hudakova, 2016). We followed Jetin (2018) contribution in detecting HS classes relevant for our analysis and we extended his classification in order to properly match our sources of data. The classes we used are: 8703 (motor cars and vehicle for transport of persons), 8706 (Chassis fitted with engines), 870710 (Bodies including cabs), which make up for class 2910 Automotive Assembly; 8708 (motor vehicles parts and accessories) and 940120 (seats) make up for class 2930 Automotive Components.

We include time and country fixed effects and a series of control variables that account for structural characteristics at the country level. We use OICA[52] data to control for **volume**, intended as the number of cars produced in each country of our dataset, as an indicator of industry size. Being characterised by high economies of scale, the number of cars produced gives an indication of the technological intensity of the sector and could possibly inform the dynamics of its local value chain (OECD, 2009). Production

[51] International Patent Classification

[52] International Organisation of Motor Vehicles Manufacturers, http://www.oica.net/production-statistics/

Volumes in fact are a crucial element as they have direct consequences on the suppliers and the different ways of production (see Mayes, 1996). An important additional control concerns the level of industrial development of each country, which we proxy by the **Employment share in manufacturing** and **Gross capital formation** based on World Bank data.

All variables are summarised in Table 1, with further specifications provided in the Appendix A. Table 2 provides summary statistics of our main variables. The variable **volume** presents less observations because Switzerland does not produce any motor vehicle (as it does not have any final assembly OEMs operating in the country) and thus it is not listed in the OICA dataset.

Table 1: List of Variables

Variable Name	***Description***	***Source***	***Classification***
N_Rob	Number of industrial robots in the Automotive Sectors divided in Automotive Motor Vehicle and Automotive Components.	International Federation of Robotics	*ISIC rev. 4*
FDI	Foreign Direct Investments measured in stock of inflow FDI in million $US. FDI are divided in Automotive Final Assembly OEM and Automotive Components.	fDi Markets dataset, Financial Times.	*NAICS 07*
Pat	Number of patents, whose IPC classes are matched with the two automotive segments through 'Algorithmic Links with Probabilities' approach (Lybbert and Zolas, 2014)	OECD Patents statistics – Triadic Patent families	*ISIC rev.4*
Exports	Export of different HS classes that relates to automotive bodies and components measured in million $US.	UN Comtrade	*HS classification*
Gross Fixed Capital Formation	Measured in Million $US	World Bank Data	*n/a*
Employment in Manufacturing	Share of people employed in the manufacturing sector out of the total amount of working population.	World Bank Data	*n/a*
Volume (produced)	Number of motor vehicles produced in each country	OICA	*n/a*

Table 2: Descriptive Statistics

Variable name	***Observations***	***Mean***	***Standard Dev.***	***Min***	***Max***
N_Rob	769	6057.046	13796.44	0	75924
FDI	769	1103.986	2087.179	0	14665.31
Pat	763	9.16452	27.94249	0	293.219
Exp_MillUS	769	14083.85	26010.67	108.231	161186.7
Gross Fixed Cap_Form	769	440850.2	871613.5	7834.047	4841477
Employm_share_manuf	769	2523502	4393846	16.227	40.526
Volume of car produced	744	25.9541	4.991809	2631	2.81e+07

4.3 Research Methods
OLS estimation

To investigate the impact of FDIs and other contextual variables (e.g., patents and exports) on the adoption of industrial robots we use a standard OLS model and regress the number of industrial robots on FDI, patents, export, and a vector of control variables. The econometric analysis consists of a standard OLS regression with time and country fixed effects where the dependent variable is the number of robots' applications per country, sub sector and year. Normalisation effects are coming from control variables in the model. The empirical fixed effects model is as follows:

$$IFR_{tcs} = \alpha + \beta FDI_{cs(t-1)} + \varphi Pat_{cs(t-1)} + \gamma Exp_{tcs} + \eta X_{tc} + \delta_t + \delta_c + \varepsilon$$

As aforementioned, Y corresponds to the number of industrial robots, FDI corresponds to inflow of FDI accounted in million dollars, Pat and Exp respectively corresponds to the number of patents and the value of export in million dollars. All these variables regard the automotive sector and specifically observations in a country *c*, at time *t*, in a segment *s*[53]. Then, we introduced a vector of control variables among which we include Volume of cars produced in each country, Employment share in manufacturing and

[53] There are 32 countries, 11 years considered and two segments of the automotive value chain (i.e., automotive assembly and automotive components).

Gross Fixed Capital formation. With the two latter variables we controlled for elements related to the industrialization and investment level of each country. In order to limit possible endogeneity due to reverse causality, in our baseline model we adopt the standard procedure of lagging the main independent variables (FDI and patents). We included time fixed effects to absorb the time variations and country fixed effects to control for unobserved heterogeneity across countries. Regressions without country fixed effects but including individual country dummies and other controls for industrialisation levels are reported in Appendix C as robustness checks, yielding no substantial differences in results.

IV estimation

Although we lagged FDIs by one year, endogeneity could still arise from potential reverse causality and from omitted variables, which could lead to biased results of the FDI coefficient undermining the causal relation we intend to prove between FDIs and industrial robots. On the one hand, reverse causality could arise due to the effects that industrial robot adoption may have on inward FDIs, by increasing the attractiveness of local industry for foreign investors. On the other hand, other country specific elements that cannot be captured with existing data may have an important role in our model thus causing omitted variable issues. We account for this issue adopting an Instrumental Variable (IV) approach that corrects for potential endogeneity bias.

We exploit the high level of granularity present in our dataset to develop an original sector specific IV. Our endogenous variable is FDI, which corresponds to all FDIs in the automotive sector that regard manufacturing activities. The information provided by the fDiMarkets dataset allows us to identify several other business activities, other than manufacturing, and we used them to build our IV[54]. We use FDIs in other activities

[54] The other activities are: Business Services Construction, Customer Contact Centre, Design, Development & Testing, Education & Training, Headquarters, ICT & Internet Infrastructure, Logistics, Distribution & Transportation, Maintenance & Servicing, Recycling, Research & Development, Sales, Marketing & Support, Shared Services Centre, Technical Support Centre.

(named FDI_other_activity) that are essentially pre- and post-production within the two automotive segments, Automotive Assembly and Automotive Components.

The intuition behind the construction of our IV is that FDI_other_activity (e.g., logistics) influence FDIs in manufacturing directly since FDIs are quite likely to co-occur and often co-locate in different business functions that complement one-another, and in fact they are highly correlated (see first stage regression reported in the Appendix B – Figure A1). Instead, they cannot have any impact on the adoption of industrial robots, our dependent variable. A direct link between our IV and our dependent variable is prevented by the fact that industrial robots are used exclusively in manufacturing activities, differently from other type of service robots (logistics, distribution, sales, training, R&D, etc.)[55] that are used in pre and postproduction activities.

It is possible that, for example, BMW invests in an industrial robot for R&D purposes but, since we are considering greenfield investments, this would necessarily pass through an investment in the shop floor -thus in manufacturing, our endogenous variable. Indeed, it is very unlikely that a company decides to undertake a greenfield investment in R&D (or any pre and post-production activities) that includes an industrial robot without the manufacturing plant nearby. To reinforce our hypothesis, we analysed the 'description' category of fDiMarkets for FDI_other_activity that gives an explanation of the type of investment. Description is available for 77% of the FDI_other_activity recorded (which are 3720) and in none of them there is any reference to an investment in robots. A final note about the case in which a company producing robot technologies, e.g. KUKA, invests in an industrial robot for R&D, the sectoral classification of the FDI would be different, i.e. it would not enter Automotive class but rather Industrial Machinery, Equipment & Tools class.

[55] The International Federation of Robotics developed a different dataset for service robots where other types of activities are involved.

5. Results

The analytical investigation of the relationship between FDIs and robotisation is structured in two main steps; first, some descriptive statistics data on the relationship between industrial robots and FDIs in two segments of the automotive value chain (i.e., Final assemblers and Components) are presented. Second, we perform the econometric analysis in order to answer to the main research question. By doing so we aim at capturing first the heterogeneous rate of robotisation across different countries and segments of the automotive value chain; and second how they have followed different patterns over the last two decades.

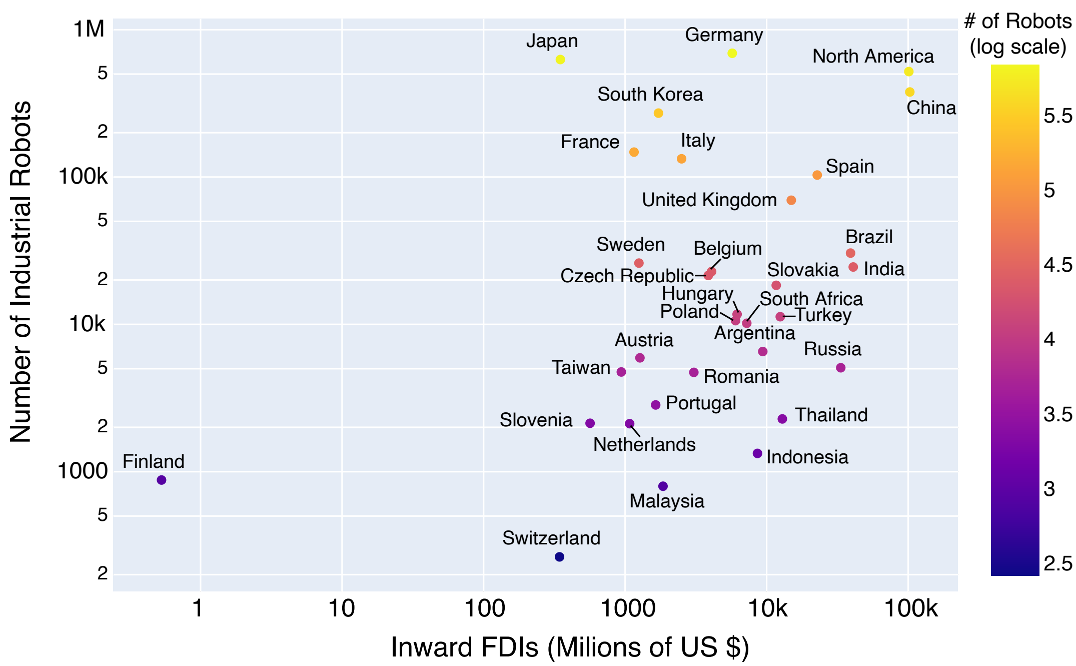
5.1 Statistical evidence

We conducted our first comparative analysis at two levels of disaggregation and used descriptive statistics to show the relationship between FDIs inflow and industrial robots adoption within the two segments 2910 (Automotive Final Assembly) and 2930 (Automotive Components). Figure 4 and 5 present the distribution between industrial robots in these two segments and inward FDIs.

Our aim is to show how different countries are placed differently according to the automotive segments each graph refers to. While it is not surprising to find the biggest automotive players in the top right quadrant, with these graphs we aim to emphasise the different position of developed, emerging and developing countries between the Assembly and the Components segments.

Figure 4 illustrates the distribution of FDIs at the OEMs level; we use the sum of inward FDIs between 2005 and 2014 and the stock of industrial robots in the same time frame. Although the lack of strong correlation is an interesting finding *per se*, as it points to high heterogeneity even for the assembly segment of the automotive sector, interesting patterns emerge once these scatterplots are divided into quadrants.

Figure 4. FDI and Industrial Robots in the Automotive Assembly Segment



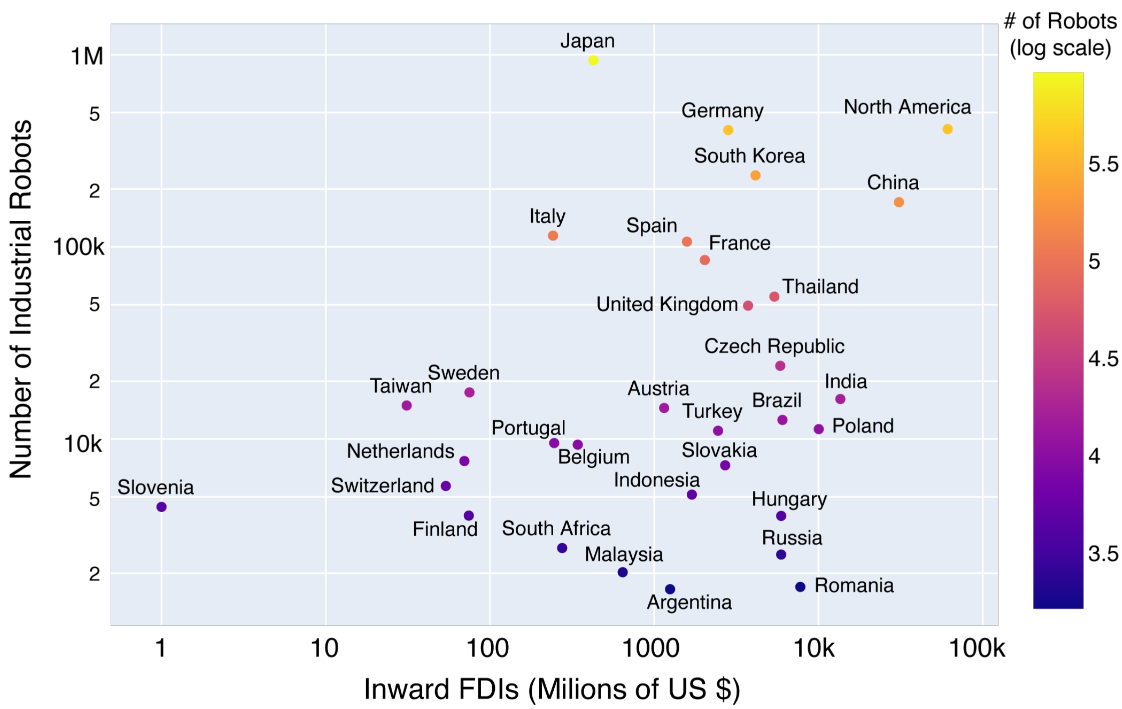
Source: Authors based on IFR and fDi Markets data, 2005-2017 data.

At the top of Figure 4, there are either industrialised countries or fast industrialisers: the upper left quadrant includes developed economies, which have a strong presence of industrial robots in their automotive industry but do not attract a high number of FDIs (e.g., Japan, France, Italy). Interestingly these are all countries that undertook important transformation plans to shift their entire economy towards automated production. If we look just at the automotive sector, this occurred despite a relative lower number of FDIs if compared to developed countries on the top right quadrant. Instead, in the upper right quadrant one finds countries where the increasing number of FDIs seems to be correlated more with the increase in robot's adoption[56].

[56] The way in which countries are disposed within the graph is also influenced by whether countries have or not a national industry or foreign ownership industry. Robotics data are not divided according to whether they are a foreign direct investment or a local investment, otherwise we could have found even more precise relations between FDIs and industrial robots' adoption.

These are countries that either have a long tradition in the sector and still play a pivotal role attracting FDIs (e.g., United Kingdom and Spain) or they are big attractors of FDIs and rapidly industrialising countries (e.g., China, Mexico within North America, and to some extent Brazil). In the bottom part of the graph there are both developed countries with a modest automotive sector and emerging economies, such as the Eastern European countries, linked up to the German automotive value chain. Dynamic economies such as Thailand, Turkey, Russia and India are also present in the right part of the graph, thus showing both a relatively high degree of attractiveness for FDIs and a general upgrade of the OEMs-related production processes (especially Turkey); these are countries growing a lot as a result of policies that encourage the development of the automotive sector as well as opening doors to FDIs (Barnes and Black, 2017).

Figure 5. FDI and Industrial Robots in the Automotive Components Segment



Source: Author based on IFR and fDi Markets data, 2005-2017 data.

Automotive components distribution across countries is presented in Figure 5. Within the top quadrants (i.e., with a large number of robots), as expected, we find industrialised countries with a highly developed automotive sector. Among emerging economies in the upper quadrants, the only case (apart from China) is Thailand, which is catching up quickly, also as a result of a new and dynamic automotive sector (Deloitte, 2019). This example could indicate that Thailand was not only able to attract an important number of FDIs, but it has also been able to channel them in the direction of technological diffusion and upgrade via development of supply chains of components producers (Sadoi, 2012). Other countries, such as India, Brazil and Russia received more FDIs than Thailand, but their respective auto components segments use fewer industrial robots (IFR, 2015).

A final consideration on these first graphs is that the better position that Thai components' segment has vis a vis its OEMs one (previous graph) is an element that suggests the presence of an important system of local suppliers. Differently, taking as an example the sluggish position of South Africa's auto components, it confirms the low number of suppliers' activities both in terms of international activities (FDIs) and in terms of local technological pull (Black et al., 2017).

5.2 Econometric analysis

The econometric analysis is divided in two parts corresponding to two separate albeit complementary levels of analysis. The first part considers the automotive sector as a whole, while the second part focuses on two sub sectors (i.e., Automotive Assembly and Automotive Components).

In Table 3 we estimate different models in order to see how our main variables change when more elements are considered with reference to the entire automotive industry (with no within-sector disaggregation). The first important result is that one-year lagged FDIs do not play a significant role in robots' adoption in all estimation results. Our IV technique (as reported in column 7) confirms these findings. Columns from 2 to 5 report the estimated regression coefficients of simple specifications where we progressively added our main independent variables in order to observe how coefficients change. Specifically, column 5 displays the regression coefficients from a full specification that considers the effects of our main independent variables and the full vector of control variables.

Lagged patents are positive and statistically significant, the increase of one patent corresponds to 42 more industrial robots and, similarly, $US 1 million more in automotive export leads to 0.2 industrial robots more. Moreover, in columns (3) and (5) we included the interaction between FDI and patent variables in order to shed further light on the relationship that FDIs may have when undertaken in the presence of innovation capacity. Results are strong and significant pointing in the direction of a positive relationship between FDIs interacted with patents and the adoption of industrial robots. Interestingly, if we consider column (3) and we assume a value of 10 for patents, the marginal effect of FDIs would be positive. In all specifications with the interacted term, this is highly statistically significant confirming what already found in the literature about the importance of absorptive capacity in order to technologically benefit from FDIs (Zanfei, 2012; Pavlinek and Zizalova, 2014 on the automotive sector). The positive effect of patents and export on the adoption of industrial robots could indicate that the gap between the ecosystem of the host-country and the FDI is less significant, consistent with Glass and Saggi (2002), Kokko et al. (2001), and the idea that higher levels of human capital in the host country are associated with larger spillovers (Iršová and Havránek, 2013).

We repeated our estimation with the IV technique (column 5). Using the 2SLS approach, the results are confirmed showing positive and statistical values of patents and export, thus providing evidence on the key role played by the industrial ecosystem of the host-country. Lagged patents confirm to be high, positive and statistically significant thus being the most relevant indicator for the adoption of industrial robots in the automotive sector. In all our specifications we kept country and year dummies with standard errors clustered at the sectoral (e.g. the two segments of the automotive industry) and country level.

Table 3. Determinants of robot adoption in automotive industry

	Y =N_Rob OLS	Y =N_Rob OLS	Y =N_Rob OLS	Y =N_Rob OLS	Y =N_Rob OLS	Y =N_Rob OLS	Y =N_Rob IV	Y =N_Rob IV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
FDI_t-1	-0.056	-0.050	-0.222	-0.117	0.004	-0.107	0.194	0.147
	(0.134)	(0.138)	(0.133)	(0.105)	(0.121)	(0.102)	(0.213)	(0.224)
Pat_t-1		38.239*	39.857	36.717	42.117**	36.502	45.096**	42.528**
		(22.119)	(27.143)	(29.425)	(21.702)	(28.118)	(23.042)	(20.817)
FDI*Pat			0.021***	0.018***		0.015***		
			(0.006)	(0.005)		(0.005)		
Exp_MillUS				0.195***	0.136*	0.191***	0.15**	0.137*
				(0.036)	(0.076)	(0.037)	(0.073)	(0.073)
Gross Fixed Cap_Form					0.007***	0.005**		0.007***
					(0.002)	(0.002)		(0.002)
Employm_share_manuf					-141.511	-102.227		-148.33
					(170.781)	(162.749)		(164.423)
Volume_lead					0.0002	0.00003		0.0002
					(0.0008)	(0.0001)		(0.0007)
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R squared	0.82	0.82	0.80	0.84	0.86	0.88	0.86	0.88
F value							20.47	17.35

*Standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The F values for the validity of the instrument are the Kleibergen-Paap rk Wald F statistics and the values are above the 10% critical value.*

The second part of our analysis, displayed in Table 4, presents similar estimation models performed with a further level of disaggregation of our variables. The high disaggregation of our data allows us to make a further step in trying to analyse if, and to what extent, there are any differences across segments of the value chain of the automotive industry. We disaggregated FDIs, patents and export in two classes, 2910 that corresponds to Automotive Assembly, and 2930 that corresponds to Automotive Components.

Our estimation results are mixed at the sub sectoral level. Columns 1 to 4 of Table 4 present OLS estimations following the same procedure as in Table 3. The impact of FDIs on Automotive final assembly is positive in all specifications, while they are negative for the Automotive Component segment; however, in none of the segments their effects are significant for the adoption of industrial robots. Patents are not significant for Automotive Assembly, while they are highly significant in the case of Automotive Components. FDIs play a role only when companies in the host-country are involved themselves in technology and innovation efforts. The level of automotive export of the host-country has a positive and significant impact for the adoption of industrial robots in both segments, being higher in the case of Automotive Components.

In column 4 we repeated the full specification adding the variable constructed by interacting FDIs and patents as above, maintaining the disaggregation for the two automotive segments. Interestingly, FDIs play a role when interacted with patents just in the case of Automotive Assembly, while the interaction creates a composite effect for Automotive Components cancelling off both the effects of patents and FDI interacted with patents. This confirms our hypothesis that patents, which better reflect the technological capabilities of each country, are the crucial variable for the adoption of industrial robots.

When we turned to our 2SLS estimation model, we could use the same type of IV, disaggregated for our two segments, which confirm our OLS results. Even at the disaggregated level, we find that patents and export, therefore the innovativeness and export competitiveness of countries in the automotive sector, play a stronger role for technology adoption. FDIs appear to have a positive and significant impact on robot adoption in the assembly stage of automotive value chain, but only when combined with sufficiently high technological competencies held by local suppliers in the host country. As we shall argue in the discussion section below, this heterogeneity in the results reflects differences in technology adoption patterns across different segments of the automotive value chain (Banga, 2014; Andreoni and Tregenna, 2020).

Table 4. Determinants of FDIs in two segments of the automotive industry

	Y =N_Rob *OLS*	***Y =N_Rob*** *OLS*	***Y =N_Rob*** *OLS*	***Y =N_Rob*** *OLS*	***Y =N_Rob*** *IV*
	(1)	(2)	(3)	(4)	(5)
FDI_t-1 **2910**	0.069 (0.206)	0.140 (0.183)	0.143 (0.168)	0.020 (0.137)	0.359 (0.351)
FDI_t-1 **2930**	-0.115 (0.154)	-0.045 (0.137)	-0.073 (0.142)	-0.183 (0.139)	0.035 (0.302)
Pat_t-1 **2910**		28.624 (24.046)	29.835 (22.053)	18.654 (15.917)	30.439 (21.200)
Pat_t-1 **2930**		49.150** (22.887)	46.634** (21.908)	75.292 (60.461)	46.755** (21.102)
FDI*PAT **2910**				0.017*** (0.003)	
FDI*PAT **2930**				0.005 (0.014)	
Exp_MillUS **2910**		0.226*** (0.045)	0.192*** (0.045)	0.224*** (0.048)	0.193*** (0.044)
Exp_MillUS **2930**		0.381*** (0.119)	0.296** (0.119)	0.260* (0.140)	0.300*** (0.115)
Gross Fixed Cap_Form			0.006*** (0.001)	0.005*** (0.001)	0.006*** (0.011)
Employm_share_manuf			-148.206 (459.669)	-92.538 (101.597)	-152.245* (89.235)
Volume_lead			0.0003 (0.0001)	0.0003 (0.0001)	0.0003 (0.0001)
Dummy_sector2	-807.87* (451.858)	-386.447 (516.550)	-146.029 (459.699)	-51.08 (460.40)	-75.028 (540.215)
Time fixed effects	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes
R squared	0.82	0.84	0.86	0.88	0.88
F value					5.608

*Standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Legend: 2910 = Automotive assembly; 2930 = Automotive components. The F value for the validity of the instrument is the Kleibergen-Paap rk Wald F statistic and the value is above the 15% critical value.*

6. Discussion

The automotive sector is characterised by specific dynamics that influence the distribution of its international activities. The length and complexity of the automotive value chain, alongside the development of production and technological complementarities, allowed countries involved in the automotive sector to achieve several goals, in terms of industrial development and broader socio-economic achievements. Against this backdrop, FDI is an essential part of international economic system and potentially a crucial catalyst for economic growth. This is related to the fact that MNCs play a key role in the transfer of knowledge and technology (Dunning, 1996; Cantwell, 2017, Papanastassiou et al., 2020).

Yet, the beneficial impact from FDIs does not happen automatically and it is not homogenous across countries and sectors. Moreover, the impact of other country and sector specific factors is crucial in explaining robot adoption directly and indirectly. Our analysis showed that:

(1) FDIs *per se* do not significantly impact on robot adoption in neither the assembly nor in the component segments of the automotive industry[57];

(2) FDIs have a positive and significant impact when combined with high innovative capacity in the host economy, but only in the assembly segment of the industry;

(3) other factors characterising the local eco-system such as innovation capacity and export competitiveness (for any given level of FDIs) play a greater role in the component segment of the industry.

[57] Our finding takes into account the fact that an important part of what happens in the robotization dynamics within the automotive sector depends on investments that are led by national firms. We found that the local ecosystem is of crucial importance, and within the local ecosystem there is a central role played by national firms.

These results reflect the different structural and behavioural characteristics of these two segments of the industry, which in turn affect the role played by FDIs and by the local eco-system in technology adoption.

In the *automotive assembly segment*, which is dominated by large MNCs, FDIs is directed to support production operations such as welding, pressing and painting which, in most of the cases, cannot be performed competitively without high levels of robotisation. This implies that MNCs active in automotive assembly largely rely on fully automated production processes, hence exerting a direct positive effect on robot adoption in the countries where their plants are located. This positive impact of FDIs in the assembly segments can be reinforced by the competitive pressure on local automotive manufacturers (if present), which may be induced to respond by purchasing the same cutting-edge robot technology (indirect positive effect via competitive pressure on local automotive makers to innovate).

A further reinforcing mechanism is the creation of backward linkages by MNCs active in the assembly segment that may resort to local suppliers of parts and components, often requiring them to meet high level technical and production standards (see Freyssenet and Lung, 2000 for the effect of standardisation process on developing countries). Meeting these standards may well drive robotisation among local firms. This indirect positive effect of FDIs (via induced robot adoption by local suppliers) is highly demanding in terms of technological and organisational competencies of local firms.

These positive (direct and indirect) impacts of FDIs in the assembly segment on robot adoption in recipient countries, can be at least partially compensated by crowding out effects, hence reducing the demand for robots by displacing local car makers and other automotive manufacturers (if present).

In addition, FDIs in the assembly segment may be accompanied by a substantial increase of imports of automotive parts and components and may even attract foreign first-tier investors active in the automotive component segment (through a follow the leader mechanism), thus crowding out local suppliers if not qualified. This negative indirect effect (via market stealing and displacing of local competitors and suppliers) is most likely to occur if FDIs mainly pursue market seeking objectives and if local suppliers compete on price rather than on innovation (Sturgeon et al., 2008; see Barnes et al., 2017 for evidence on these patterns in the South African case).

Consistent with this line of argument, our results suggest that the positive effects prevail in the case of FDIs in the assembly segment, with a particular importance of the indirect impact via competitive pressure on local automotive manufacturers and via the creation of backward linkages and demand of high-quality components. Both of these indirect effects are likely to take place only in the presence of a lively local eco-system, characterised by dynamic and innovative firms and institutions. In fact, the role played by this combination of FDI effects and of local innovation capacity is broadly confirmed by our findings in Table 4, showing that robot adoption is positively and significantly affected by the interacted term FDI*patents in the assembly segment.

If we now turn to the upstream segment of the automotive value chain, it is worth mentioning that *component manufacturers* (from large first tier international suppliers, to lower-level tiers of domestic suppliers) are very heterogeneous players. Their outlets range from hyper-specialised worldwide quasi-monopolistic niches to national and regional markets for broader varieties and variants of automotive components, wherein oligopolistic rivalry prevails. Such suppliers take their decisions to automate production processes according to a number of parameters, including capital expenditure considerations, the organisational opportunity (and potential capability challenges) to adopt a new technology, and the specific production requirements and product standards they have to comply with. Hence robot adoption in the case of component suppliers is very much dependent on innovation capacity and on the competitive pressures in both domestic and international markets. This is consistent with our results in Table 4 showing that robot adoption in the component segment is positively and significantly affected by host countries' patents and by exporting, as measures of local innovativeness and competitiveness. This interpretation is also in line with the recent GVC literature (Kano et al., 2020) that sheds light on the importance of local capabilities to be able not only to link up to GVCs but also to climbing up the value-added content of what is produced (Banga, 2014; Andreoni and Tregenna, 2020).

By contrast, FDIs in the automotive component segments are most likely to be associated with market stealing effects. In fact, international suppliers investing in a country might easily crowd out national suppliers that are competing in the same market, at least for low and intermediate levels of innovativeness of the local eco-system. Hence the positive direct effect of FDIs in this segment, determined by the purchase of robot by MNCs specialised in component manufacturing, will probably be compensated by the indirect negative effect due to the exit of local suppliers. This interpretive line is broadly consistent with our results, as the interactive term FDI*Patents turns out not significant in the automotive component segments in Table 4.

To conclude, by narrowing down our analysis to a specific industrial sector and a specific type of technology, we found that the role of FDIs is not a determinant of this type of technology adoption *per se*, rather it becomes significant only when interacted with our proxy for innovation capacity. This confirms what already found in the literature, that effect of FDIs on technological upgrading is considerably stronger among those endowed with higher levels of capabilities and thus absorptive capacity (Kemeny, 2010). We also contribute to extant literature, by showing how different segments of the automotive value chains are characterised by distinctive technology adoption patterns. This sectoral focus is per se relevant as the automotive industry provides a major contribution to GDP, employment and industrial spillovers (Irandoust, 1999). Our findings reveal that FDIs, which are considered a major source of economic growth opportunity, could actually trigger local industrial robots' adoption only when there is already an existing set of elements such as innovation capacity and export competitiveness.

7. Conclusion

This essay examines the relationship between inward FDIs and industrial robots' adoption, disaggregating the automotive sector and looking at how FDIs and industrial robots are distributed across different segments of the value chain. The granularity of our data permits to innovatively develop a pioneering analysis on the role played by FDIs in the adoption of industrial robots in the automotive sector. We also considered possible other channels through which industrial robots' adoption can happen, namely the innovativeness and competitiveness of the industrial ecosystem. Due to the high-level disaggregation of our data, we presented results on how these mechanisms work along different segments of the value chain.

Consistent with an extensive literature (Findlay 1978; Kokko 1994; Blomstrom and Wolff 1997; Meyer and Sinani, 2009, Castellani et al., 2016), we find that FDIs in automotive do not have a significant effect *per se,* and their impact is positive only if combined with sufficient innovation capacity in the host economy. When disaggregating at different segments of the value chain, the combination of FDIs and local innovativeness has a positive and significant impact only in the case of automotive assembly. Other context specific factors reflecting the level of innovativeness and competitiveness of the local eco-system play a greater role in the case of component manufacturing than in the automotive assembly segment. These findings shed some light on how technology adoption dynamics differ along different segments of the value chain. Our results open for a new stream of research that goes beyond the existent empirical literature on the new technologies, which remains at the macro level and mainly focusses on the impact of robotics on labour. We have highlighted the importance of studies at a fine-grained sectoral level, which might help disclose hidden dynamics and yield interesting insights that are difficult to grasp at an aggregated level. We attempt to investigate this line of analysis in Essay III looking at the determinants of technology adoption in the automotive sector in South Africa through a series of semi-structured interviews, whose details helped in better understanding the microeconomic dynamics at the firm level.

At the policy level, an increasing number of countries is focusing on the design and implementation of innovation policies to adopt and foster new technologies. Our paper points to the necessity of building up local basic productive capabilities that serve as a key factor in order to then adopt and use new types of technologies (UNIDO, 2020; Andreoni et al., 2021). This is likely to be particularly important and demanding for emerging countries as a key to the adoption of new digital technologies and to upgrade their role in GVCs. Further sectoral and technology specific research is needed in order to disentangle technology adoption dynamics, as a crucial aspect for the future, and to explore national and regional patterns of digital transformation in greater details.

Appendix A - On data

Table. A1. FDIs in thousands of US dollars for two segments of the automotive value chain.

Country	FDI_Automotive Components	FDI_Automotive Assembly
Argentina	1,240.52	7,838.55
Austria	1,148.76	1,272.57
Belgium	200.760	4,036.12
Brazil	5,538.31	38,359.10
China	29,419.83	102,516.38
Czech Republic	5,365.29	3,869.7
Finland	74.3	0.53
France	1,892.15	983.58
Germany	2,699.63	3,817.17
Hungary	5,637.48	6,031.66
India	12,746.89	39,659.91
Indonesia	1,654.22	8439.9
Italy	169.35	2,384.89
Japan	242.43	348.83
Malaysia	576.96	1773
Netherlands	69.84	1076.8
North America	55,638.74	92,338.11
Poland	9,485.28	6,127.62
Portugal	235.45	1,644.1
Romania	7,494.44	3,059.6
Russia	5,692.70	31,721.26
Slovakia	2,420.04	10,448.36
Slovenia	n/a	358.07
South Africa	275.06	7,224.38
South Korea	4,054.40	1,720.48
Spain	1,304.27	20,947.99
Sweden	75	1,027.2
Switzerland	23.3	343.9497
Taiwan	31.1	940.1
Thailand	5,257.01	12,684.37
Turkey	2,181.89	12,431.86
United Kingdom	3,609.27	14,207.51

Table A2. Number of robots adopted in two segments of the automotive value chain

Country	N_robots Automotive Components	N_robots Automotive Assembly
Argentina	1,312	5,112
Austria	12,636	4,359
Belgium	8,192	19,178
Brazil	10,018	25,246
China	51,121	157,531
Czech Republic	18,641	17,569
Finland	3,249	819
France	78,792	138,895
Germany	328,890	563,755
Hungary	2,973	7,654
India	7,281	23,425
Indonesia	492	155
Italy	98,378	125,865
Japan	794,381	527,497
Malaysia	894	409
Netherlands	6,163	1,498
North America	331,119	435,488
Poland	10,457	8,505
Portugal	6,639	1,944
Romania	1,257	3,586
Russia	2,080	4,615
Slovakia	5,748	14,242
Slovenia	3,479	1,659
South Africa	2,181	7,822
South Korea	185,087	221,759
Spain	99,254	94,396
Sweden	15,215	22,094
Switzerland	4,878	223
Taiwan	4,461	1,186
Thailand	1,677	82
Turkey	8,318	9,158
United Kingdom	44,539	62,340

Appendix B - On the 2SLS.

Table A3. First-stage regressions of IV models reported in Table 3.

Y: FDI t-1	First stage	First stage
	(1)	(2)
FDI_other_activity	6.256***	6.294***
	(1.382)	(1.511)
Pat_t-1	-2.302	-2.373*
	(1.180)	(1.231)
Exp_MillUS	-0.003	-0.003
	(0.003)	(0.003)
Gross Fixed Cap_Form		0.0003
		(0.000)
Employm_share_manuf		4.00
		(39.531)
Volume_lead		-3.42
		(0.799)
Time fixed effects	Yes	Yes
Country fixed effects	Yes	Yes
R squared	0.34	0.34

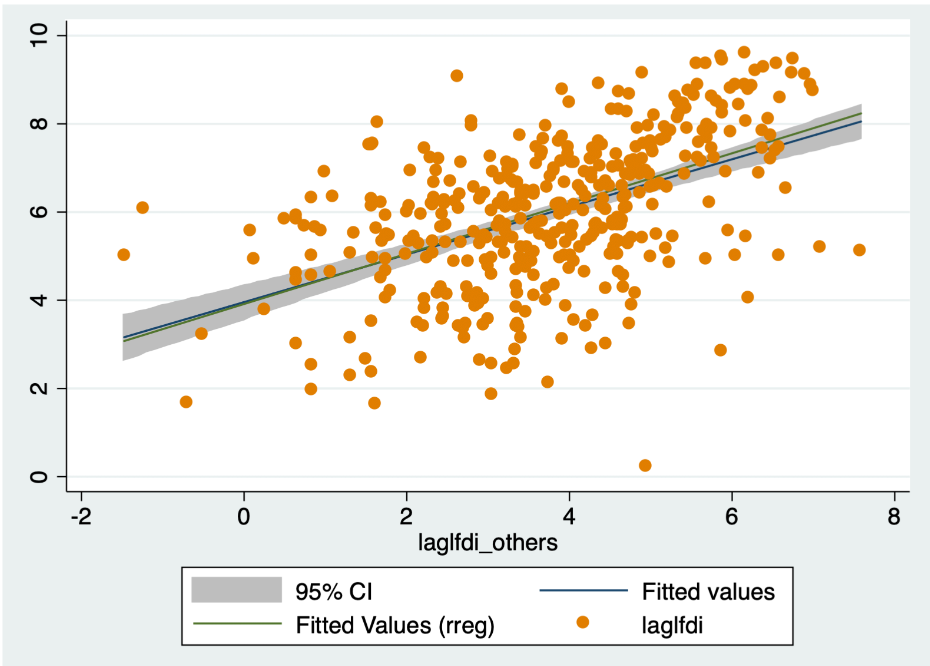
Standard errors in parentheses *** p < 0.01, ** p < 0.05, * p < 0.1

Table A4. First-stage regressions of IV models reported in Table 4.

Y: FDI t-1	First stage	First stage	First stage	First stage
	(1)	(1)	(3)	(4)
	2910	**2910**	**2930**	**2930**
FDI_other_activity	9.656***	9.145***	5.757***	5.750***
	(1.611)	(1.6040)	(1.499)	(1.613)
Pat_t-1	-1.50	-2.286	-1.961	-2.377
	(1.315)	(1.324)	(1.643)	(1.630)
Exp_MillUS	0.003*	0.0001	0.132**	0.136**
	(0.001)	(0.001)	(0.005)	(0.000)
Gross Fixed Cap_Form		-0.00005		-0.00004
		(0.00008)		(0.000008)
Employm_share_manuf		12.097		4.149
		(29.294)		(35.463)
Volume_lead		-2.28		-2.24
		(0.00001)		(0.00001)
Time fixed effects	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes
R squared	0.44	0.45	0.38	0.37

Standard errors in parentheses *** p < 0.01, ** p < 0.05, * p < 0.1

Figure A1: Scatterplot correlation of first-stage regression.



Lines are fitted by OLS regression. Vertical axes: lagged FDI in automotive manufacturing activities. The slope coefficient is 0.5 with robust standard error 0.05; the t-statistic, F-statistic and R-squared are 10.66, 113.65, and 0.24, respectively.

Appendix C - Robustness check

We conducted a robustness check, controlling for the level of countries' industrialisation. Specifically, instead of controlling for country fixed effect, we divided the countries into four categories: emerging, industrialised, Eastern Europe and China. In doing so, we adopted a revised UNIDO classification of industrialised and emerging economies, which considers China as a category in itself (see Teng and Lo, 2019[58]). Moreover, due to specificities related to the automotive sector, we decided to isolate Eastern Europe.

[58] "Determinants of Developing Countries' Export Upgrading: The Role of China and Productive Investment", Working Paper No. 227/2019 SOAS Department of Economics, https://www.soas.ac.uk/economics/research/workingpapers/file142705.pdf

TABLE A5. Robustness Check (*i*)

	Y =N_Rob OLS	Y =N_Rob OLS	Y =N_Rob IV
	(1)	(2)	(3)
FDI_t-1	-0.98	-0.087	0.519
	(0.221)	(0.100)	(0.427)
Pat_t-1	199.34**	63.725	124.687*
	(68.828)	(41.859)	(66.452)
FDI*Pat		0.0073	
		(0.007)	
Exp_MillUS		0.312***	0.301***
		(0.029)	(0.037)
Gross Fixed Cap_Form		0.0009 (0.001)	0.002 (0.001)
Employm_ share_manuf		282.974* (113.257)	382.948** (150.571)
Volume_lead		0.0002* (0.0001)	0.0003* (0.0001)
Emerging	1467.144*	3706.637***	4520.099**
	805.3781	(1384.468)	(1822.032)
Industrialised	7872.169*** 3690.908	4940.061 *** (1469.493)	5642.212*** (2095.563)
dummy_China	8043.545 * 2103.426	3028.607 (4723.087)	-1725.137 (5659.732)
Time fixed effects	Yes	Yes	Yes
Country fixed effects	No	No	No
R squared	0.26	0.77	0.74
F value			16.73

Standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The F value for the validity of the instrument is the Kleibergen-Paap rk Wald F statistic and the value is above the 10 per cent critical value.

TABLE A6. Robustness Check (*ii*)

	Y =N_Rob OLS	Y =N_Rob OLS	Y =N_Rob IV
	(1)	(2)	(3)
FDI_t-1 2910	-0.300 (0.382)	-0.0400121 (0.115)	0.463 (0.341)
FDI_t-1 2930	-0.187 (0.230)	-0.181 (0.14)	0.338 (0.452)
Pat_t-1 2910		18.080 (14.735)	41.721** (17.790)
Pat_t-1 2930		135.6542 (83.943)	150.142*** (37.442)
FDI*Pat 2910		.0126*** (0.003)	
FDI*Pat 2930		-0.004 (0.013)	
Exp_MillUS 2910		0.323*** (0.018)	0.332*** (0.171)
Exp_MillUS 2930		0.391*** (0.071)	0.519*** (0.070)
Gross Fixed Cap_Form		.0001 (0.0012)	0.0005 (0.001)
Employm_share_manuf		265.383*** (55.080)	336.60*** (62.374)
Volume_lead		0.0002** (0.0001)	0.0003*** (0.0001)
Emerging	8.735758 (204.6036)	3668.114*** (789.120)	4506.494*** (789.082)
Industrialised	8658.485*** (804.6494)	4532.883*** (699.184)	5011.644*** (788.577)
Dummy_China	7564.867*** (1849.799)	4483.073 (3379.577)	2742.778 (3147.508)
Dummy_sector 2	-884.363 (1016.92)	-373.944 (446.806)	-641.017 (629.512)
Time fixed effects	Yes	Yes	Yes
Country fixed effects	No	No	No
R squared	0.11	0.79	0.76
F value			5.23

Standard errors in parentheses *** p < 0.01, ** p < 0.05, * p < 0.1. The F value for the validity of the instrument is the Kleibergen-Paap rk Wald F statistic and the value is above the per cent critical value.

Essay III

Opening the black box of technology adoption: a study on the drivers of automation in the South African automotive sector.

1. Introduction

During the past years technological innovations reached exceptionally sophisticated levels, unthinkable just some decades ago. These rapid technological improvements contributed to raise concerns on whether this new wave of innovations presents such strong peculiarities to justify the idea of a disruptive, rather than incremental, fourth industrial revolution (Dosi and Virgillito, 2019; see Essay I for a discussion on this).

If technology is at the heart of economic growth (Mowery and Rosenberg, 1990; Chang, 2002; Çalõúkan, 2015), and if the mechanisms behind the diffusion and adoption of new technologies are of fundamental importance - as discussed in Essay I - it becomes then crucial to study the determinants of technological innovation – which we also call and intend as technological adoption.

Unfortunately, despite a considerable hype around the analysis of the latest forms of technological change, and their effects on productivity, there is little effort in studying how technological change happens and what the determinants of its adoption are. Moreover, this great hype overlooks the realistic space and opportunity to actually adopt these technologies, which are country, sector and firm specific.

In the attempt of contributing to a growing field of literature that tries to bridge new technologies' dynamics, on the one hand, and sectoral diffusion and application, on the other hand, this essay is focussed on the analysis of the specific drivers that leads to technology adoption.

More specifically, in this study we looked at technological change - intended as process innovation - in the automotive industry in the South African context, and its interdependency between process innovation and organizational change. The focus on South Africa imposed to enrich our analysis with the perspective of a fast-emerging economy, thus shedding further light on the relationship between technology adoption and industrialisation, with reference to a country that is highly integrated in the global automotive value chain. The characteristics of such integration have an influence on the types of technologies that are introduced - especially but not exclusively in foreign firms - and on how they are used.

The data collection was organised in such a way to remain open to the discussion around different types of technologies belonging to the 4IR realm. Nonetheless, apart from few highly innovative firms that are innovating along different technologies, the main focus during our interviews was the adoption of new types of industrial robots (sections 6 and 7) that present increased possibilities deriving from connectivity and digitalisation.

Although this type of analysis can be addressed undertaking different perspectives, the firm is adopted as the privileged unit of analysis to observe technical change with an attempt to look inside productive organisations and down to the production floor (Rosenberg, 1982; Andreoni and Chang, 2018). In this study we intend to revert two dominant trends; (*i*) the idea that we are living in a time of rapid increase in automation (i.e., the substitution of labour with machines), rather arguing that automation started long time ago and the newest features of 4IR is digitalisation not automation *per se*; (*ii*) the necessity to go beyond the concept of robot density that has been widely used to explain trends in employment and other organisational aspects (Acemoglu and Restrepo, 2017; Aksoy et al., 2020). The attempt to dig into shopfloor dynamics, in relation to technology adoption mechanisms, allows us to go beyond econometric calculations that tend to be deterministic (Hirsch-Kreinsen, 2018) and that assess the advent and impact of new technologies. These calculations generally overlook dynamics related to product, process and organisations whose differences deeply shape the space for technological adoption. Econometric techniques can, instead, be helpful in better understanding the diffusion of new technologies, as discussed in Essay II, and in formulating hypotheses around technology adoption.

The analysis in this *essay* investigates the hypothesis formulated in Essay II around the importance that local ecosystem variables have for the adoption of new technologies. Specifically, our inquiry about the determinants for technology adoption started with three main research questions:

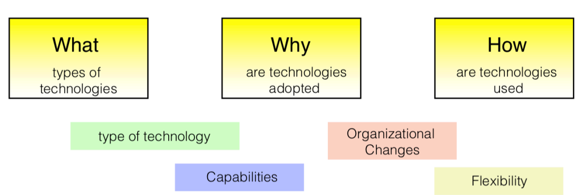
(i) *what* types of technologies belonging to the fourth industrial revolution realm are adopted by automotive firms. We selected a series of technologies (Figure 3 in the methodological section) individuated on the basis of a literature review on the more diffused digital production technologies in the automotive sector.

(ii) why are these technologies adopted, thus exploring the determinants of the adoption.

(iii) how are these technologies used across different firms. The latter element is explored through the lenses of flexibility, which is related to the level of automation pursued by different firms. The relationship between automation and flexibility is an old subject of interest, that appears to be still relevant today.

These three questions represents the yellow boxes in Figure 1, while the type of technology, capabilities, organisational changes and flexibility are the analytical concepts developed in this essay, which we use to respond to our research questions.

Figure 1. Conceptual framework of the literature review and research questions



Source: Author

The analysis of the three research questions' responses allow to put forwards a new framework that individuates the determinants of technology adoption and to formulate some considerations on how 4IR technologies change the relationship between flexibility and automation.

The unique set of information presented in this essay draws on an extensive period of fieldwork in South Africa where more than 35 interviews were collected across 28 different types of organisations and along different stages of the automotive value chain (i.e., OEM, suppliers, system integrators, institutions).

This essay is structured in three main sections.

First, sections 2 and 3 recall some theoretical concepts from Essay I - with specific focus on capabilities and path dependence trajectories - that are particularly useful to identify and discuss the empirical evidence. These concepts explore the *what* and *why* of our research framework, specifically discussing the role that certain types of technologies have over others, and which are the main drivers for their adoption. A brief introduction on modularization is presented, particularly focussing on some features that are related to the level of flexibility and to the fact that that firms automate and intend flexibility in different ways, because they have different priorities and productive capabilities. Particularly, exploring the *how* (part of our framework, the relationship between technology and organisation is here explored with reference to the dynamics related to the levels and the trade-offs between flexibility and automation.

Second, section 4 is dedicated to a broad and detailed explanation of the methodology used and the steps that characterised the data collection process. This *essay* represents the qualitative side of the mixed methods approach where the hypothesis elaborated in Essay II are investigated. After the methodological part, a detailed section on the South African automotive sector is discussed in section 5.

The third part is constituted by the empirical findings. Section 6 presents the case studies, divided per types of actors interviewed - i.e., OEMs and suppliers - and introduces the main findings following the structure of the research questions. Section 7 analytically discusses the results. Finally, the essay concludes with section 8 putting forwards a series of policy implications for the South African automotive industry, that will be further explored in the concluding chapter of the thesis.

2. Technological change that matters (what)

The nature of technological change and the immediate effects it has on both productivity levels and process re-organisation has been one of the most discussed debates in economics (Nelson and Winter, 1982; Dosi et al., 1988; Lazonick, 1990; Morroni, 1992; Dosi, 2000). History has been full of technological innovations that were never adopted. This can be associated with multiple factors, such as the lack of possibility to use some innovations in multiple sectors, the lack of complementarity with, and the resistance of, old technologies, and so on. The diffusion process that constitutes the starting point for this type of analysis, differs from the Schumpeterian emphasis on invention and it shifts more towards the innovation and imitation parts of the process.

The elements that drive technological change are very difficult to predict. Despite many economists tried to describe the channels through which technologies emerge (for the studies on diffusion Rosenberg, 1970, 1976, 1979; Rogers, 1995; Davies, 1986; De Pietro et al., 1990), there are few blueprints, and technological changes seem to be very much time, country and industry specific.

> "*[T]his technology does not develop in a unilinear way, there is always a spectrum of possibilities and alternatives that are limited in time—as some are selected and others denied—by social choices of those who have the power to choose; these choices reflect their intents, social position and relations with other within society*"

(Noble 1979)

The mere disposal of an innovation technology does not mean it will be adopted, and there are in fact multiple directions that it could take to develop. It follows that the actual adoption depends on a number of factors. Among these factors, two categories have a crucial role: the ones related to profitability and the ones related to sector specificities, such as infra sectoral and intra sectoral interdependencies, have a crucial role[59].

On the one hand, profitability comes from different sources that are either demand driven - intended as the need to produce more due to a demand push from the market (this is often related to more productivity) - or supply driven, such as an increase in material quality, or a change of materials' properties (e.g., aluminium materials that triggered the adoption of specific welding machines in the automotive sector). Profitability regards both adopters and users, and it is an important aspect of that collective process that unfold in a series of interrelated and complementary innovations (Freeman et al., 1982). In this process, technology supply markets and the maturity of the technology diffused are crucial. For example, Rosenberg (1970) describes and compares the different use of machine tools in the United Kingdom and the United States during their industrialisation phases. While the former's productive structure was more based on variety and high-tech product and thus struggled with standardisation, the latter was more able to accommodate machines' necessities, such as high volume and low variety thus reaching spectacular levels of standardization and economies of scale. This was also reflected in the production of automotive products, that were higher level and better quality in the United Kingdom, and higher volume and more standardised in the United States (Rosenberg, 1963).

On the other hand, technologies can be, and in fact have been, complemented or substituted in the production process (Stoneman and Kwon, 1994). As an example of this complementarity, the fast improving of automotive engines development led to a stronger braking system, pointing in the direction of "*complex technologies* [that] *create internal compulsion and pressures which initiate exploratory activities in particular directions*" (Rosenberg, 1969:4). It was indeed the study of technical characteristics of specific innovations developed simultaneously to diffusion (Rosenberg, 1963; Sahal, 1983), that has been crucial for the understanding of how the spread of new technologies among specific types of organisation happen. This process of incremental innovation is

[59] We refer to section 4 of Essay I for a further elaboration on this topic.

fostered by indivisibilities (Andreoni, 2014) and it can be much more relevant than the original 'act of innovation', which tends more towards a collective invention (Allen, 1983; Freeman, 1982), a process that depends heavily on the capabilities of different actors operating in the production system. Along this argument, adopters are creative, and they often do not use an innovation as intended by the original design (Rice and Rogers,1980). This is even more observable in emerging economies where the mechanism of foreign innovations' adaptation to local conditions involve a high degree of learning and innovation (Amsden, 1989). Beyond being re-adapted and re-intended, an innovation to take off needs to reach critical mass, attracting the number of users necessary to influence and trigger a rapid and wide adoption within a production system.

2.1 Adopters' path dependency and pre-existing capabilities [60] **(why)**

This section recalled the discussion on technological change and adoption deeply discussed in Essay I (section 2, 3 and 4). Diffusion mechanisms tend to be incremental, and they are influenced by the problems that need to be solved, where technicians are likely to put a lot of their effort. In this process of trial and error, problem-solving and search for complementarities, the availability of pre-existing capabilities that allow users to adopt and innovate, and which depend on country and sector specificities, is of crucial importance. Therefore, when considering emerging economies undertaking this process, the concept of technological gap, that has been widely explored in the literature and observed as a discriminant for rapid economic growth (Findlay, 1978; Abramovitz, 1994; Kokko, 1994; Glass and Saggi, 2002), could determine whether a country adopts and uses a technology or not. This is also one of the reasons behind the fast advance of late industrializers; for example, in the case of Japanese rapid industrialization, during the 1960s and 1970s, this was largely driven by initial imported technology that was then adopted and upgraded locally on the basis of pre-existing capabilities (Amsden, 1989).

[60] This section intends to recall the most relevant aspects that complete the theoretical framework for this analysis, and which have been fully developed in Essay I.

Within this context, the opportunity to adopt new technologies depends on two highly interrelated factors, which could be considered two sides of the same coin: past technological adoptions (i.e., path dependency) and absorptive capacity – the latter strongly depending on the former. The incremental nature of technological change raises the issues of productive structures' level of path dependency. Decisions to adopt new technologies and to pursue value creation are also induced and triggered by the industrial ecosystem, a space where learning activities are influenced by the resilience of the productive structure and the processes by which this structure is adjusted over time (Andreoni, 2018). If we acknowledge that technologies are not just blueprint or collection of artefacts, and technological change is never a random phenomenon (Rosenberg, 1970), then complementary skills, tacit and codifiable know how that are built upon the pre-existing of industrial capabilities, are crucial in determining the type of technologies adopted and the way in which they are adopted (Nelson and Winter, 1982; Dosi et al., 2000; Andreoni, 2014). These capabilities are also a crucial component of the structural conditions of the firm and the environment where the firm exists and operates.

Against this backdrop, being the process so dependent on cumulativeness and pre-existing capabilities, opportunities and space for leapfrogging are minimised (Soete, 1985; Lee et al., 2005). This is particularly evident in relation to the building up of technological knowledge that depends on previous investments and existing capabilities to integrate the new technologies in an existing environment, often retrofitting entire processes. The process is influenced by organisations' absorptive capacity, which determines the ability to learn new knowledge (Cohen and Levinthal, 1990)[61]. It is widely recognized that countries' absorptive capacity is crucial, as it determines the extent to which they can rapidly and efficiently introduce foreign technologies into their economy (Soete, 1985). There are many difficulties in importing technologies off the shelf and the local adaptation of technology is of fundamental importance for development and growth (Hausmann and Rodrik, 2002). With a similar argument, Khan

[61] See also Essay 2 of this thesis for an elaboration on absorptive capacity.

(2000) stresses the importance for the construction of learning capabilities that can involve substantial amount of innovation in the process of copying and adapting to local conditions. In relation to this, with a focus on development economics, Amsden (1989) noticed the difficulties in overcoming technological ignorance by East Asian economies that struggled to work out the detailed technological applications of theory.

2.2 Technological adoption in the automotive sector: the role of system integration and modularization (how)

The globalisation of production had important consequences not only on where goods are produced but also on the way in which production is undertaken and organised, and this is because technological change tends to go together with organisational innovation – at least when the efficiencies promised by new technologies are reached (Dosi, 1988; Perez, 2003). For example, if we consider the process of outsourcing and production deverticalisation, it was both the improvements in hardware, software and connectivity of production technologies, and the emergence of new ways of organising production, that led globalisation to flourish.

Outsourcing and fragmentation of production started essentially with manufacturing activities, but these processes soon involved other types of value chain's activities (e.g., R&D, testing, logistics) with an even further fragmentation within the same type of activities, with new forms of "trade in tasks" (Grossmann and Rossi-Hansberg, 2006). The breaking down of activities in smaller pieces, allowed firms to decrease their level of complexity, and to increase their efficiencies while becoming more competitive by performing simple and repetitive tasks in a shorter time through the outsourcing of large chunks of their previously in-house activities (Milberg and Winkler 2013).

The mutual interaction between technology and organisation (discussed in Essay I) has been observed with the emergence of new technologies that contributed to new models of organisation deeply reshaping production structures over the world. This process had two direct and interrelated consequences on the way in which big MNCs organise: on the one hand, they needed a much deeper relationship with their key suppliers, to whom they started to outsource entire activities and responsibilities. The novelties associated with supply chain management enable MNCs to effectively manage complex supply chains across national borders, something that requires effective coordination and that crucially depends on strong relationship with their suppliers.

This is very clear in the automotive sector, where first-tier suppliers become responsible not only for the assembly of parts into complete units, but also for the management of the second-tier suppliers that produce individual parts of the system (Humphrey, 2000); in practise these first tier suppliers started as focal firms in the sectoral value chain orchestrating the production and technological activities of multiple suppliers and complementors (Sturgeon, 2002; Pisano and Shi, 2009). In other words, these suppliers started to act as system integrators[62], leaving to big MNCs the 'commanding heights' of the global business system (Nolan, 2001). This is reflected also in the power they display when acting in developing countries often hampering the development of a local indigenous industry.

On the other hand – in a parallel and in a complementary way to increasing outsourcing - modularization arose in the 1980s as a new organisational model that would reconfigure automotive production. This process is important to consider in the current discussion of technology adoption as it influences the way in which firms use technologies along different stages of production, and it shows how an organisational process can take different forms depending on the business model. Modularity emerged mostly from the need to simplify the management of complex systems, "*breaking them down into parameters and tasks that are interdependent within and independent across the modules*" (Baldwin and Clark, 1997). This simplification process meant also platforms' reduction and standardisation with the aim of gaining efficiency in design, - that allows the dimensions of the automobile to be varied (Buiga, 2012) - higher

[62] Resembling the engineering concept that indicated the testing and verifying of components performance and the integration of this into the system (Johnson 2003), system integrator firms coordinate and integrate different components of supply firms. This happened to the point that the detailed disaggregation of stages of production made the auto producers becoming an "assembly industry" (Dicken, 2011).

economies of scale in production and sourcing, and of better responding to demand changes (Suk et al., 2007; Lampòn et al., 2017).

In the automotive sector modularization is more complex to reach, as the automobile is not as modular as – for instance - the personal computer, and neither is the supply chain associated with the car industry; this happens because modules and systems do not overlap as congruently in automobiles as in the case of computers. (Ro et al., 2007; Fujimoto, 2007)[63]. Furthermore, modularization in the automotive industry emerged as a way to improve production efficiency, both on the assembly process (MacDuffie, 2013), and on the improvement of production flexibility (Salerno, 2001), in order to allow complementarity between scale and scope economies by sharing a growing number of parts between an increasing number of models (Jetin, 1999)

Thus, the role of MNCs and big suppliers as system integrators and the emergence of modularization, intended as a series of interlinked hierarchies that make up one complex system (Simon, 1996), became a new way of organising production that triggered also new ways of business organisation. For many companies, increasing modularization went together with an increasing and more efficient fragmentation of production; in the automotive industry this meant a shift towards the supply of complete modules (called also *systems*), such as seats or dashboards, rather than individual components. Within this context, MNCs organise their modularization differently showing a high degree of heterogeneity that confirm their different priorities, as well as ways of organising their business process.

Modularization generally refers to longer units in sub assembly and it is often referred to the process of outsourcing of units in subassembly to suppliers (Takeishi and

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[63] Specifically, there are some fundamental differences in product architecture in the automotive industry that alter the nature of the modularity challenge. For instance, if we consider modularity in use
"*OEMs have not moved toward modularity in the Dell Computer sense of mass customized mix-and-match parts. It is not as feasible to replace the Visteon-made cockpit in a Ford Taurus with a Magna-made cockpit as it is to replace one hard disk drive with another in a laptop. The cockpit can be built separately but still is highly customized and integral to the vehicle. Thus, OEMs are investing a great deal in specific assets of suppliers—specific engineering skills, tooling, manufacturing capability, program management skills—when they engage a supplier to engineer and build modules*". (Ro et al., 2007)

Fujimoto, 2003), to better synchronise supply chain management (Ro et al., 2007). Modularization is not identical across different firms; rather, the benefit of it depends upon where the value is seen to lie. There are three facets in the modularization of the automotive sector (Takeishi and Fujimoto, 2003), and they are the consequence of complex experimental processes where learning develops within and between OEMs and suppliers (Helper, MacDuffie and Sabel, 2000):

i) modularization in product architecture, which mainly refers to modularization in design.

ii) modularization in the production process.

iii) modularization in inter-firm system, which is the outsourcing of subsystems to external key suppliers.[64]

Few companies in the automotive sector have advanced in the modularization of design. This situation reflects the fact that, both for functional, technological and historical reasons, the current dominant product architecture for motor vehicles is integral rather than modular. This is also because automotive parts present limited cross-product and cross-firm standardization (Camuffo, 2002; Johannson et al., 2013). Nonetheless modularization in design has the potential to reduce lead time and cost for design and development, as independent design teams could act without affecting other modules (Sako, 2000; Brusoni and Prencipe, 2011). It is worth to note that product architecture and its degree of modularization play an important role in how innovation and technology can interact with the production process.

"*If there is a degree of stability in product architecture, innovation may be spurred by parallel processing of modular design teams each free to adopt new technology within the module without affecting other modules*" (Tomke and Reinersten, 1998).

[64] Other authors built a similar classification adding to modularization in design, and to modularization in product architecture the other concept of modularization in use, which means reaching higher product variety by offering mix and match options for different customers (Baldwin and Clark, 1997; Sako and Murray, 1999)

European and American car makers have been more active in the modularization in inter-firm systems, for example VW and Mercedes Benz pioneered modularization in 1990s with individual components that were sub-assembled on a separate line and then installed as a module into the body on the final assembly. There are three main Europe-related reasons for this trend. First, they had a great advantage coming from supplier labour costs. Second, as a company strategy, they have been increasingly cutting costs and giving responsibilities to their key suppliers. Third, this trend was accelerated by the concentration towards a fewer and larger Tier 1 suppliers able to play the role of module design integrator (Cusumano and Takeishi, 1991; Takeishi and Fujimoto, 2003). It is still a matter of question, whether this cooperation between final assemblers and suppliers involves a two-way relationship, or a mere imposition of OEMs' wishes over component producers (see Alcorta, 1995).

Japanese car makers, instead, have developed a leading role in the modularization in production, which also inspired the lean production model. Modularity in production aims at increasing operation efficiency and modules are interpreted as subassemblies that are easy to test and install. Also, at a lower level in the production hierarchy, modular sub assembly are used as a way of postponing customization, thus increasing efficiency of components interchangeability and late customization. This model resulted in inventory reduction, one of the main aspects of the Japanese lean production model.

Differently from their counterparts in the United States and Europe, Japanese final assemblers have instead been quite reluctant in outsourcing module procedures (modularization in inter-firm system) for a number of different reasons. Japanese tend to prefer vertical integration and to work closely with sub-assemblers - that are often part of the same conglomerate - a strategy that firs better lean production and just in time organisational models (Fujimoto, 2001; Pandremenos et al., 2009). Moreover, their cost advantage in outsourcing is low, partially because they do not have extra space to have the supplier next door - as space for new buildings is limited in Japan- and partially because Japanese car makers are generally doubtful of the capacity of suppliers to handle autonomously (in fact they tend to be quite integrated and highly connected with the supply chain) a larger scope of tasks (Cole and Yakushiji, 1984; Takeishi and

Fushimoto, 2003; Fuentes et al., 2012 for a study on Spanish automotive firms; MacDuffie, 2013; see Johannsen et al., 2013 for a case on lean automotive in Sweden)[65,66].

Although it may appear that the organisational tasks that derive from the process just described can be disentangled and analysed, they are deeply interrelated and depending on each other (see Brusoni and Prencipe, 2011). The contributions on the task partitioning (Von Hippel, 1989; Scazzieri and Landersmann, 1996; Andreoni and Scazzieri, 2014) stress the importance of the interrelationships between different tasks in the innovation process and how these in fact necessitate to change and interrelate during the process. The way in which a product is designed has a series of implications for process design (also *vice versa*), and this requires adequate ways of communication within the organisation, up to the point that the organisation would need to either bridging or eliminating task boundary (Von Hippel, 1989). Studies on these aspects show how Japanese are more prone to flatten such boundaries, as they encourage a general high level of communication (Clark, 1989)[67].

[65] These differences resemble those in the larger financial and manufacturing institutions where automotive firms have been embedded since their first appearance. For example, the American General Motors had close links with Dupont - that entered the company – and it developed a collaboration with Sloan for the creation of the multidivisional structure that Chandler would study some decades later. In Japan industrial groupings (the vertical zaibatsu and the horizontal keiretsu) were the supportive institutions to provide capital, members to cooperate with, information pool technology, and organization of management. Japan coordinated components supply system owes much to the close relationship between OEMs and its special component suppliers, that were often part of the same industrial group, thus financially and technologically dependent on OEMs (Shimizu, 2017).

[66] Cole and Yakushiji (1984) mention that stamping plants tend to be next door to final assemblers in Japan, and geographically separated from final assemblers in the United States.

[67] Clark et al. (1989) in a study on the automotive sector made a comparison between Japanese, European and American companies on how information pass from designers of sheet metal parts and designers of the dies used to produce these parts. They note that in the Japanese companies there tend to be larger overlap in terms of time, with more exchange of information during this time and an even formal passage of information more frequently. This resulted in Japanese die designers to being in a better position to design dies while suggesting changes to part designers in a timely way that would reduce cost and complexity.

3. Automation increases flexibility: myth or reality? *(how)*

In relation to technological change, there is no single answer in terms of whether or not new technologies enhance either modularity or integrality in product architecture and production process. The differences outlined in the previous sections made clear that this depends on whether the value of innovation is seen to lie within the module, across systems or at the component level. On the basis of where firms see value creating opportunities, and of their business priorities firms would have a specific level of product standardization, of production flexibility and of automation.

There has been a great emphasis on the role that new digital production technologies play in relation to an increase of customization, due to higher automation and a consequent higher degree of flexibility. The relation between automation and flexibility is of crucial importance, especially to determine whether flexibility plays any sort of driving force for the adoption of new technologies. Flexibility comes from the programmability of the computers controlling the machines and it is intended as "*the capacity to switch rapidly to the production of a far wider scope of goods than before*" (Morroni, 1991). It depends on a number of elements such as product design, production processes, the type of technologies and the way in which technologies are used. A further definition of flexible automation defines it as the capability of making different products in a short time frame, while allowing the production of different part types with overlapping life-cycles. Flexible automation allows the production of a variety of part types in small or unit batch sizes (Stecke and Parker, 2000).

There is a long tradition that studied the relationship between flexibility and automation. In the past, there was a general agreement that industrial automation tended to lead to less production flexibility, higher output rates and increasing vertical integration (Morroni, 1992; Alcorta, 1995)[68]. A study of the FIAT plant in Cassino confirms that

[68] Previous research conducted by Alcorta, (1993 and 1995) found that one key effect of industrial automation for European firms is that automation increased internal production of components that were previously farmed out, thus leading to vertical integration. New equipment had such a production capacity and relatively low setting up times that the only way to keep it fully utilised was by producing components internally. The result was that component producers were simultaneously under pressure from final assemblers to diversify and from the new technologies to integrate vertically.

automation necessarily introduced a degree of inflexibility and the firm responded by replacing a very long final assembly line with a shorter one fed with multiple subassembly lines (Sako, 2003).

There are a series of other studies that confirm this trend between automation and flexibility. Upton (1995) analyses companies with older equipment and found that as the age of technology increased there was a decrease in product flexibility[69], with a parallel increase in process flexibility. Conventional wisdom says that advanced manufacturing technologies (AMT) increases flexibility, but this is not always the case (Zammuto, O'Connor, 1992) and there are contradictory results: a study on Spanish manufacturing companies finds that increased the level of volume flexibility but in parallel production and new design flexibility decreased (Suarez et al., 1996). Jaikumar (1986) observed that while there is very little association between the use of ATM and flexibility for plants in the United States, plants in Japan using similar technology exhibited much greater flexibility across several dimensions. Also, the lack of association between automation and flexibility is worsen by the fact that AMTs require a very different set of managerial skills (Adler, 1988).

This trend seems to be reverted when discussing the potential of fourth industrial revolution technologies (see Essay I for an analytical discussion on the 4IR). Despite being highly sector and firm specific, the so-called fourth industrial revolution technologies are indeed designed to make existing production systems adaptive, flexible and reconfigurable (Vancza et al., 2011). Therefore, the real issue at stake is whether or not flexibility is already something that firms either look for or are ready for[70]. A number

[69] Intended as design flexibility that is regarded as the incremental cost and time of modifying a design, the ability to accommodate evolving design requirements or having high design flexibility, can be very beneficial (Thomke, 1997).

[70] The aim of flexibility and the pace at which firms proceed towards the fourth industrial revolution depends on firms and sector specificities that may accelerate or slow down this process. In the automotive industry, where firms are characterized by batch production automation is more difficult because of frequent deviation from the steady state during the switching on and off from operations (see also Cainarca et al., 1988).

of studies confirms that organisations are not ready for flexibility. For example, a recent study on automation in Eastern and Central European automotive firms reported that:

"*We simply do not have the capacity to engage in a lengthy exercise of screening our process, elaborating a digital technology plan, looking for technology suppliers, interacting with them, restructuring the processes and implementing the new solutions*" (Szalavetz, 2020).

These aspects are also related to the variability of production environment and particularly to the complexity of the production process, as generally the greater the complexity of the production process, the more difficult it is to automate the process (Krywdzwski, 2020).

There are a number of issues that the automotive sector faces when looking at flexibility. We recall four of them.

1. Product variety – often associated with a higher level of customization – does not imply production flexibility *per se*. If, for a long time, inflexible production lines and higher productivity led by the introduction of new automated machines was consistent with the standardization of products, the situation started to change in the 1990s. OEMs started to present initiatives to deal with in line complexity due to the increasing product variety, such as postponing customization as downstream as possible in the process. This requires manufacturing flexibility that is increasing flexibility of the process equipment in the plant (e.g., CNC and robots) and low set up times. Much of the ability to create product variety does not lie within equipment flexibility itself, but it stems from the architecture of the product, that if designed in a specific way can allow to postpone customization (Ulrich, 1995; Sako and Murray, 2000).

2. The high majority of robotic stations in use in the automotive sector – and generally in the manufacturing industries - allow only a very small tolerance[71] when performing a specific task – or set of tasks. This means that if the tolerance is not kept

[71] Machine tolerance is the amount of deviation in a specific dimension of a part caused by the manufacturing process.

the robot is not able to react appropriately because automatic stations are not yet flexible enough to compensate abrupt variance of tolerance. The type of flexibility given by the fact that machines are reprogramming comes with a high costs and long idle times that inevitably increase with more machines. A study undertaken by the Fraunhofer Institute assessed that 36% of companies that adopted automation think that they exaggerated automation in the past as it led to less flexible systems in the automotive sector (Gorlach and Wessel, 2008; see Wiktorsson and Granlund, 2016 for a study on Swedish firms).

3. A constant tension between two contrasting forces: (*i*) the process of modularization that requires standardisation, as interfaces between modular organisation units must be well defined in a standard way; (*ii*) the tendency towards a more flexible specialisation and an increase fading in task boundaries typical of the lean production organisation (Ruigrok and Van Tulder, 1995). Japanese carmakers have placed great emphasis on redesigning the components within a subassembly module, increasing components sharing across different car makers, and organising and training their workers for multiple tasks and skills (*tanoko*), in order to eliminate any non-value adding time (*muda*) and combining different task flexibility, or task-partitioning (Cusumano, 1988; Von Hippel, 1989).

4. As this study confirms, decisions around whether to automate or not are made also on the bases of business strategies. For example, education systems organisation within companies have different impacts. Research on automation approached in the 1980s and 1990s reported that Japanese companies were very prone to improve flexibility (in the sense of a rapid adaptation of product mix and production volumes), and this was accompanied by labour models that strongly emphasised skill development also for production workers. Differently, in Germany high tech automation was focused on continuous professionalisation but leaving manual areas with semi-skilled workers. In the United States the imprint towards Taylorism organisation made tight job demarcation (Krywdzwski, 2020). In retrospect, the Japanese imperative in terms of human capital investment, emerged as one of the most important policy differences between American and Japanese automotive companies (Cole and Yakushiji, 1984). This is consistent with findings from regional trends for flexible automation that confirm that plant using flexible forms of work organisation (such as teamwork and job rotation typical of the Japanese), emphasising high level of training are likely to implement flexible automation more heavily (MacDuffie, 1996).

4. Methodology

This section discusses the methodological approach adopted for this research. The latter was conducted over a four-month period in South Africa where more than 35 semi-interviews were conducted with different actors of the automotive value chain, namely OEMs, suppliers and institutions and system integrator firms (section 4.2 and 4.3). The interviews were conducted following a questionnaire that was sent before the meeting (Appendix A); the answers were then enriched during the plant visits where the researcher could see and ask questions regarding the functioning of new technologies.

4.1. Research approach

This study on the drivers of technology was designed to include different actors along the automotive value chain. It is a qualitative type of analysis that privileges an inductive approach where a series of broad hypotheses are formulated, on the basis of both previous studies and a systematic literature review on the topic. During the entire period of fieldwork, as well as before and after it, the researcher has been open for completely new findings and integration of the research questions and iterative triangulation between literature review, case evidence and intuition took place (Lewis, 1998). This facilitated the analysis whose aim was possibly to build a theory, or contribute to a new piece of theory, rather than to test one.

The analysis stems from a series of interviews with the following different players: lead final assembler firms (from now on OEM), suppliers at different level of the supply chain, system integrators that are crucial players in the adoption and setting up of new technologies, and institutional players. This deep involvement in terms of multiple players for each stage of the value chain increased the external validity of our analysis (Yin, 2009; Gibbert et al., 2008). The selection of multiple cases is important also in terms of generalisation as they tend to conduct to more robust findings (Herriott and Firestone, 1983).

This analysis considers multiple cases as one would consider multiple experiments, in order to follow a 'replication' design not a sampling logic (Yin, 2009). The findings are, like experiments, generalizable to theoretical propositions, as an analytical type of generalisation, not – clearly - to populations (Lipsey and Lancaster, 1956). Although less generalisable, the finding of this analysis stem from a study that tries to include as much variables as possible into consideration; economic phenomena are open systems and each different methodology inevitably loses some parts of the whole story (see open vs close-end approaches, Starr, 2012). We lose generalisability in the attempt to gain an output that it is closer to the reality of the phenomenon we analyse. As Schramm (1971) noted that the essence of a case study is that it tries to illuminate a decision or a set of decisions, why they were taken, how they were implemented, and with what results.

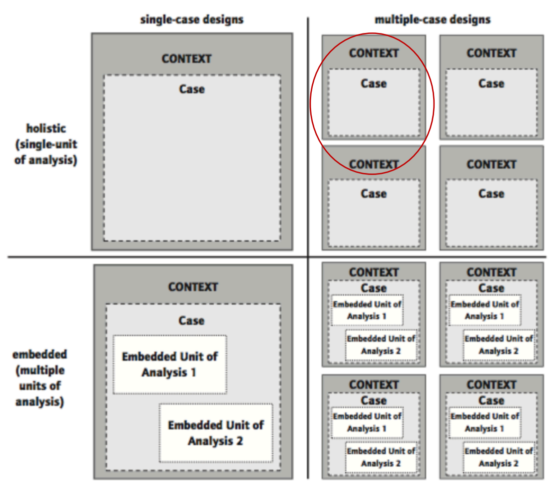
This design approach allows to have a multifaceted perspective and a holistic view of such an interrelated phenomenon as the one of technology adoption. The case study approach is particularly useful as we are at early stages of research (Gibbert et al., 2008) in the field of the newest (fourth industrial revolution) technologies adoption. While the field of technological adoption is not recent nor new, the element of novelty is in relation to the adoption of the most recent technologies. The case study was the preferred methodology as the topic and the research questions constitute an empirical enquiry that investigates a contemporary phenomenon in depth and within its real-life contexts (Yin and Davis, 2007); relevant surveys on the topic are generally unavailable or unreliable because too broad (a too general definition of 4IR technologies). In addition, the case study is the preferred method to adopt since we have: **(i)** a how/why type of research question; **(ii)** the analysis concerns a contemporary set of events; **(iii)** investigators has little/no control over the events (Yin, 2009).

The focus on the firm, as the privileged unit of analysis is of crucial importance for the research questions analysed in this essay. The firm is, in fact, "*the centre for the transmission of relevant knowledge and techniques from one industry to another, and for the application of known techniques to new uses, was, to a very considerable degree,* *the individual firm*" (Rosenberg, 1970:154). This definition of the unit of analysis is very much related to the way research questions were structured initially[72].

Following Yin (2009), each case study of our multiple strategy must be carefully selected so that it either: a) predicts similar results, b) predicts contrasting results but for anticipatable reasons. This case study was designed to be undertaken along the automotive value chain, and it is a holistic multiple case study (Yin, 2009).

In this sense, the same unit of analysis (i.e. the firm) is embedded in a specific context. The research considers several case studies (each interview) with one unit of analysis (the firm itself) and different contexts that apply to each firm. In fact, while if we consider the OEMs the context can be considered similar, the situation changes when we consider different stages of the value chain, i.e. suppliers, that act in very different contexts. The environment of Tier 1 multinational supplier is very different from the context of a Tier 2 or 3 South African supplier.

Figure 2. Case study classification



Source: Yin (2009)

[72] Despite the focus on the firm, in the case study scenario, there are many more variables than the one object of the analysis, which is the data point object of the study (Yin, 2009). Other variables can be helpful as they can constitute multiple sources of evidence to then triangulate.

4.2 Case study design and sample selection

The automotive industry, often called the 'industry of the industries' (Womack et al. 1990: 1) is the object of this study. It is considered one of the most important manufacturing sectors for economic growth and development (Dicken, 2011) and it has constituted a pillar for industrial development in many countries, South Africa included.

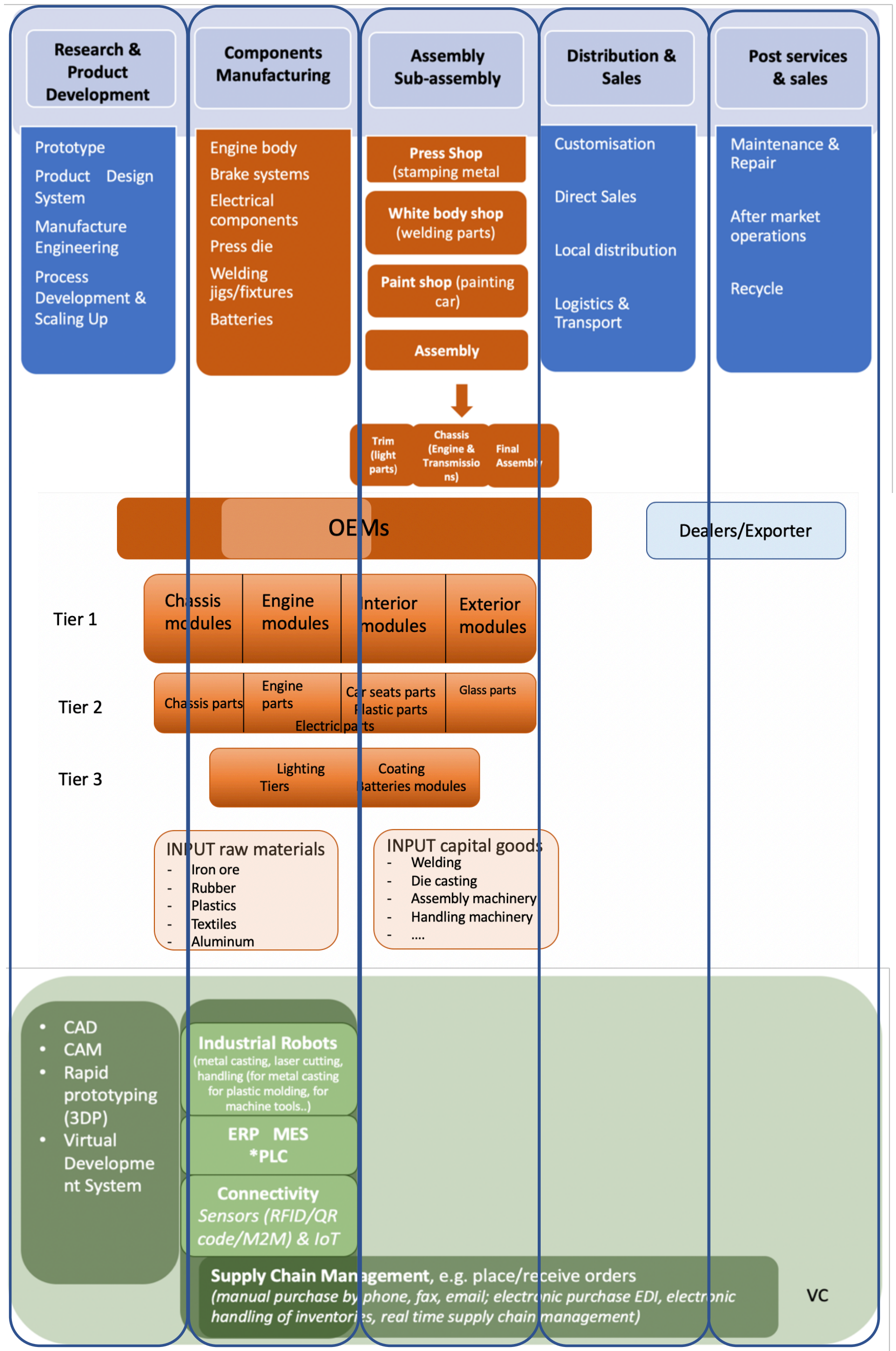
The process of firm selection was an important step for this research. It starts well before the first trip to South Africa and it focuses on the study and analysis of the automotive value chain in the country. In order to study the phenomenon of technological adoption of specific technologies, across the value chain, the main purpose was to have a sufficient representation of different stages of the value chain and of other actors considered critical for the adoption of the value chain. It was possible to access six out of the seven OEMs active in the country and a total of twelve suppliers. In order to get access to such a big number of players, it was crucial to have interviews with the three South African institutions NAACAM (National Association of Automotive Component and Allied Manufacturers), NAAMSA (The National Association of Automobile Manufacturers of South Africa) and AIDC (Automotive Industrial Development Centre). Moreover, the access to the body shop line system integrator DESing, one of the most popular in the country and entirely focused on the automotive sector, and with the robotic company Yaskawa, were crucial nodes to test our hypothesis. Lastly, and of fundamental importance, multiple conversations with two of the major experts on the South African automotive industry have been extremely helpful.

The map reported below helps to disentangle the different layers of the analysis regarding technologies[73]. The researcher was open to receive different responses from the interviewees. The access to industry experts and academics through informal meetings provided further elements to validate our questionnaire and eliminate possible

[73] Level I is about the value chain of the automotive sector, the different stages that could be represented also in the classical smiling curve, and this part looks at the production phase (assembly and sub assembly). Level II regards the supply chain, whose dynamics could reveal important mechanisms of technological spillovers. In fact, we find quite a number of cases where there have been cascade effects. Level III regards the specific types of technologies and their use along different step of the value chain.

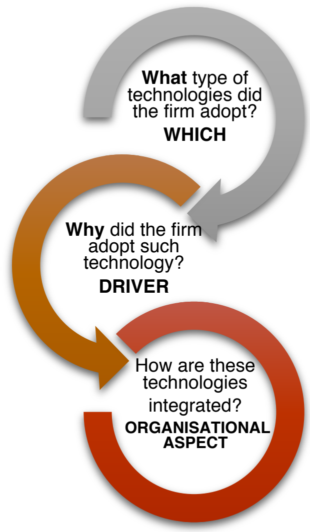
ambiguity during the interviews. The questionnaire inserted in Appendix A considered three set of research questions (Figure 4).

Figure 3. Research map used during the interviews



Source: Author

Figure 4. Map of the research questions



Source: Author

Most of the interviews tended to focus on the adoption and use of industrial robots, and this mainly relates to their higher adoption when compared to other fourth industrial revolution technologies. Industrial robots emerged to be the only technology widely diffused among OEMs and fairly diffused among suppliers. Following the importance to analyse and discuss innovations that are economically relevant, the researcher was ready to adjust during and after the first interviews. Most of the other newest technologies, such as Internet of Things, Artificial Intelligence and virtual reality are of scarce use and (or) at a very preliminary stage (e.g., pivot projects).

The selection of the case studies was determined as follows: all OEMs in the country were contacted, and Mercedes Benz was the only OEM we were not able to reach. In terms of suppliers, we use contacts from the South African institutions, personal contacts with a strategic Italian player active in the South African context and, beginning with this supplier, we tended to act with a snow balling technique, proceeding from the

OEMs down to Tier 1, Tier 2 and Tier 3 where possible[74]. We tried to access different suppliers, some belonging to similar components – the same supply chain - in order to explore the cascade effects, and others because belonging to different manufacturing components in order to observe the relationship between technologies and different commodities[75]. In this sense, cases were selected "*because they are particularly suitable for illuminating and extending relationships and logic among constructs*" (Eisenhart and Grebner, 2007: 27). When we were able to proceed in this way, complete value chain segments emerged, with interesting findings.

4.3 Data collection and analysis

The results of this study are based on both primary and secondary data collected from several different sources. Primary data were collected during interviews that consisted of two parts, one discussing the questions in the office, and the second during shopfloor visits that were granted by all interviewee, apart from Isuzu and Atlantis Foundries due to the fact that the shift was already concluded at the late afternoon time of our interview. In some cases, firms were more generous, and visits of the entire plant with all shop floors and production lines were possible, in other cases visits were limited to production line where only technologies discussed during the interview were applied. In all cases, the access was done according and following all security measures. Secondary data were analysed before, during and after the collection of primary data and they were indispensable to better design the research question and to then triangulate the findings, thus improving the accuracy of the picture emerging (Jick, 1979; Gibbert et al., 2008). The secondary sources that have been analysed came from three main sources; i) datasets such as IFR statistics and fDi markets, ii) online sources such as company web sites, annual reports, books, papers; iii) hard documents such as internal documents kindly released by different actors, mainly the firms themselves, and detailed publications that were provided during the interviews by the three institutions NAACAM and NAAMSA and AIDC.

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[74] Similarly, if we interviewed a Tier 1, we asked for its suppliers, so to have a snowballing effect.

[75] We were able to interview suppliers in the production of different commodities, although with a predominance of metal commodities.

The interviews were conducted during four months of field work in South Africa, between April and September 2019. There are four automotive districts in South Africa, and they are: Durban in the KwaZulu Natal region, Rosslyn, Port Elizabeth and East London. The research took place in the first three, with two trips in Durban, one in Port Elizabeth and multiple trips to Rosslyn[76]. The fourth pole in East London was not part of the research. The continuous presence in the country proved to be essential in order to keep up with calls, emails and follow ups required to set up the interviews. Interviews were conducted with multiple individuals[77] coming from different levels in the corporate hierarchy, and from different areas, to have different perspectives on the adoption of new technologies. There was also the possibility with two key suppliers to have follow up interviews with a second plant visit.

All interviewees were given personal anonymity. Interviews were recorded, with the agreement of all interviewees, and later transcribed. A total of 34 semi-structured focused interviews were conducted and they commonly lasted between one and five hours (the difference mainly depends on the plant visit). Each interview had three main parts. First, the purpose of the study was explained, background questions about the firm were asked, especially the interviewee role in the firm, whether the firm was indigenous or international, and for how long it has been operating in the country. Second, the first set of questions on technologies' adoption mirrors the exploratory *what* question (first level Figure 4), about which type of technologies have been introduced and when. Third the why and how questions, which cover much of the time during the interviews, and almost exclusively the time during the visits in the plant. Informants were encouraged to provide more details when their descriptions were brief – and some elements given for granted - or when novel strands of narrative emerged (Strauss and Corbin, 1990). As acknowledged by Starr (2012), the Smithian "pin factory" visit laid out the value of visiting shopfloor as a means to gain unexpected, new and empirically

[76] The interviewer was based in Johannesburg, which made the numerous trips to Rosslyn easier.
[77] The author was a visiting PhD student at the SARChI (South African Research Chair in Industrial Development within the University of Johannesburg) took part of the Deep Dive project. This is a research project on the adoption of 4IR technologies in three South African sectors: mining, automotive and business services.

grounded insights into key economic processes (McGoun, 1936)[78]. Finally, once the case studies were analysed together, alternative theoretical relationships were searched for, in case the data fit better to alternative theories than the initial emergent theory (Gilbert, 2005).

4.4 Limitations

The methodology of the present multiple case study does come with some limitations. First, and consistently with one of the most common critique to case study analysis, the number of firms is limited. While the possibility to interview six out of the seven OEMs present in the country, gives a high representation of this final piece of the automotive value chain, the situation with suppliers is different.

Second, this analysis considers a single industry. This has a series of 'pros' and 'cons'; while the topic of technological change is highly sector specific and thus this approach provides deep insights to the peculiarities and dynamics of the automotive sector, it limits the generalizability of the findings. Clearly, there are some sectoral dynamics applied to technological change that make some technologies, and some specific drivers of their adoption pointless for other industries.

Third, the study refers to South Africa. While at the OEMs level there is some generalizability, especially due to the tendency of OEMs to have standard plant around the world, at the supplier level our conclusions are quite limited to the South African context. Being an emerging economy and with a high focus on the automotive sector as a vehicle for industrialization, we believe that some implications, purely on the technological aspect of our research, can be drawn also for other economies at a similar developmental stage.

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[78] Perhaps one of the most influential work in this sense was the year Ronald Coase spent traveling to US factories, talking to decision-makers and observing businesses patterns; as mentioned in Coase (1988), this material contributed centrally to the development of his understanding of horizontal and vertical integration, presented in his seminal 'Nature of the Firm' (1937).

5. The automotive sector

This section draws on what was presented in Essay II (section 3) around the automotive sector in general; avoiding repetitions, in this part we focus on the technology and organisational related elements of the automotive industry. The last part (section 5.2) presents an overview of the South African automotive sector.

The automotive sector has always been an influential ‘trend setting industry’ (Womack et al., 1990), due to its continuous innovation trend both on the technological and organisational aspects. On the technology side, the automotive has always been the bedrock of manufacturing automation advances due to its high-volume production, high process sophistication, high levels of standardisation and modularisation that allow the deployment of advanced technologies. Indeed, automation and industrial robots' deployment in the automotive industry are present since the application of the first Unimate robots at FORD in 1960. On the organisational side, it is where Fordism mass production and lean production raised first, and where outsourcing mechanisms and the emergence of global value chain were more visible.

In addition, the sector has been playing a crucial role for industrial development and technological capabilities creation (Humphrey, 2000). The number of spillovers both on labour and on production, and the countless complementarities and similarities that can spur development in other related sectors of the economy is probably with no comparison in the manufacturing realm. The multiplier on employment is significant, (1:4 ratio being the overall industry benchmark[79]), and the key role the sector plays in upgrading the overall productive structure (e.g., robotisation, electronics, plastics) can be seen across a broad spectrum of development experiences. It is true for early industrialisers like Germany and the United States[80] as well as late industrialisers like

[79] Center for Automotive Research (2015), https://www.cargroup.org/wp-content/uploads/2017/02/Contribution-of-the-Automotive-Industry-to-the-Economies-of-All-Fifty-States-and-the-United-States2015.pdf

[80] Lower fuel taxes, high investments in better roads and highways, large quantities of cheap consumer credits to buy cars and low sale taxes and registration fees are just some of the policies that help the United States in stimulating a stable and high demand for motor vehicles (see Cole and Yakushiji, 1984).

South Korea, Brazil, Mexico, the Mercosur area and the more recent Thai experience. South Africa, as presented at the end of this section, has been pursuing a similar process.

The automotive global value chain has been among the first in undertaking important measures of outsourcing and deverticalisation of its productive structure. It is one of the sectors that could exploit and benefit from both the first unbundling (the so-called old competition that spurred competition between sectors, e.g., different auto producers), and the second unbundling (the so-called new globalisation where competition appeared to be within sectors, e.g., bumpers, engines, brake systems) (Baldwin, 2016). The idea, in line with the more general process of global value chain emergence, was that MNCs could benefit if focusing on the core activities, the one with more value added, while outsourcing to less developed economies poor value adding activities, such as assembly and certain types of production. For example, ICT technologies (that widely diffused from the 1980s with the third industrial revolution) enabled the modularization of production, "*where separate modules can function as an integrated whole*" (Berger, 2006: 75). For each separate module to fit, firms create standards and platforms which can be produced in a synchronised way thanks to the coordination enabled by ICT technologies between geographically distant players. In order to exploit the opportunities of this new organisation of production, both final assemblers and suppliers need to bridge their activities in the international supply chains so to continue carrying out exchanges (Dicken, 2011).

5.1 Technology, design and globalisation

During the last century, the automotive sector has been one of the most prolific sectors in terms of technological and organisational innovations. During the 2nd Industrial Revolution, through the advent of continuous line production, assembly line organisation and mass production techniques the automotive industry completely changed. In the 1980s, with the later Taylorism increasingly replaced by the Japanese models of lean production and just in time supply chain management, the automotive sector has been reshaped once again. Along with these evolutionary processes, the two objectives of exploiting economies of scale on the one hand, and retaining flexibility in production, on the other hand, have been seen as irreconcilables. Nonetheless, advancements in flexible automation in the last two decades seemed to indicate increasing scale-efficient production, while allowing for more customization.

Therefore, the automotive sector at the global level has been deeply reshaped in the past decades. With reference to the South African case study at the centre of this Essay, we identify three main features of the automotive global value chain that are central for the discussion of our results (section 7).

First, the progressive trend towards different models of cars pushes companies to standardize platform and design, which is intended as the tendency to have unique model-based plant that operate at full scale, rather than plants with the production of different models. In order to optimize costs, the automotive industry developed a strong tendency to reduce the number of platforms in each company. This process of standardization characterizes not only dynamics within countries but also between countries and regions (Humphrey, 2000). Companies such as Ford, GM, VW, Peugeot have been standardizing platforms across companies and divisions (Freyssenet and Lung, 2000). Because of its level of globalization, this industry caused the standardization process to affect also emerging markets. While in the past, OEMs used to produce models tailored to local market characteristics, with a whole set of positive consequences and spillovers for the local productive structure, in the past two decades, OEMs updated their models prioritising platform rationalisation - i.e., lowering of the models produced- rather than market proximity. With the new system, that has been called the "follow design" strategy, fewer variations are allowed and there is strict centralized control over the design process. This strategy needs to adapt to prices and expectations of emerging markets; accordingly, technological content and quality were revised downward by local engineers (so to have low-cost production sites) with a slow diffusion of innovation through the double logic of trickle down from high end to low end models, from domestic bases to emerging countries (Julien and Pardi, 2013).

Second, for the dynamics exposed in section 2 there has been a strengthening of key first tier suppliers, which means that they are more involved in design. The increase in complexity and sophistication also called for a hierarchical and dynamic division of responsibility that invested first tier suppliers (Bounya, 2018). For example, as recalled in Essay II, over the past four decades component manufacturers dropped from 40.000 in 1970 to less than 3000 in 2015 (Wong, 2017). This also leads to the fact that standardization increasingly suggested that the same suppliers should follow the assembler to the various emerging markets in which OEMs set up their operations. In this way the OEM has a guarantee that the component will be identical to that used in other markets. Suppliers become also responsible for the rest of the supply chain to meet the OEMs' assembly standards (see also Barnes and Morris, 2004). As Humphrey (2000:252), reported

> "*Instead of dealing with a large number of local suppliers whose designs and prototypes have to be homologated, and whose production and quality systems have to be audited and improved, the assembler deals with a limited number (certainly less than 100) of follow sources providing parts or sub- assemblies. When the globally preferred supplier is unable or unwilling to establish a local production facility, the assembler's second preference is to use another of its global suppliers - either making the part under license from the globally preferred supplier or providing its own design. This company will have experience in supplying parts to the assembler, and it should have the required level of management and quality expertise. The least preferred option is for a local company to produce the part, either under license or using its own design. In this case, the assembler has much more work to do in monitoring the production processes and quality systems of the local supplier*".

This is known as the "follow sourcing" strategy (Humphrey and Salerno, 2000), that emerged both as a result of "follow design" and as a preference of OEMs to deal with suppliers already used in other locations. With the increase diffusion of follow design and follow sourcing strategies, when OEMs introduce a car produced in Europe, United States or Japan in an emerging/developing economy the design is likely to be the same and so the suppliers. This is likely to have a negative impact for local companies, as developing countries are likely to lose design capabilities, and opportunities to link up to global value chains.

Third, and related to the previous point, OEMs require that Tier 1 of specific commodities (such as high standard products like metal commodities) localize geographically either close to the assembly or in site to better synchronise just in time delivery (Frigant and Lung, 2002). Suppliers follow strategy is also conditioned by the market dimension, as there are thresholds to be met in the demand side that affect localization decision and, in turn, organizational arrangements.

Differently, Tier 2 and Tier 3 suppliers that produce less technology intensive and more labour-intensive products locates at a greater distance. Barnes and Morris (2004: 800), in a study of the German influence in the automotive South African context state that:

"*to avoid the build-up of global inventories, a necessary complement to this process of global sourcing is the development of follower supply relationships. This involves the first tier (and sometimes even the second tier) suppliers locating greenfield plants in close proximity to final assembly plants throughout the global operations of their assembler customers or alternatively purchasing existing operations in countries where the assemblers operate*".

Clearly, and as it is explored in depth in the next section, this has important consequences in terms of obstacles for the emergence of suppliers in developing countries.

5.2 The automotive sector in South Africa

Historical legacy and policy regimes

South Africa is one of the biggest economies on the African continent. Its historical and political economy legacies are important determinants also for its industrial development trajectories. The automotive industry in the country is a typical example of the pressures confronting developing economies with a nationally important industry, that contributes 6.9% to GDP (in 2019), yet internationally insignificant, with South African global vehicle output being less than 0.7%. Despite the government's intention to move forward, the automotive sector still embeds typical characteristics from the pre-apartheid period such as strong concentration, foreign ownership, and poor development of the most relevant parts of the value chain (see Table 1 to see how the composition of the ownership changed). Although the sector presents a number of structural limitations, it still is the backbone of manufacturing production within an economic structure that is very similar to the one inherited in 1994, characterised by very little diversification (Andreoni and Tregenna, 2018). Approximately one third of value addition within the domestic manufacturing sector derives, either directly or indirectly, from the automotive sector, positioning the industry and its broader value chain, as a key player in the country (Barnes et al., 2018).

History of South African assemblers ownership

South African assember	Ownership: 1990	Ownership: 1998	Ownership: 2007	Ownership: 1990 to 2007
Toyota	100% local (listed on Johannesburg Stock Exchange)	Local: 72.2% (JSE listed), Toyota (Japan): 27.8%	Toyota: 75% Wesco (South Africa): 25%	*SA to TNC-dominated Joint Venture*
Volkswagen	Volkswagen AG: 100%	Volkswagen AG: 100%	Volkswagen AG: 100%	*TNC – no change*
BMW	BMW AG: 100%	BMW AG: 100%	BMW AG: 100%	*TNC – no change*
Daimler Chrysler	DaimlerChrysler (Mercedes Benz): 50%, Local 50%	DaimlerChrysler (Mercedes Benz): 100%	DaimlerChrysler: 100%	*Joint Venture to TNC*
Ford	100% local (Anglo American)	Anglo American: 45%, Ford: 45%, Employee trust: 10%	Ford: 100%	*SA to TNC*
Nissan	87% local, Nissan Diesel: 4.3%, Mitsui & Co. (Japan): 8.7%	Sankorp (local): 37%, Nissan: 50%, Nissan Diesel: 4.3%, Mitsui: 8.7%	Nissan: 87%, Nissan Diesel: 4.3%, Mitsui: 8.7%	*Primarily SA to TNC*
General Motors	100% local (management)	Local managers: 51%, General Motors: 49%	General Motors: 100%	*SA to TNC*

Table 1. Source: Barnes and Morris, 2008.

Historically, the South African automotive industry has been widely integrated into the global automotive value chain and it is recognized as an international production base, especially among emerging economies. The sector, back in the 1960s, produced 87.000 units recording the highest level in a developing country (Hartzenberg and Muradzikwa, 2002). The recent trend is more modest, Figure 5 reports the number of motor vehicle units produced in South Africa since 1999[81]. In relation to production technologies, despite the long tradition in the sector, South Africa automotive sector has been always depending on imported technology. This is true also before the beginning of the trade liberalisation process and it can be ascribed to the fact that foreign ownership was always present, and this despite the high degree of local ownership during the apartheid period[82], when both first-tier suppliers and final assemblers operated under license from European, Japanese or American firms (Black, 2011).

Figure 5. Number of motor vehicles produced in South Africa

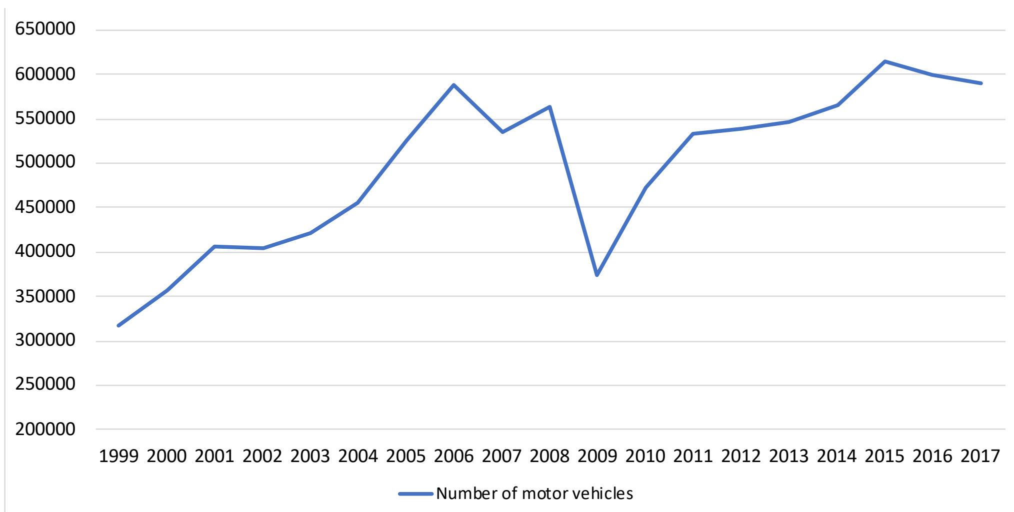

Figure 5. Source: Author based on OICA statistics

The automotive sector in South Africa went through a number of different policy regimes, that altered the structure of the industry. Despite the fact that the major change was anticipated in 1989, with the introduction of the phase VI of the local content programme giving a first signal of a shift from protection towards export orientation

[81] OICA started to collect this type of data in 1999.

[82] However, because of international sanctions against apartheid from the late 1970s, Ford and General Motors disinvested, selling their holdings to local companies. Toyota and Nissan carried on assembling under franchise, and dominated the market. Volkswagen and BMW operated through wholly owned subsidiaries, whilst Mercedes Benz maintained 50% equity in Mercedes Benz SA. Hence, in comparison to other countries there was substantially less foreign presence in the industry in the early 1990s. Barnes and Morris 2008

(Gelb and Black, 2004), the crucial watershed is 1995 when, with the end of the apartheid regime, the country undertook a process of rapid change opening up to international competition, with a strong and consistent series of policies aimed at attracting FDIs[83]. The series of government support's policies were put in place to bring about the process of industrial restructuring and to reorient and reinforce firms that, as typically happen in protected developing countries, operated at much lower scale with a focus towards the domestic market (Katz, 1987; Black, 1996). The three most important policy programmes that were implemented are the MIDP (Motor Industry Development Programme – 1995-2012), the APDP (Automotive Production and Development Programme 2014-2020) and the most recent SAAM (South African Automotive Masterplan 2020-2030).

First, the MIDP introduced in 1995, imposed a strong direction towards a deeper export orientation, with the attraction of foreign multinational companies, that were considered instrumental in bringing about the process of industrial restructuring. The core aim of this policy package was to encourage industry specialization and model rationalization through a combination of lower tariffs (25% in 2012) and MNCs ability to offset import duties by exporting. The programme entrenched a crucial principle that would shape the slackened growth and the challenges of the automotive sector in the coming years: the principle of import export complementation by which exports could earn import rebate credits. In this way automotive firms started to use import credits to source components and vehicles almost at international prices and the country experienced a rapid increase in the share of imports. Moreover, due to large losses in the industry in 1997 and 1998, especially in the component industry, OEMs increased their inclination to use imported components (Hartzenberg and Muradzikwa, 2002). A further important measure introduced in 2000 as part of the MIDP consisted in the introduction of productive asset allowance, with the aim to encourage investment in plant modernization, through a non-

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[83] The impact of such inflow is difficult to assess, as it is well acknowledged in the literature on FDI and international competition, the impact of such FDIs is very much contingent on specific circumstances of the local environment. For example, the inflow of foreign firms can trigger the creation of a competitive environment and an upgrading of local firms, but it could also narrow down the need for indigenous technological adaptation (Lorentzen and Barnes, 2004). See Essay 2, section 2 of this thesis for a complete review of the role of FDIs on local economies

tradable duty credit calculated at 2% of qualifying investments (Kaggwa et al., 2007). During these years until 2012, the policy shifted from import substitution to a rapid structural change towards export production, with both imports and exports increasing at the same time and at a fast pace (Barnes et al., 2015).

Second, the APDP, introduced in 2013, maintained the import export rebate mechanism while requiring OEMs to produce at least 50.000 units to qualify for government support. This programme was articulated in four elements: tariffs, vehicle assembly allowance, production incentives and automotive investment scheme (AIS), which marked the implementation of the first cash-based incentive (a non-taxable cash grant) for the SA automotive industry. Although the import export credit system encouraged final assemblers to invest in some automotive components, such as leather seats and, especially, catalytic converters production, the mechanisms of rewarding exports with import rebates led also to important distortions. This "policy paradox", that was extended to 2020, had the objective to push, as explained by Barnes et al. (2018)

"*OEMs [to balance] their production between domestic market supply and exports under the APDP, while simultaneously balancing their CBU* [complete build up] *import programmes with local production for the South African market. However, neither has happened: OEMs have preferred to grow both their exports and their import programmes into South Africa.*

Third, the most recent program is the South African Automotive Masterplan (SAAM) that includes a series of ambitious objectives such as: i) South African vehicle production to reach 1% of global output; ii) increase local content to 60%[84]; iii) double employment in the auto value chain; iv) improve auto industry competitive levels to that of leading international competitors; v) transformation of the South African automotive value chain; vi) deepen value addition within SA auto value chains.

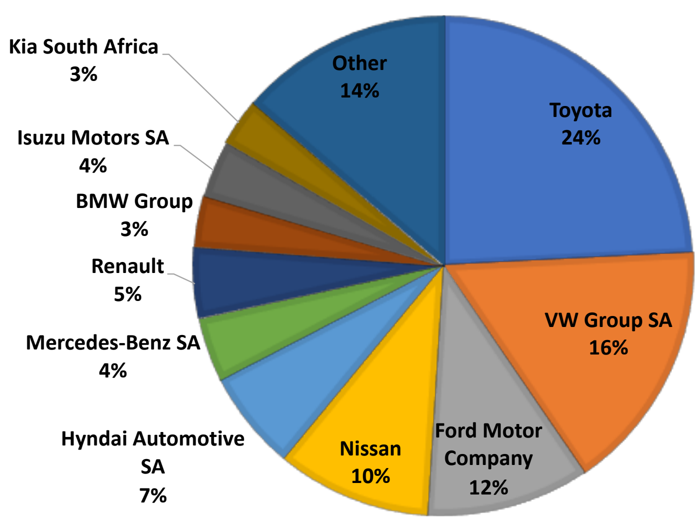
[84] This element comes with specificities as materials differ in their value. A 25% standard value is regarded as local value added on the following qualifying raw materials: Aluminum, Brass, Leather, Platinum Group Metal, Stainless steel, steel.

The degree at which South Africa will reach these goals depends on how some structural features of its automotive industry model evolve. The rest of the section is dedicated to give an overview of the sector today.

Overview of the sector

The automotive industry contributes to 6.9% of the South African GDP, to 30.1% of manufacturing output (2019 data) and it employs between 110000 and 120000 people[85]. South Africa represents 0.68% of the global production share, with 631983 motor vehicles produced in 2019 (+3.5% compared to 2018) ranking 22nd globally, and it represents 0.69% of the global market consumption share. In terms of final assembler industrial players, they are all foreign companies that tend to have strong ties with their headquarters back in Europe, United States or Japan. Figure 6 presents the overall market share, with a predominance of the Japanese and German OEMs.

Figure 6. South Africa overall new vehicle market share (2019)

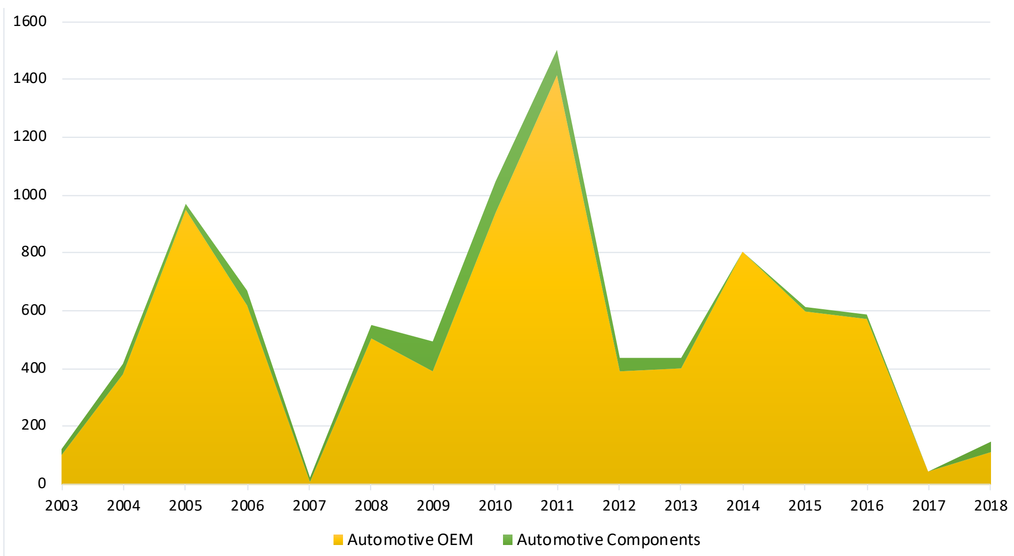


Source: Author's own elaboration based on Automotive Industry Export Council (SARS data)

[85] https://aiec.co.za/downloads/AutomotiveExportManual.pdf

The almost exclusive presence of foreign OEMs, that tend to bring also their international first tier suppliers ("follow the leader" strategy aforementioned), is confirmed also in terms of the high share of inward automotive FDIs that are coming into the country (Figure 7). Some features emerge from FDI data. First, the high majority of FDIs is in final assembly (97% of the total) rather than in automotive components, thus giving a first signal of the underdeveloped local supply chain.

Figure 7. Greenfield FDIs to South Africa, automotive sector (2003-2018)



Source: Author based on fDi Markets dataset.

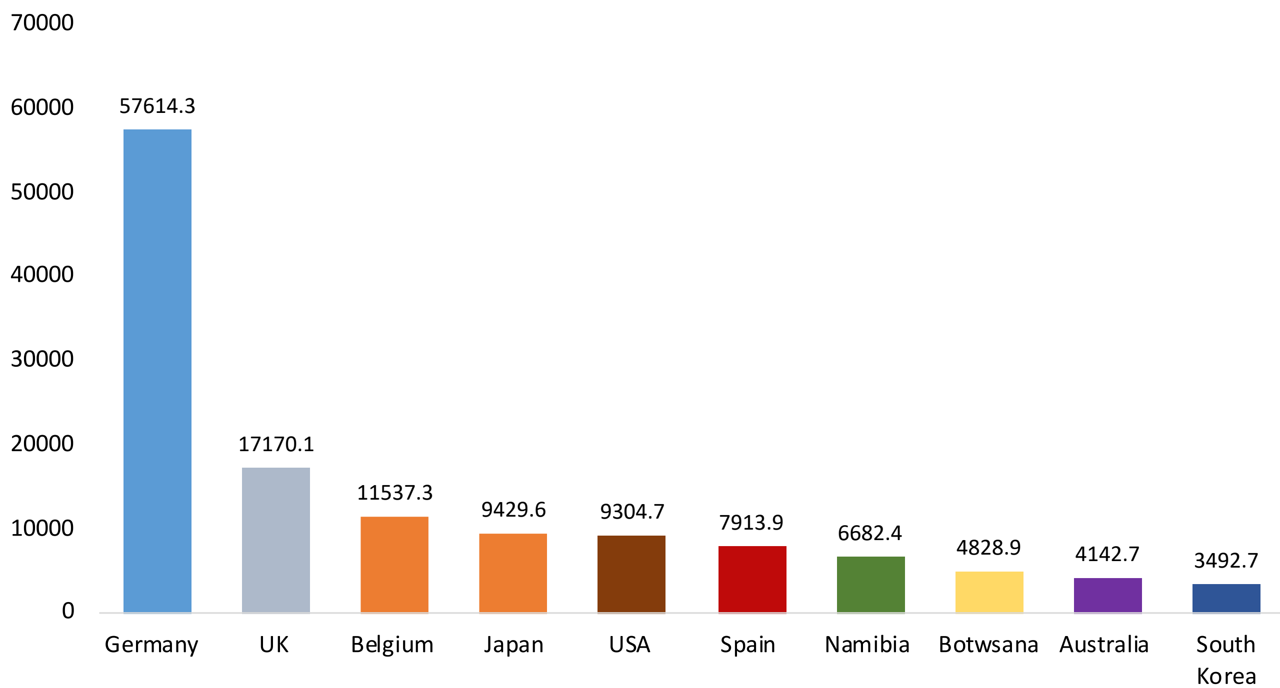
Automotive Inward FDI in South Africa

	Total	**From Germany**
Inward greenfield FDI	8876.2705	3197.7345
Automotive OEM FDI	8235.3605	2930.7445
Automotive Components FDI	640.91	266.99

Table 2. Source: Author based on fDi Markets dataset (total values 2003-2017).

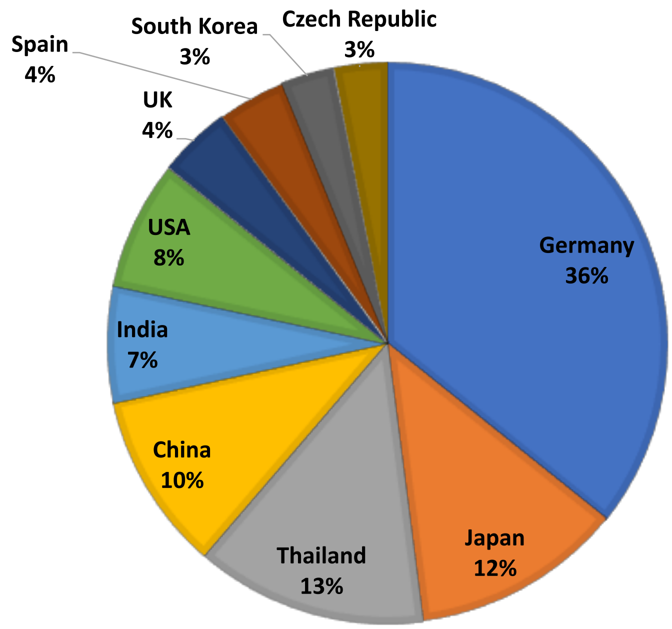
Second, within the total number of FDI, the high majority comes from one specific country, Germany, from which South Africa is highly dependent (see Barnes and Morris, 2004 for an interesting contribution on this issue). More than 36% of total automotive FDIs in South Africa come from Germany that has remained the South African automotive industry's top export and import destination for components and motor vehicles over the past two decades (Figure 8 for export, Figure 9 for import).

Figure 8. South Africa industry's top export destinations (Rand Million), 2018



Source: Author's own elaboration based on Automotive Industry Export Council (SARS data)

Figure 9. South Africa imports top automotive countries of origin (Rand Million), 2018



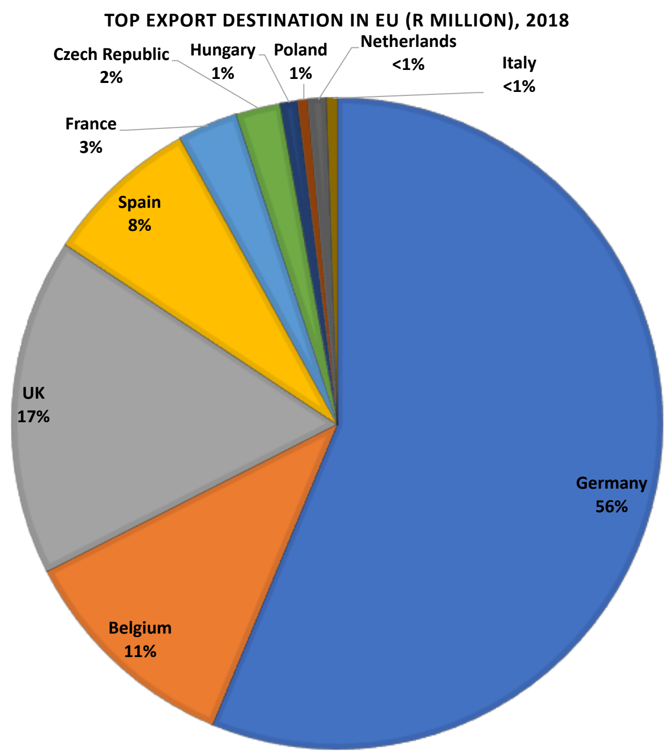
Source: Author's own elaboration based on Automotive Industry Export Council (SARS data)

The country has a high propensity to export and exports make up more than 60% of total production[86]. Also, domestically manufactured vehicles are not necessarily for the domestic market, but they are rather destined to generate the import credits mentioned in the previous section. Europe and Africa are two important destinations for South African production (Figure 10 and Figure 11): the former in terms of export value, the latter in terms of opportunity for regional integration. The automotive sector is characterised by regional dynamics, much more than global (Barnes et al., 2015; Jetin, 2018), with the most important blocks (e.g., ASEAN, Mercosur, Europe, and the NAFTA) that are all pulled together by regional and geopolitical ties. Within regionalisation, the modular production discussed above has changed the trade-offs between proximity (favouring it, with an increasing scope for deeper regionalisation), and global sourcing (downplaying the low costs advantage) (Jetin, 2018).

[86] Automotive Export Manual, 2019

The globalisation had deep consequences also in the way in which the value chain is governed. In particular, the changes in the assembly supplier relations have occurred at the same time as the OEMs increased the integration of their regional and global operations using common platforms. For what concerns Africa, regional integration is making steady progress and a key objective is to improve the prospects for industrialisation by expanding the regional market. Nonetheless, there is a long way to go in converting overarching agreements into actual free regional trade (Black et al., 2019), also considering that the market is mainly dominated by second-hand vehicles[87].

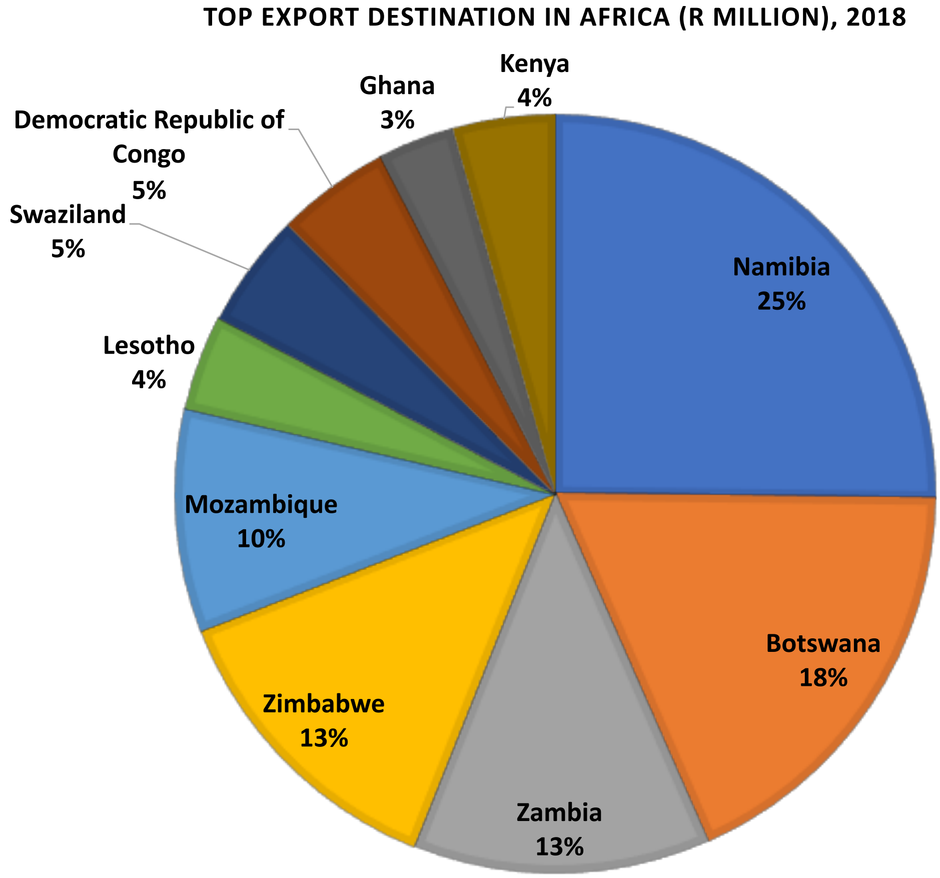
Figure 10. South Africa Top Export Destination in EU (Rand Million), 2018



Source: Author's own elaboration based on Automotive Industry Export Council (SARS data)

[87] "For countries which neither themselves constitute large markets nor adjoin such markets, an automotive space could take the form of a regional market where trade agreements grant easier market access to member states and effectively enlarge the market" Humphrey and Oater (2000: 17). This is similar to what happened in the ASEAN countries, where the automotive industry played a leading role in driving regional integration. This example points to the fact that a mix between specialization and complementation could be an important factor to create regional integration.

Figure 11. South Africa top Export Destination in Africa (Rand Million), 2018



Source: Author's own elaboration based on Automotive Industry Export Council (SARS data)

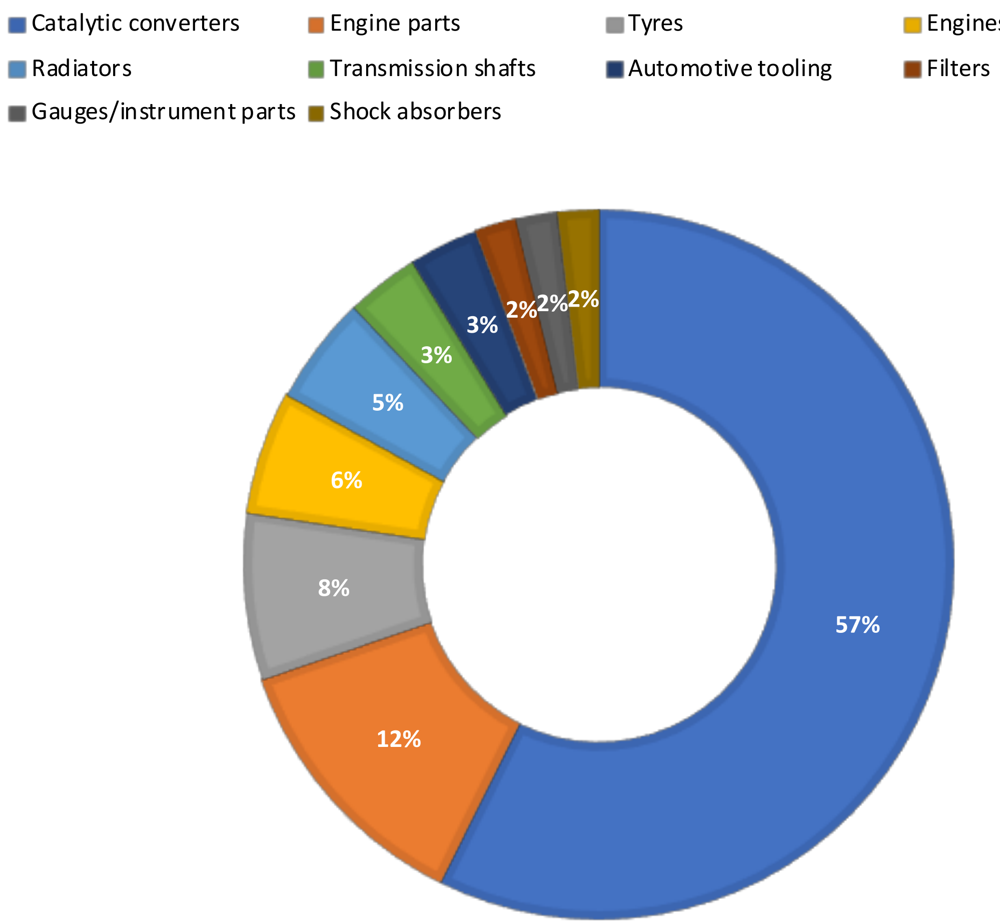
A closer examination of the South African context underlines how the exclusive presence of few, and strong foreign final assemblers narrows incredibly down the space and opportunities for South African suppliers to enter automotive global value chains, with severe effects also in terms of reaching the necessary economies of scale needed to develop productive capabilities and to enlarge their businesses.

This is observable at least under three aspects, that are three critical challenges the country faces, and that clearly emerge in our analysis at the firm level presented in the next section.

(i) *Volume, how many but also what type of products?*

The automotive sector remains scale intensive and therefore the scale of production is crucial, both for OEMs to operate effectively and especially for suppliers to grow and perform competitively. Considerable progress has been made in terms of scale of production, with current average model production that is around 65.000 units per annum, and a total of 631.983 units produced in 2019 (Figure 5). The value of exports also increased from $US 1.2 billion in 1995 to $US 10.6 billion in 2012 with the number of vehicles exported that increased from 16000 units in 1995 to 278000 in 2012, and to 351139 in 2018 (Barnes et al., 2015 updated with SARS data from 2018). Within the export of components, 57% is covered by catalytic converters which became the centre of investments by foreign OEMs for local production. In order to better exploit the mechanisms of import exports rebates, the OEMs invested hugely in the localisation of catalytic converters and by 2002 South Africa exported 12% of them globally (Gelb and Black, 2004). Despite a first positive glance, catalytic converter production has a series of limitations. They are a commodity type of product, which is for the most part disconnected from the assembly operations, thus presenting low possibility for technology spillovers. Furthermore, and with a focus on the automotive global value chain, catalytic converters are responsible for higher level of domestic value added mainly due to their platinum-based composition (Andreoni et al., 2021). Instead, most of the high-tech, manufacturing complex, components are either produced locally by foreign companies or imported directly from suppliers that have established relationships with the final assemblers' headquarters.

Figure 12. South Africa top Automotive Components Export by Value (Rand Million), 2018

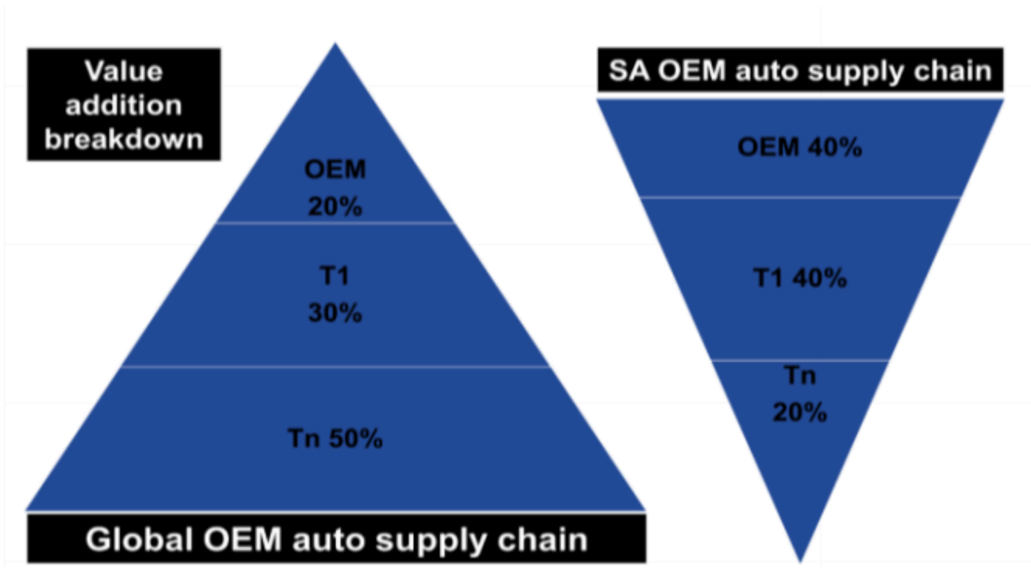


Source: Author's own elaboration based on Automotive Industry Export Council (SARS data)

(ii) *(Poor) Value addition, despite vehicle platform rationalization*

The aforementioned introduction of a small number of relatively high-volume models should have facilitated increased local content but this has been offset by ongoing import liberalization (Barnes et al., 2014). The increase in units produced has not been accompanied by higher local content, with important consequences also on firms' capabilities and technological acquisition. The average South African automotive component manufacturer generated value added equal to 2.6 times their total employee costs, a figure that compares poorly to the 4.5 times recorded at Indian and Thai firms benchmark in 2016 (Barnes et al., 2018). The poor increase in local content is particularly evident in Tiers 2 and 3 that lag behind in terms of value created and weak ties with international markets. Moreover, the lack of small and medium enterprises also engraved the problem of the missing middle, intended as companies that would act as bridges between the international oriented firms and the local companies, especially for technology diffusion (Andreoni, 2019). This situation has led to the so-called inverted pyramids, with the South African automotive industry concentrated around OEM and tier 1 suppliers, which are mainly big firms, while smaller firms are concentrated at the bottom of the pyramid and unable to grow.

Figure 13. Inverted value addition pyramid

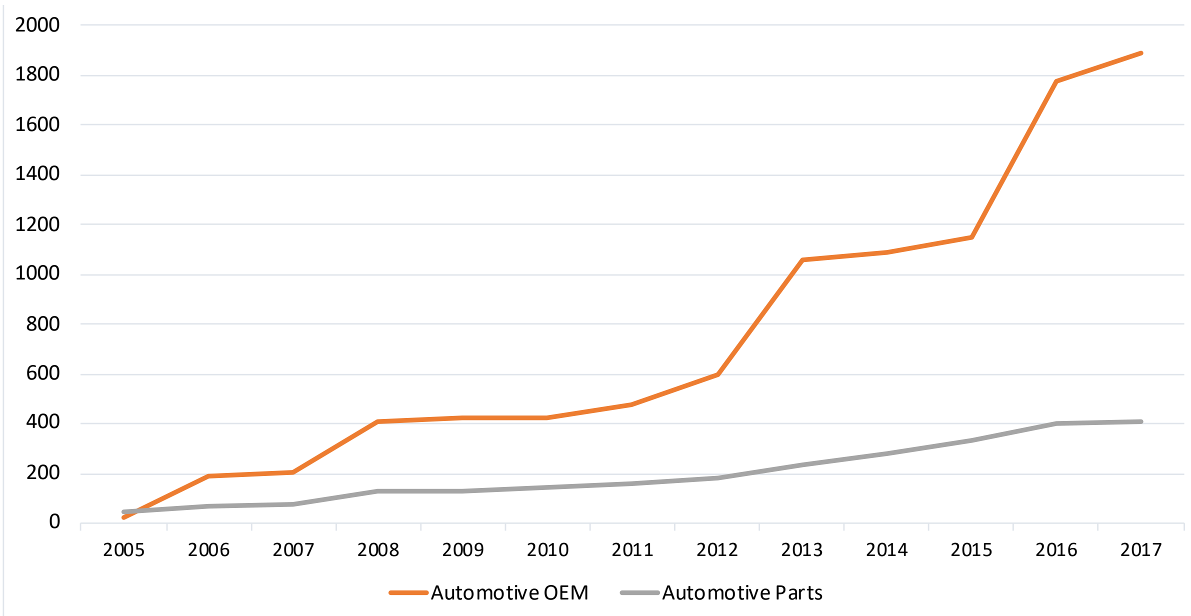


Source: Barnes, 2014

(iii) *Few, and imported, technologies.*

The lack of domestic development in terms of value chain is also reflected in the adoption of technologies within different segments of the value chain. For example, a closer examination of industrial robots' adoption, reported in Figure 14, shows the disproportion of robots' adoption in automotive final assemblers and automotive components.

Figure 14. Industrial Robots adoption (2005-2017)



Source: Author based on International Federation of Robotics data. *Notes: vertical axes, number of robots*.

In terms of technologies, the South African automotive industry has become a technology colony, "capable of introducing and industrialising selected multinational technologies, but largely incapable of contributing to processes of global innovation" (Barnes et al., 2018: 32; see also Barnes and Morris, 2004), and "driven by rigid and detailed externally generated technical specifications of an increasingly higher order, which have to be met by local producers" (Barnes and Morris, 2008:43). The country is characterised by an increasing inability to inform new products development process due to lead sourcing and global homologation tendencies. Internal engineering capabilities have been shifted away from R&D towards process function (and, if any, exclusively R&D process related) in order to produce to higher technical specifications coming from headquarters.

"[…] *Local firms have therefore lost their small R&D teams, which tended to customise product lines to South African conditions. Instead, they have invested heavily in more advanced testing equipment associated with production conformance requirements and have considerably expanded the number and quality of their process engineering management teams. Given the increased complexity of products"*

(Barnes and Morris, 2008:43)

This is also reflected in the type of FDIs that South Africa receives. Out of more than 8.8 billion FDIs inflow between 2003 and 2017, 8.1 billion are in manufacturing, with just 0.6 billion in other activities, such as R&D. All R&D takes place somewhere else and the product development process is excluded from South African firm level activities (Barnes and Morris, 2004).

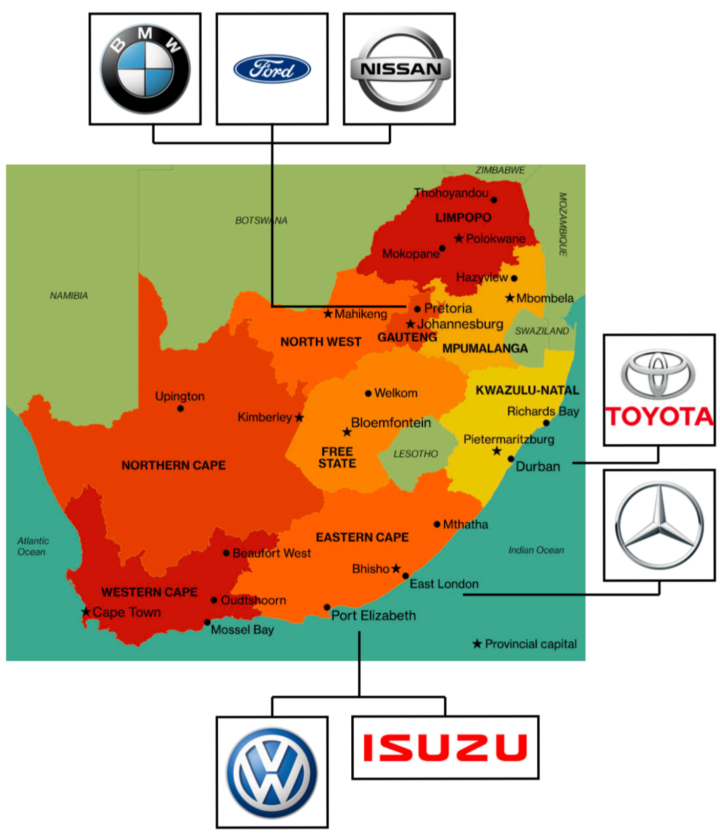
6. Case studies

The breadth (in terms of the number of players accessed in the South African automotive sector) and length of the period spent in the field allowed for the collection of a considerable amount of information. For the purpose of this chapter, the most important elements of the case studies will be presented, and then discussed in the next section. For the sake of clarity, tables will help the presentation of the case studies, and the three categories of interviews will be presented in the following order: OEMs, suppliers Tier 1, 2, 3 and lastly, system integrators and institutions. As different players present different characteristics, the conceptual map presented in the Methodology section and the questionnaire reported in the Appendix A assumed different connotations, and were adapted, according to different players interviewed. For example, while it made sense to ask suppliers if they had an ERP or PLC system, as not all of them have it, especially in a context like South Africa, the question would be superfluous for OEMs as they are at the forefront of connectivity and technology use in each of their plant (this goes back to our what question, i.e., what type of technologies are adopted.

6.1 Automotive assemblers

There are seven OEMs that assemble passenger vehicles in South Africa, they are all MNCs 100% owned by their parent companies abroad: BMW, Ford, Isuzu, Mercedes Benz, Nissan, Toyota, Volkswagen (VW). This research is based on interviews with all of them, apart from Mercedes Benz. They are "geographically dispersed" (Naude, 2012) in three main districts (Figure 6): Rosslyn where BMW, Ford and Nissan are based. Port Elizabeth where VW and Isuzu are based. KwaZulu Natal where Toyota is based. An interesting aspect that emerged from the interviews is that OEMs in South Africa participate in an OEMs purchasing council and they meet four times a year. This is something very peculiar to South Africa and linked to the effort that the government is putting in trying to engage to a series of policy to localise while maintaining flow of international business.

Figure 15. Geographical distribution of OEMs in South Africa



Source: Author

The interviews with all OEMs followed the same structure. After a general introduction of the company and of the main operations conducted in South Africa (e.g., year of establishment, model produced, number of plants in operation), the questions were divided in two parts. First, we asked about the introduction of new technologies in the last decade, with reference to the technologies we selected from the so called 4IR technologies (Figure 3 and Appendix A). Being the subsidiaries all foreign-owned, a common element emerged from the interviews is the need for all OEMs to have capital expenditures approved by the head office (in the logic of binding global reporting to headquarters), therefore needing a top-down approval with all expenses related to costs that are to be sustained by the subsidiary[88]. Due to diffusion issues, in the majority of the cases (as reported in Table 3) the focus of the conversation was around the use of industrial robots both for their wide diffusion and the rapid evolution they experienced in the last decades. Once discussed the *what*, i.e. the type of technologies, the interview proceeded to discuss the reasons (*why*) of the adoption, i.e. its main drivers. The discussion around the drivers, revealed different ways in which technologies are used, and interesting insights around the relationship between technology, production process and product design. It clearly emerged from the first interviews the opportunity to focus on a couple of production technologies (e.g., industrial robots) that are widely diffused and explore the drivers behind their adoption.

To conclude, the final part of the interviews revolved around the challenges with supply chain actors, with a focus on technology innovations and critical bottlenecks along the supply chain (Appendix A).

[88] This dynamic emerged very similar in Central and Eastern Europe (Szalavetz, 2020) and in Spain *(Aléaz-Aller et al., 2020).*

Company	Model/s produced	Number of vehicles produced	Main technologies object of the interview	Specific area of plant visit	N. of people interviewed	Employees[89]
BMW	3 Series and X3 (launched in 2018)	76,000	Industrial robots	Body shop	Two	3,500
Ford	Ranger, Everest	168,000 (ca.)	Industrial robots	Body shop, Final assembly	One	3,700
Isuzu	Isuzu KB and D-Max	n\a	Industrial robots	n/a	Two	130
Nissan	NP200, NP300 Hardbody	32,836	Industrial robots	Body shop	Two	2,501
Toyota	Hilux, Quantum, Corolla 4 doors (and previous models) and Fortuner	242,000	Industrial robots	Body shop	Three	8,539
VW	Polo new and previous series (designated Vivo)	200,000	Industrial robots, virtual reality, 3DP.	Press shop, Body shop, Paint shop, final assembly	Four	4,167

Table 3. OEMs interviewed. Source: Author based on case studies (Appendix B)

[89] Data from 2018. The Motor Vehicle Industry, African Business Information.

Keeping in mind what was mentioned in Essay I and earlier in this chapter, the so-called fourth industrial revolution is about the digitalisation of entire production systems; nonetheless such digitalisation needs as a antecedent step the automation of some production processes, which something that is incrementally taking place. Our research lies at this crossroad, between the automation of the third industrial revolution and the digitalisation of the fourth industrial revolution. Two main areas emerged from the interviews with OEMs: connectivity across and within the plant and degree and drivers of automation.

Connectivity across and within plants.

Connectivity standards appear to be similar across OEMs. They all have ERP systems, and they present a certain degree of connectivity between machines, some that are connected real time through ethernet connection, and some that are stand-alone machines that still have to be integrated into the system. All of them are monitored through international systems and they are tightly interconnected with the mother plant, where design, logistics and other pre and post-production activities are managed. Mother plants are not always in OEMs' headquarters, for example Isuzu has its mother plant in Thailand. In some cases, they have a sister plant, that produces the same models, and against which they compete. For example, VW plant in South Africa has a sister plant in Pamplona (Spain) and both plants are examined in terms of units produced, productivity, level of automation and so on. On the activity side, none of the OEM subsidiaries in South Africa has a central team for design and research, just some small offices for local adaptations, as they are all between Europe, East Asia and Australia.

All OEMs have their own connectivity and monitoring system managed from the headquarter whose direct control often in the form of "blinding global reporting" (Pardi, 2019) emerged as a clear feature across the interviews.

Each system is different although it is designed for a similar aim. Toyota uses the *poka yoke*[90] system to collect every single data in the plant. Ford uses the FIS (Factory Information System), that is a system shared between different plants and that monitors and tracks machines in real time. Sometimes, as in the case of Toyota the plant is dictated up until the level of automation by TMC – Toyota Motor Corporation (see below). Nissan confirms that the plant is subjected to the ABM system that ranks all plants globally giving a score from 1 to 5, so they know at any time where they fit in the world. Plants are tracked from raw materials to logistics.

A final note on connectivity is the supply chain management common system CX, that has been put in place across all OEMs in the country in order to place orders automatically to suppliers. Suppliers had to build interfaces to be able to read those orders, with an important step forwards in terms of standardisation.

Level and drivers of automation at different stages of the OEMs' plants *(why)*

The level of automation related to specific production technologies, i.e., industrial robots, emerged to be different across OEMs but similarly distributed along the different OEMs stages of production. In Figure 16 we reproduced final assembler stages of production. Each of the OEMs interviewed have a much higher level of automation in processes where they need higher precision in the task execution, such as in paint shop and body shop, rather than final assembly and press shop[91]. Press shop operations are standard, they require similar type of machines that are synchronised and programmed to perform similar tasks. Body shop automation is driven from both quality and quantity. After a boost in automation in the 1980s and 1990s, body shop level of automation barely changed in the last decade, while it experienced an increase in the sophistication levels of industrial robots. In paint shop there are five main activities that are all mostly automated: electro-coating, primer/surfacer application, interior painting, topcoat painting, and application of joint

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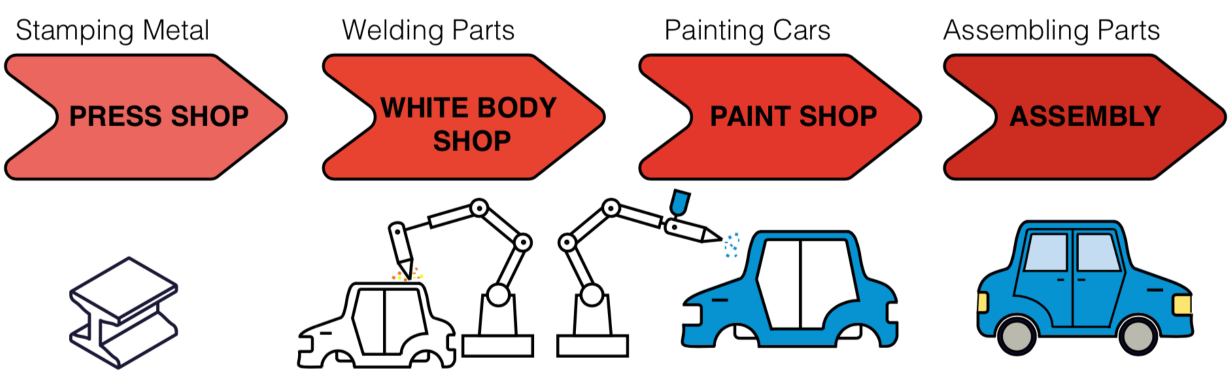
[90] Poka-yoke is simply a system designed to prevent inadvertent errors made by workers performing a process. The idea is to take over repetitive tasks that rely on memory or vigilance and guard against any lapses in focus. Poka-yoke can be seen as one of the three common components of Zero-Defect Quality Control performed by Japanese companies

[91] Only VW, Toyota and Nissan have the press shop in house. The other OEMs companies outsourced to Tier 1 press companies.

sealer (MacDuffie and Pil, 1996). Through automation and the use of electrostatic coating, paint shop quality experienced a crucial boost in the final quality of the product. As for final assembling, all our interviewees confirm that humans still do things better for the specific tasks and the coordination that are requested to perform, even if one interviewee pointed out that this may be just a matter of time. This is related to the level of tolerance of the machines that is still far from the human ability to perform task variety; multi-tasking robots exist but they are still expensive and not diffused at all among the OEMs we interview. When tasks are automated in final assembly, the main driver is ergonomics.

It is important to further consider that all OEMs interviewed put the capex equation issue at the top of the list. A technology to be adopted has to be economically convenient in terms of the return on investments; this balance is, of course, not the same across different OEMs, but it is a crucial element to consider.

Figure 16. Final assembler production stages



Source: Author

Against this backdrop, three main drivers emerged for technology adoption by OEMs. First, automation is driven by the necessity to have high quality products, thus with a production process characterised by perfect consistency. Second, automation is driven by an increase in volume (i.e., the number of units produced), as the latter leads to a high return on investment. Third, safety and ergonomics, which are related issues around the worker-machine relationship.

These drivers play different roles depending on how the OEM is organised. Flexibility was never mentioned as a driver for the adoption of new technologies, but it rather emerged as an element characterising the ways in which some OEMs use technologies. In relation to flexibility, the interview made explicit that there are two ways in which industrial robots are deployed: either through the setting up of a new set of robots that completely replace the old ones, or through retrofitting and a more flexible use of new and existing technologies. The rigidity comes from the inevitable decline in productivity when introducing a new machine into an existing operating line. In order to keep up with productivity there need to be a series of capabilities, that our study confirms to be more developed in the Japanese OEMs, such as: (i) minimum set up between jobs which depends on workers able to perform different types of jobs; (ii) capacity in the material movement system and adequate storage; (iii) layout of workstations within the system which minimises distances and times (these aspects previously mentioned in the literature emerged clearly during our interviews, see Buzacott, 1982).

A final point that emerged during the interviews and that will be discussed more in details in the next section is a sort of differentiation in how companies operate, on the basis of their nationality. There is in fact, both in the drivers that push towards further automation and in the organisation of production a clear difference between the Japanese (Toyota, Nissan, Isuzu) and the German (VW and BMW). The American Ford appeared to be closer to the German model. For example, referring to the concept of flexibility, while in the three Japanese firms, especially Toyota and Nissan, there was a unique direction in the relationship between flexibility and automation, in the sense of an increase in flexibility with the use of industrial robots, there was instead an opposite direction, towards rigidity, for the German OEMs that affirm a supremacy of a rigid use of new technologies. Rigidity emerged as something that American and German OEMs aim for, and that better complements with their objective of full capacity and standardisation of the task. "*We required absolute no deviation or variability in our process*" (Ford Manufacturing Operation Manager, 29th August 2019), reported one of the interviewees referring to the whole set of problems that emerge if there is variability of the task performed. The same interviewee reported that:

"*we want the robot to be rigid, with the volume and the huge amount of issues you have the more rigidity I have, the easier it is for me to put my fingers in any issue. I can't deal with variability*." (Ford Manufacturing Operation Manager, 29th August 2019).

These differences are reflected in different automation levels between OEMs. For instance, BMW and VW automation level is higher than the other OEMs. Ford is undertaking a process towards more automation also with the launch of the new product cycle in 2022. These three OEMs present a rigid use of industrial robots that tend not to be reprogrammed. Differently, for the Japanese Toyota, Nissan and Isuzu, the automation level is lower as production technologies are used across different production cycles and they tend to be used in a more flexible way. Apart from industrial robot's technology, some other technologies indicated in Figure 3 were mentioned during our interviews. All OEMs have ERP and PLC systems, yet only VW mentioned virtual reality technologies (that we were also allowed to see) to train employees. VW also reported that they have a pilot project on cobot.

6.2 Suppliers

The heterogeneity among suppliers was, of course, much higher than the one between OEMs, thus resulting in a more variegated outcome from the semi-structured interviews. The spectrum of the type of suppliers, both in terms of commodity produced and of ownership, either indigenous or international, create a huge variety reflected in the type and the way in which they use technologies. Generally, in terms of connectivity and digitalisation, companies in South Africa – especially indigenous companies - are in the difficult process to leap from Industry 2.0 to Industry 4.0, passing through and trying to implement automation and robotisation typical of Industry 3.0 (see Essay I). The analysis is based on interviews with the following local suppliers: Feltex, Trident Steel, Silverton

Engineering, Multitool Engineering, Supreme Spring, ATE, Auto Industrial, Smith Manufacturing and Atlantis Foundries; and the following international suppliers: MA, Sumitomo, and Sodecia (Appendix C). These suppliers are very heterogeneous, being at different level of the supply chain (Tier 1, 2, and 3) and producing different types of products; Table 3 presents their characteristics.

The most critical and common trait that emerged during the interviews is the importance, and often the lack, of volume that is still of crucial importance to reach economies of scale in this sector. More than half of the suppliers interviewed confirmed that they are way under capacity. The issue on volume tends to have a cascade effects also along the value chain. For instance, the company Trident that produces laminated steel tried to work with the steel firm ArcelorMittal to improve quality, since they intend to reduce the import of such steel, but for ArcelorMittal the request to undertake such a big investment only for the steel local demand is not enough (see Andreoni et al., 2021 for a historical and analytical contribution on the most important aspects of the agreements between the South African government and ArcerolMittal). In other words, processing the "right volume", intended as the one that allows the full utilization of machines is hard to reach in the South African context. This under capacity creates a series of bottlenecks, both in terms of productivity and of production capabilities development.[92]

[92] "The business assistance agreement reached with Mittal on the purchase of its initial stake and the commitment to a 'developmental steel price' proved not to be effective. In addition, after the initial restructuring, Mittal extracted profits from the South Africa business while funding acquisitions and investments in developed countries (Zalk, 2017). This meant that the expected benefits from Mittal's ownership in South Africa were not realized" (Andreoni et al., 2021).

Company and nationality	Technology investments: types and drivers	Main products	Plant visits	Size (n. of employees)
Feltex *South African*	They try to automate the non-value adding activities, where it is possible to predict and replicate. Drivers for automation are a mix between an attempt to: i) simplify the process ii) maintain productivity iii) control the process.	Acoustic products, NVH, armrest, headrest, firewall parts, tunnel insulators, tufted carpets	Yes	19729*
Trident Steel *South African*	Main technological investment is in machinery, e.g., blanking presses. Also, investment in technology upgrade on the data system in order to be more efficient.	Skin panels main product (e.g., for the whole Toyota chassis)	Yes	60**
Silverton Engineering *South African*	ERP system, and full integrated MRP system Introduction of new technologies is product driven mainly to get the consistency required	Inner components of the skin panels	Yes	915*
Sumitomo *Japanese*	Big push for technology adoption: *1) OEM pull, almost every investment was on the back of their requirement* *2) Market requirement, variety requires new machines* *3) Quality is probably the biggest single driver*	Production of tires	Yes	1000**
Multitool Engineering *South African*	Mainly adoption of industrial robots. Volume is the main driver for the introduction of new technologies	Jigs, tools and die making, transport hanger brackets, metal pressing (pressing company)	Yes	23**

MA *Italian*	In the body shop introduction of new industrial robots is mainly commodity/product driven (e.g., with aluminium). In the press shop (the core business) the main push is volume and productivity.	Metal sheets, inner and outer doors.	Yes	1400*
ATE *South African*	They had robotics in the past, now redefinition of core businesses. All new technologies they have been introducing are based on volume.	Different types of product for after-market, and brake pads.	Yes	3110**
Supreme Spring *South African*	Paint machines are the biggest change we have seen, huge driver in terms of quality of the final product. They have second hand industrial robots, main drivers are volume or OEM push.	Spring, stabilizers, bars.	Yes	1459*
Auto Industrial *South African*	They have ERP system and increasing number of industrial robots. New robotic cell, first time they did anything like that, to reduce the scrap rate and become more productive because the customer wanted the quality check on every single piece. Everything was done in house. Two forces that drive automation: quality/precision and productivity	Chassis components; doors brake for vehicles brake drums in the rear	Yes	677*
Smith Manufacturing *South African – licensing agreement with DENSO*	They have industrial robots and 3DP technologies to make tool. IoT is at its infancy, already installed in some machines. Slow retrofitting process. The main reason for the latest industrial robots (dispensing paste and quality check) is quality and efficiency.	Condensers, air cooler, cooling modules, air cleaner	Yes	689*

Atlantis Foundries *Germany*	It introduced new industrial robots and a new AI system. The main driver for these investments about automation is **quality,** next **efficiency** on moulding lines retrofitting things on existing lines.	Automotive casting, engine components	No	800*
Sodecia *Portuguese*	ERP system and connection of all machines via ethernet cable. New industrial robots depend on volume.	Roofs, rear ends, main floors, front rails, fire walls, doors	Yes	85***

Table 4. Suppliers interviewed. Source: Author based on case studies (Appendix C).

* *Data from 2018. The Motor Vehicle Industry, African Business Information.*

** *Data from https://www.dnb.com/business-directory.html*

*** *Data from NAACAM. https://naacam.org.za/member/sodecia-automotive-pretoria-pty-ltd/*

Drivers of technologies adoption *(why)*

Our interviews with suppliers clearly revealed that technology adoption is still a matter of integration of basic technologies, and the main aim is the automation of specific tasks, while digitalisation and especially connectivity remain marginal. Suppliers, which are both local and international, have very different levels of automation and the interviews illustrated the high degree of commodity specificities in relation to technology adoption. The spectrum covers cases from *Multitool engineering* which is a local tool company that has been recently starting to work with the automotive sector and has very little automation, to *MA*, a big Italian MNC that works very close, almost as an arm length, to BMW, and deploys the latest technologies available.

The total number of suppliers confirm to have an ERP system[93], either already in place or in the process to activate it; and they all have an interface in place to read the orders coming from the CX system used by OEMs. Connectivity investments (e.g., sensors, supply chain management, maintenance systems) and industrial robots are the two main sets of digital production technologies adopted. Some companies have been active in both types of production technologies, although it is more common to have one big investment at a time. For instance, Trident Steel made a big investment in 2015 in their plant in Durban, a *Cut to Length* line used to process hard raw material (generally used for the chassis or the undercarriage). On the connectivity side, Trident Steel also made an investment in machine maintenance and they are now able to measure the stroke rate of the lines and to control remotely every single machine running. This was possible thanks to the introduction of an innovative business intelligence system according to which they can now observe what the yield is, where the scrap is, the breaktime, and the tool change, among other functions. The entire system flows through their ethernet connection. Another example comes from the company *Sumitomo* that invested in the genealogy project introduced four years ago in order to have full traceability of components. The system is crucial for analytics, as it links elements through the process, and it helps in understanding where defects are produced.

While for the technology related to connectivity (e.g., traceability and sensoring), there seems to be a purely internal driver, i.e., that depends on firms' internal decision, for industrial robots' adoption the situation is more diversified and the drivers are both related to internal decision push

[93] Different companies mentioned the ERP system SAP as the one in use.

force and OEMs pull forces. This was also confirmed during our interview with the robotic company Yaskawa that works mainly with Tier 1 suppliers.

Two main drivers for automation emerged from the interviews with suppliers: quality of the product (often synonym of precision) and productivity, which is often related to volume as for the OEMs. Similarly, to what emerged from the interviews with OEMs, flexibility is not mentioned as a driver for automation among suppliers, instead quite the opposite.

Correspondingly to what observed for OEMs, there has been a big push in automating the painting process. For *Supreme Spring* paint is the biggest change they have seen in the last couple of decades. They automated the process as there was a lot of corrosion (both on spring and on chassis), so they upgraded the process on the coal springs with a financially important investment. *Supreme Spring* has three different plants, each dedicated to a different set of products, and they introduced electrostatic coating for coal springs, while maintaining a less automated type of painting facilities for stabilizing bars. This leads to another crucial point that emerged during our interviews, which is the fact that some specific commodities trigger the adoption of specific technologies.

A final note reported by all suppliers with an international counterpart is that suppliers' plants in South African are much less automated compared to their counterparts in Europe/South East Asia.

South African supply chain features influence technology adoption

We found that there are at least two broad categories in which we can divide technologies adopted by suppliers. A first group of technologies that is adopted in response to firms' internal strategy, such as a specific capex dedicated to quality or workers' safety improvements; a second group that is entirely OEM-driven and it comes "attached" to the bid for new products, thus in relation to the following business cycle.

Suppliers reported that supply chain in South Africa is quite short, as the OEMs reaches upstream the value chain "up to the mill", which is different from the long supply chain at the international level. Furthermore, OEMs' orders in low volume and high varieties go often against the interests of suppliers that cannot reach economies of scale, which remain a crucial factor to reach productivity.

For example, the supplier *Feltex* has seven business units in total and a higher level of variety that has a negative impact on the productivity and on the capital utilisation rate. The firm produces carpet variations for the Toyota model Hilux (which is around 100.000 units), both single cab and double cab, with a variety of more than 25 different carpet measures. These varieties and the related numerous idle times in production processes become inefficiencies that manifest themselves into the process: whenever they are doing a tool change, they ultimately lose in productivity. When new technologies come "attached" to new product or processes, they are supplied directly by OEMs that invest in the tools of suppliers, sometimes controlling the process, others leaving the process organisation to the supplier. These tools after the production cycle become spare parts, and – as reported by one interviewee - unless there are important retrofitting capabilities, the result is to have bits of machine processes here and there.

6.3 Automotive system integrators and institutions

During the time in South Africa, we undertook two different types of interviews to Yaskawa, the Japanese robotic company, and the system integrator company DESign[94]. The information gathered on both occasions was precious at it shed lights in some of the mechanisms behind robot adoption and the functioning of the automotive global value chain. We also found confirmation of hypothesis formulated before the beginning of our study and during the interviews with the other players.

Yaskawa confirmed the complexity and cost of the setting up of cells and system integrations. For example, when purchasing an industrial robot, only 30% of the cost is related to the machine, the rest is related to its integration. They also confirm that automation is not about becoming more flexible but about becoming more productive and or performing a task with better quality. In this sense, it is common to set up standard cells (also called purpose-built systems), that also have faster and more efficient implementation.

The body shop system integrator company DESign operates widely in South Africa, using a specific business model. They receive the job per hour, and the automation level (the number of people that want to have on the line) which is the most important thing. They are prescribed where

[94] DESign (together with Jandamark) is one of the most important system integrator company in the country.

and what to buy from the OEMs according to their contracts at the headquarter level, and they often purchase the technology directly for the OEMs. They confirm that the issue of retrofitting is a big challenge and that requires specific types of capabilities. In fact, when it comes to retrofit, it becomes quite complex because the vehicle cycle is around ten years, and in such amount of time, technology advances exponentially in terms of safety systems, network, etc. Thus, since retrofitting implies to have new and old robots in the same line, this means combining two levels of technology and of network product which makes the integration problematic. For what concerns flexibility, it comes in when DESign has a direction from the beginning, a direct indication that in that specific body shop two different models will be produced. But there has to be clear definition from the beginning, and it has not happened in South Africa yet.

Finally, we had the chance to interview NAACAM (National Association of Automotive Component and Allied Manufacturers), and NAAMSA (The National Association of Automobile Manufacturers of South Africa), gaining interesting perspectives on the role of different stakeholders in the local automotive industry, and important contacts to then proceed with the interviews. Also, the interview with AIDC provided an interesting lens in relation to government objectives and perspective on the development of the automotive sector (Appendix D).

7. Results and Discussion:

7.1 Case study summary

The adoption of digital production technologies is a multifaceted phenomenon characterised by heterogeneity within and along different stages of the value chain. This research finds that the adoption is closely related to productivity gains as well as the overall benefit and costs associated with technologies' adoption. Nonetheless, other elements, such as different approaches about "ways of manufacturing" and the correspondent different set of capabilities developed within organisations, play a role in the adoption of digital technologies. The results are obviously different between OEMs and suppliers. The former, whether the subsidiary or the headquarter, have full autonomy over what they decide to automate. The latter are more dependent on the standard that the OEMs prescribe and the prescriptions that are often given in terms of the type of production process. Suppliers are also more financially constrained. This section discusses the most relevant findings from the research.

Overall, our findings confirm that the main drivers to automate are ***(i)*** reducing production costs in the presence of an increase in volume (**productivity**), ***(ii)*** possibility of achieving a product of higher quality through use of robots (**quality**); ***(iii)*** possibility of eliminating dirty, dangerous, monotonous jobs (**safety and ergonomics**). Similar findings emerged from other studies, among which there are a work on technical change in the automotive sector promoted by the Massachusetts Institute of Technology (MIT) whose results are summarised in Sjösdedt (1987). More recently, similar drivers are also reported in Krzywdzwski (2020) that individuates costs, quality and precision, and ergonomics. Szalavetz (2020) individuates similar drivers in his study on Central and Eastern Europe: quality, flexibility and transparency of operations; operator workload (ergonomics); improving productivity and process efficiency; resolving problems of labour shortage (due to important labour shortages in CEE). Studies on Canadian (Baldwin and Lin, 2002) and Spanish firms (Gomez and Vargas, 2009) also reached similar results.

The link between flexibility and automation is not as clear-cut as it could appear. High levels of customization and flexibility come at high costs, both of production and organisation. Most of the times, customization and flexibility are not even part of companies' objectives. Flexibility does not emerge to be a driver in itself for the introduction of technology, but it unfolds in different ways. The high importance of volume, that is reported as a crucial element, clearly presents a trade off with flexibility, which is associated to higher level of customization. Due to the importance that scale economies still have in the production of automobiles and its components, the role of flexibility is not a crucial determinant for the adoption of new technologies.

The assimilation process of new technologies tends to happen also through mechanisms of retrofitting, which will be discussed in this section. Retrofitting is intended both as an introduction of a new machine into an existing line and as modifications regarding a single device such as to allow it to perform new tasks. Capabilities in retrofitting tend to minimise costs, but reducing costs is by far the only element that leads to it; retrofitting also reflects the customisation instances of market demand connected with specificities of the adopters (Cainarca et al., 1988). This research found that there is a high level of retrofitting both at (some) OEMs and suppliers' level. As discussed in the theoretical part and in the Essay I, retrofitting capabilities become crucial when discussing technological change, especially considering that radical and complex innovations can only be assimilated gradually and require a step-by-step approach to adoption (Cainarca et al., 1988).

A final general note on costs. Introducing new technologies is costly, both for the pure cost of purchasing new machines and building up new lines, and for the complexity of retrofitting. As found in other types of similar studies (Drahokupil, 2020), costs are the first type of obstacles that firms say to encounter. A number of suppliers, especially in the metal commodities, express how they prefer not to do a tool change because it takes time and consequently productivity goes down. The supplier *Sodecia* mentioned that one month is their time to set up a robotic cell, and from the moment they have it installed in the shop floor, it is one week to have it fully functioning.

Also, costs are those related to the purchasing of stand-alone machines (and their components for future maintenance) and to software integration costs; the latter depend on the diffusion of standard communication protocols and compatible interfaces between different machines, which make integration costs high. Moreover, there are costs related to training process, workers' resistance and management attitude; these costs tend to be lower in companies that invested more in training of the entire workforce, such as Japanese firms. Difficulties in the integration of new technologies are even more evident due to the fact that the hoped-for effects of technological change do not materialised until they are accompanied by changes in organisational structures (Jürgens, 1997).

7.2 Drivers behind automation: a new framework for technology adoption **(why)**

As anticipated, there are three main drivers that clearly emerged to push automation: productivity (in relation to *volume* increase), improved quality, safety and ergonomics.

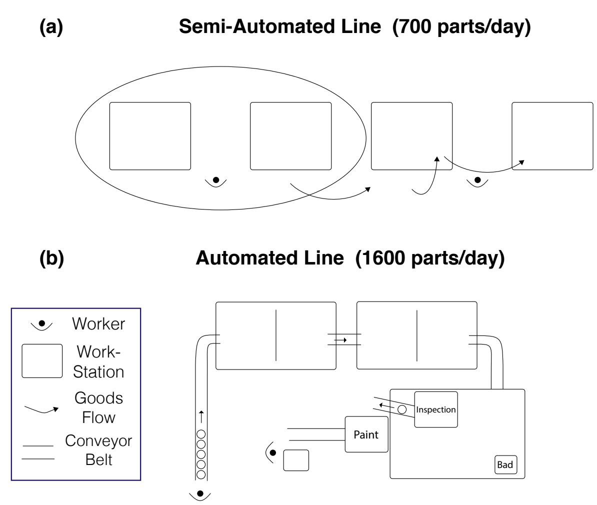
Volume has been unanimously reported as a crucial driver for automation, mainly as it justifies the economic investment while making the firm more productive. For suppliers this seems to be the single most important element, and the absence of volume prevents to make certain type of investment that would allow for more productivity. The efficiency pushing force towards continuous processes, especially in specific type of commodities, is obstructed due to the lack of proper volume.

The supplier *Feltex* has one line that manufacturers huge block of polyurethane foam. Ideally, they would do 500mt of it, but they never get 500mt of order, instead their demand is between 100mt and 150mt. The hard pressure machine used to produce the polyurethane foam works better after it is switched on for 20-30 minutes, but in 15 minutes the company already produces what it needs.

"*As soon as we have an automated process working nicely, we have to switch it off. This can create bottlenecks, and it creates huge problems with productivity. Machines are still of the type that they don't like to be switched off*" (Feltex CEO, 2nd September 2019)

This indicates that the machine itself does not allow flexibility and time-related tolerance. Volume is crucial also in metal components such as brake pads, doors, and brakes. An interesting example that gives a sense of the importance that volume plays comes from the supplier *Auto Industrial* that introduced a new robotic cell, as part of a pioneering project for the company. The interviewee reported the need to reduce rejection rate (which was 3% in 200 units). As the investment is costly, the real opportunity for the technological upgrade that allowed to reduce rejection rate only came from an increase in volume orders, which gave *Auto Industrial* the financial capacity to implement the project - they were able to insert the price in the initial 'bid'. As reported in Figure 17 they went from a semi-automated line (a) to an automated line (b).

Figure 17. Example of a cell before and after automation



Source: Author based on the semi-structured interview

With the new machine they now have one big cell, two new big machines inside, and a conveyor. They manage to reduce cycle time, while maintaining the same number of two operators that have to check from time to time that everything is happening correctly. At the back of the new cell there are three things happening: i) the balancing on the corner, ii) the inspection on the side, and iii) the paint for the final product. The robot offloads from the conveyor and puts the part in the balancing. If the part passes the balancing then it goes for inspection, and ultimately for painting. If it fails in any of these points, there is another exit conveyor, and the robot would just place the component out. Then the operator is responsible to take the part, and to check through the screen the reason why it failed.

This cell is a sort of pivot project, the first and only case where they organize the entire process of the product manufacturing in one cell, including the painting that is generally transported and done somewhere else. In this new cell there is an ideal cycle time of 68 seconds for each part, and the interviewee reported that with this benchmark in mind, they know how close or far they are from this goal[95]. There is little flexibility in the cell, as it produces two parts for the Ford Ranger, but they are very similar (4x2 and 4x4 model). This technological upgrade had also a complementary aspect related to more data coming from the machine and analysed by two engineers every day for four hours. At the time of the interview this was done manually but the interviewee mentioned the aim of the company to implement a real time data driven process.

The case just described regarded a firm's internal decision to automate. There may be also other cases, where suppliers are 'forced' to automate certain processes following OEMs' prescription related to quality or safety issues. In these cases, automation happens despite the "right" amount of volume (the volume that would allow a machine to operate at full capacity) and this may cause high levels of under capacity. For instance, *Supreme Spring* makes a specific type of spring for Toyota Corolla in a dedicated line (a line just for passenger cars that differs from the others for pick-ups) that runs only once a month, due to the fact that the spring line for passenger cars are

[95] During the interview, the plant manager reported that one side of the line is in fact 68 seconds, even if the robot could process a part every 40 seconds, instead of waiting for 28 seconds. "*If we get a part out every 70 seconds the performance is not good, and if we miss four cycles and we don't have anything there is a breakdown and the operator has to go and manually scan and understand why the line stops*".

different and in one week they complete their orders for the month. This hot forming spring line was reported to be a big investment that, due to low volume, is not exploited fully.

A final element on volume regards its interrelation with the cost variable. Indeed, for some components, it is the combination between volume and costs that determines whether a component that can be manufactured either manually or automatically is eventually produced. For instance, *MA* that produces for two different OEMs a similar product has one manual and one automated line, because of different volume and cost structure.

Improved **quality** is a crucial driver as there are specific operations that cannot be undertaken in more manual ways. International standards, and internal standards set by single firms have an important role in this sense. For instance, *MA* had to adopt the use of the laser welding robots as imposed by *BMW* in accordance with a new type of material; the introduction of aluminium that is more difficult to weld because more sensitive to heat lead to the introduction of a new type of machine. Another example of quality as the main driver, comes from the firm *Atlantis Foundries* that implemented an AI project for quality check and managed to decrease the error from 6% to 4.3%.

We found that painting technologies, both across OEMs and suppliers, were either upgraded in order to eliminate defects and have better products or outsourced (only suppliers). *Sumitomo*, the Japanese supplier that manufactures tyres, mentioned several times that the biggest driver for their investment in automation was quality, that is often linked to what the OEMs require. Two examples mentioned during the interview are: a new auto powder machine and a new stitching machine that delivered better quality, more speed and lower cost. Also, the interview from Sumitomo reported that the automation of the process enabled a better and quicker solutions to emerging problems, as it became easier to detect where the problem arises (see Appendix E for a complete description of Sumitomo process).

Ergonomics and safety were reported as two important drivers from OEMs, and especially from Japanese OEMs and suppliers. Interestingly, Toyota has two levels of automation that are subjected to different types of decision: current automation, which is TMC[96]-led and it is purely

[96] Toyota Motor Corporation

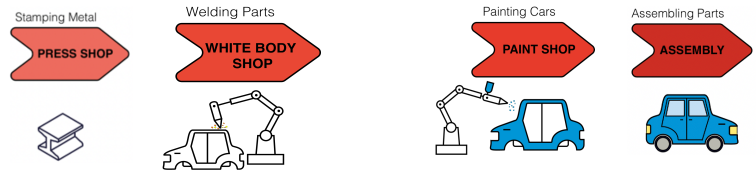
based on volume, and new automation which regards workers' ergonomics and safety; the latter can also be decided in autonomy by the subsidiary.

Some of these drivers may be more or less OEM pulled. While some suppliers say that industrial robots are completely OEMs driven, others report that it is more an internal decision. We find that the former applies to Tier 1 suppliers while the latter more autonomous case is more related to Tier 2-3 suppliers. An explanation for this could be that Tier 1 are more directly linked to OEMs prescriptions even when it comes to production process, while the other suppliers upstream are prescribed on the product and less on the process.

A final note on the drivers, discussed below, is the integration of new machines on existing lines (i.e., the retrofitting process), which tends to happen in the majority of the cases, unless companies are financially able to build shop floor from scratch for each model. It is important to underline that even retrofitting is costly. The interviews with the Japanese supplier *Sumitomo* shed some light on the fact that automation can bring diseconomies that are related to the big challenges coming from integration, especially considering that robots are around only one third of the total cost for setting up a new cell. Sometimes this challenge prevents the possibility to innovate. Other times firms decide to devote a specific part of the yearly capex to overcome such challenges in retrofitting. Toyota interviewee reported that:

"*we do incremental change in the kaizen way, new technologies for Toyota is retrofitting, which entails an entire set of different capabilities compared to the setting up of a new body shop*" (Toyota purchasing engineer, 2nd September 2019).

Table 5 presents the main findings on technology adoption's determinants that emerged from our interviews. We systematised our findings in a table where the stages of production are matched with the drivers that resulted from the semi-structured interviews. Our research reveals that within the broad realm of technology adoption determinants, the ones related to technicalities of the production processes and the products manufactured are of crucial importance, yet often overlooked in economic studies of technological change. Although the table is built on OEMs' production processes, it can easily be applied to suppliers depending on the type of task performed.



QUALITY	Improvement of the task performed in terms of better quality, more sophistication, reducing of scrap and error rates.	**X**	**X**	**X**	
QUANTITY	An increase in the number of units purchased by the customer leads to the adoption of an automated machine that increases productivity and quantity.		**X**		
COST	A reduction of costs measured in the time in which there is a return on the investment could come from more orders and products manufacturers and decrease of labour costs.	**X**	**X**		
ERGONOMICS AND SAFETY	Better ergonomics and safety become crucial when tasks that are particularly strenuous for workers, or when they become dangerous because of dangerous material or machines.		**X**	**X**	**X**
FLEXIBILITY	The ability to pass from one type of task to another in a short period of time; this ability could be in relation to product, process, volume variations, machine integration. Machine maintenance appears to be a complementary aspect of automotive firms' flexibility	(strongly depends on the priorities established at the firm level)			

Table 5. A new framework: Drivers and stages of production

7.3 Is automation about flexibility? Germany vs Japan

The outcome of this study confirmed that flexibility is not a driver nor an outcome of automation *per se*; it is rather connected to the way in which different companies produce their product, to their "manufacturing philosophy". Flexibility never emerged as a response to the question "*what did drive the introduction of the X technology?*". Rather, flexibility was more related to manufacturing philosophies and how they differ when it comes to the use of technology and to flexibility. The interview with the system integrator company DESign confirmed the differences we collected during our interviews with firms, and it shed further light on the approaches of Japanese OEMs on the one hand, and German (and the American Ford) on the other hand.

"*While the Germans are very rigid in their standard and in the quality of their stuff-machines-items, Japanese are more concerned on the quality of the product coming off the line. So, if you can get a high-quality product out of the line with old robots why would you waste money in new equipment?"* (DESign manager 4th August 2019).

Nonetheless, for those operations that are critical, and whose quality depends on the adoption of the latest technologies, the situation is different.

"*If you go to the Japanese lines here in South Africa body shops are very old but the paint shop, which is very critical, is new* [indicating that] *they have a tendency to reuse and abuse in body shop, but in the paint shop they have new high-quality machines*". (DESign manager 4th August 2019)

Japanese OEMs and suppliers confirm their capabilities in reusing industrial robots when this does not affect the quality of the process. This is very consistent with their 'eliminating waste' approach, which is part of the manufacturing philosophy of lean production that addresses elimination of waste and makes the production process flow more streamlined and efficient (Bhasin and Burcher, 2006; Jasti and Kodali, 2014)[97].

[97] Three basic policies followed by the Japanese carmakers (Cusumano, 1988): 1) just in time manufacturing, faster set up times for machine tools and stamping presses, tighter synchronisation between sub-assembly production and final assembly; 2) temporary reduction of process complexity: unnecessary complexity in product designs and manufacturing processes; 3) vertical de-integration, decreasing levels of in house vertical integration between component production and final assembly and consequent building network of subsidiaries and subcontractors. The study found confirmations in the first two elements, while we did not deepen the level of vertical de-integration of the South African subsidiary.

Toyota Production System has been targeted at removing any kind of waste and inconsistency in the production system, and it consists of two main pillars which are Just-in-Time (JIT) and Jidoka, the former "*is the idea of continuing production without stoppage by supplying only the kinds and quantities of items when they are needed for each production process (called "just-in-time"),* [while the latter *means] stopping the machine at the moment any abnormality is detected, preventing the production of defective items*" (Kikuchi and Suzuki, 2018).

The interviews with Toyota and Nissan, and with the supplier Smith Manufacturing (DENSO licence), gave further evidence of these Japanese principles. During our plant visits in Toyota, we were able to see how the production process was organised, how an industrial robot was changing position and being reprogrammed. The shopfloor manager explained how a machine used to do a specific task until yesterday could be used to do something else. This flexibility clearly presents a trade-off between the full utilisation of the machine (i.e., three shifts seven days a week) and its flexible use - as flexibility implies idle times. Japanese are more flexible, but they also use technologies "accepting" some longer idle time when the machine is not in use.

According to our interviews, such flexibility is also very related to machines' maintenance, as a higher devotion to maintenance allows a longer use of the machines and it is related to a flexible use of the machine. In fact, Japanese OEMs invest more in maintenance and they have better capabilities in maintaining machines (as repeatedly reported by both BMW and the supplier MA) because they want to use them for longer periods of time. Having at disposal more machines for longer period of times also enhance flexibility as more machines can be interchanged. The flexibility in the use of machines mirrors the Japanese organisational flexibility also along the value chain: Japanese are prepared that if they have fluctuations, they can shift models across common platforms, they can transfer workers between factories and in the worst case they can fall back on their first-tier suppliers who can also assemble (Pardi, 2007).

Our study also reveals that flexibility does not mean the same thing to different types of actors[98]. During the interviewee with BMW two types of flexibilities were mentioned; the one of robots

[98] Flexibility has been widely debated in the literature, among the many contributions: Mandelbaum (1978) distinguishes between state and action flexibility; the managerial literature distinguishes between the technological flexibility and managerial flexibility (De Toni and Tonchia, 1998). Gupta (1993) classifies four levels of flexibility (intended as the ability to manage uncertainty): i) machine flexibility (ability to process a variety of different parts effectively); ii) cell flexibility (building blocks are: workers, machines, load/unload equipment, intra cell movement devices); iii) plant flexibility (determination of costs of coping with uncertainty); iv) corporate flexibility

that perform two different tasks (e.g., when the robot has inter-changeable arms), and the one of robots that perform the same task for different models, thus displaying variability and product flexibility. While it is much easier to find the former in German OEMs, as this flexibility is embedded in the most recent technologies, the latter is absent in German OEMs and often present in Japanese OEMs and suppliers. German firms are still in the process to reconciled automation and flexibility with variety, to the point that they restricted flexibility – of the body shop – by having each line producing only one model.

"*There is a cultural difference between Japanese and German/American. The Japanese […] they have a route they follow, a process, [that] sometimes for us South Africans is too slow. But you can do whatever it will not speed it up, because its' their pace. The European people, they are fairly systematic and if they say they are going to do 605 vehicles a day they are going to do that*", (Trident Steel Director, 31st July 2019[99])

There is also a cost component and managerial element. Toyota interviewee reported that:

"*Japan works on a different cost structure from the rest of the world, if you can afford you can have it, otherwise you can't. For the German the volume doesn't matter they would automate anyway*" (Toyota purchasing engineer, 2nd September 2019)

Costs reduction, in line with the waste reduction approach of the Japanese, was always a common trait of technology adoption for Japanese firms that could see cost reduction in the adoption of new machine only if this was accompanied by flexibility (Alder, 1988; Jürgens et al., 1993; Krzywdzinski, 2020). This also implied a preference for simpler and more robust solutions and, sometimes, for the abandonment of automation, as it happened in the 1990s when Japanese OEMs after having automated the final assembly process went back to less automation due to diseconomies and lack of flexibility (Krzywdzinski, 2020). Our interview with Toyota confirms what previously emerged in the literature that there is a particular attention of Japanese firms around cost reduction and flexibility; in this sense, higher automation either moves the process towards lower costs or more flexibility or it does not materialise. The importance for the Japanese

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99 This *firm supplies all seven OEMs in the country for a metal product.*

to remain flexible is also confirmed by the plant in the Toyota City in Japan. While Takaoka 1 is fully automated, Takaoka 2 is not automated at all, it is the "most flexible plant in the world" as there is no assembly line, and this allows stations to be converted within a very short amount of time (Schmitt, 2019).

On the other side of the spectrum, European companies always saw high tech up do date automation as a pre-requisite for high quality and productivity, while flexibility has been considered less important, and more problematic due to complex reprogramming. The attention for technology by German OEMs -and their close suppliers- is confirmed by previous literature that defined BMW as a high technophile company; Birkunshaw et al. (2016) report the following extract of the interview: "*the excitement for new technical solutions is strongly present on all levels in the firms. This is the glue that holds us together*".

This was confirmed during our interview and our body shop visit in BMW in Rosslyn, where the lines are almost completely automated, and they were entirely replaced for the new car model - thus confirming the tendency of the German BMW and VW (very similar also for FORD plant) to completely set up new body shops and replacing all used machines with new ones. The fact that these companies are substituting entire lines of machines more often, means that they are required to have fewer retrofitting capabilities, intended as those capabilities of integrating new machines and technologies in existing lines.

These differences mirror different priorities that companies have and the different priorities that inspire their production. Japanese OEMs are more focused on process efficiency which includes production techniques and efficient organisation of the whole value chain. German OEMs focus more on product technology, on the art of designing and constructing a car, also due to the more recent history of Western producers in responding to a high-performance luxury market in segmented national economies (Sjoestedt, 1987; Cole and Yakushiji, 1984). This is also in line with German OEMs vertical specialization strategy, keeping high-value and high-tech production stages at home. For instance, VW's management of modular platforms is completely centralised in Germany where between 20000 and 30000 total employees are (Pardi, 2019).

A final aspect on OEMs flexibility regards the space of the body shop. During the interview with BMW and VW, interviewees reported the risk that robotic equipment sits idle during the cycle time, and the diseconomies that would require not to have too many machines operating in a small space. Japanese OEMs, in the opposite direction, maintain spare robots (as we could also see during our visit in Toyota body shop) and allow numerous idle times as they learnt how to be flexible. MacDuffie and Pil (1996) in their study on how Japanese manufacturers operate reported that they become extremely skilled at designing and moving robots around to minimize such interference.

To conclude, both types of OEMs confirmed that they are still very far from an entire synchronized body shop (so even further to a smart factory) where all the machines interact and exchange information; they all reported that they have both "online" connected machines, and stand-alone ones.

On the suppliers' level, the situation appears to be similar, which indicates "cascade effects" for suppliers that work with either Japanese or German OEMs. Suppliers of German OEMs tend to work with line and cell at full capacity performing the same type of task in repetition, when allowed by volumes and production organisation, and they have flexibility in the use of machines. Automation does not lead flexibility for the firm *Atlantis Foundries* that mentioned how automation makes the work better and with better quality but not really and not necessarily more flexible. Interestingly, similarly to what reported by Japanese OEMs, the South African supplier *Auto Industrial* puts forward another explanation regarding flexibility, as something that presents a trade off with high volumes. If there are high volumes there is no flexibility, as there is full utilisation of the machine, continuously repeating the same tasks; our entire sample of OEMs and suppliers reveal that full utilisation corresponds to a rigid use of the machine. The same company referring to increase in variety reported that:

"*in our paint lines now, we are starting to automate, we used to have a problem with changes from one task to another, the line had to stop for 30 minutes to change. The variety of components is pushing us to automate, as with a robot spray you just change the program and it can spray in different ways*". (Auto Industrial Lean Manager, 7th May 2019)

Also, different suppliers mention that an increase flexibility comes with time: as machines are dedicated to projects (i.e., motor vehicle cycles), once the project ends suppliers are more able to use the machine for different purposes – as for the OEMs this becomes spare part and they do not have exclusivity anymore. Again, this points in the direction that flexibility is an aspect that emerges not has a driver to use the technology, but more as the need to find a better way to use capital equipment.

Suppliers have a tendency to say that they need to become more flexible, but this is difficult due to financial and organisational reasons. Some of them are already in the process to overcome their challenges. For instance, within *MA*, they are developing a 'standard MA cell' that would take an inner and an outer, it would present it to a jig, and it would allow to make the assembly with no possibility of interchange. At the moment, the cell is programmed to produce only one part for the life. If tomorrow the customer dies or leaves, since it would be their equipment, they want to be able to reconvert the cell to produce another part for us. This process would allow to go towards the direction of becoming as flexible as the Japanese, even if at the moment they never change a cell while it is running.

7.4 The link between design of the product and flexibility of the machine

As the collection of data from interviews increased, we realised that there was a tendency to refer the level of flexibility to design, as if having machines that last longer would be a prerogative that each OEM has when designing new products. As mentioned by one of the suppliers interviewed:

"*Japanese tend to design products with the operators in mind but we* [referring to the Western manufacturing view] *are not that good in that, we design the car, and we try to understand where the operator fits*". (Ford Manufacturing Operation Manager, 29th August 2019).

The link between design and the utilisation of the machine goes back to Rosenberg's studies.

"*There is an intimate interrelationship between composition of demand and homogeneity of product, on the one hand, and the range of technological possibilities open to society on the other hand*" (Rosenberg, 1970).

In his study of American and English ways of producing, with a specific focus on the production of motor vehicles, Rosenberg analysed how American producers tended to standardize the machine and to suppress product variety, with a leading role of machine tool producers. The preoccupation of the productive process in the United States was mirrored by the technical perfection and the details of the final product in a purely engineering perspective by the United Kingdom, whose engineers developed an early reputation for high-priced high-quality capabilities[100]. "*English observers often noted with some astonishment that American products were designed to accommodate not the consumer but the machine*" (Rosenberg, 1970: 558).

The argument is different, although based on a similar relationship, for what concerns the comparison between Japanese and German use of automated technologies in the automotive sector. The key of any product in automotive, and more generally in manufacturing, is that the flexibility around how to manufacture a product lies in how the product was designed. The increasing complication of design led to a further effort in the integration and modularization of small material flows to certain pre-assembly station, which increases flexibility and shortens final assembly. Japanese have been much better in this, as showing by the pace at which they design new models. "*It is no accident that the development of a new model may take up to seven years in Daimler, and just three in Nissan*" (Sjoestedt, 1987).

In other words, design act as *trait d'union* between technology and organisation (Dosi and Nelson, 2010), also linking the use phases within the organisational process (Masino, 2011). If Japanese tend to produce having the operator in mind, German companies are not required to have flexibility in their equipment as they will simply change it. While design of Japanese product tends to remain more stable throughout different production cycles, so as to use similar - when not identical - platforms, German platforms change every 7-8 years. Japanese succeeded in maintaining flexibility not because of sophisticated digitalisation, but because of "well-thought-out product architecture" with regard to their manufacturability (Fujimoto, 1997). This happens to the point that both BMW and VW confirm the tendency to change almost the entire body shop with new production cycles. Ford reported the same dynamics, with reference to the new production model coming out in 2022, for which they were already setting up an entire new body shop at the time of our visit.

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[100] "*Mass production technology essentially originated in the United States. […] In America the producer of capital goods took the initiative in matters of machine design and successfully suppressed variations in product design which served no clearly defined purpose. [There was] a high degree of standardization in the machinery, which very much simplified his own production problems and in turn reduced the price of capital goods. […while] In United Kingdom the vast absence of standardization vastly complicated the process of adopting the technology and organization of mass production […] which […] seriously inhibited the growth of specialization by firms*." (Rosenberg, 1970).

Japanese OEMs use robotics for 2-3 production cycles, "*we tend to maintain it for 25 years*" said our interviewee at Toyota, who confirms also that the company makes slightly different types of platforms in a single line (single cab, double cab, SUV), therefore exploiting robotics flexibility for model derivatives. Machines are moved around the plant and there is a huge component of retrofitting that continuously happen. In addition, Japanese OEMs use specific gripping that tend to be universal during welding, to the point that they can weld eight different models in one line (Jürgens, 2020).

With reference to industrial robots' adoption and use, we can conclude that there is a difference in the use of robotic cells across process of different lines; while German OEMs (and Ford) tend to use the robotic cell at full capacity for three shifts performing the same tasks for the entire cycle, having then the cell becoming spare parts, Japanese are more flexible and more adaptive in switching on and off the cell. Suppliers of German OEMs do not perceive flexibility in relation to the adoption of new technology, and they use machines that are programmed to do one thing, and the cell remains a "black box", *MA* interviewee. Differently, Japanese OEMs inside a four robots' cell do different tasks as robots have different interchangeable fixtures to change, for instance, from manufacturing a front door to a rear door. As they use the robots better and longer, their cost is definitely lower.

A final note on flexibility regards the process of modularization. Similarly, to the implications drawn by Rosenberg on the American production processes[101], Japanese flexibility and different use of the machine is reflected in their high use of modularization in production and their extreme success at subcontracting with perfect inter firm coordination, schedule and standards in subcontracts. The field work in South Africa, although not focused on the different ways in which OEMs manage their supply management, shed further line also on this aspect.

7.5 Drivers for the adoption of automated technologies also depends on the commodities produced and the stage of the supply chain

The possibility to interview different actors at different stages of the value chain, with different technological processes and various financial, organisational and productive capabilities led to the emergence of specific type of challenges. On the production aspect, small batch productions are

[101] American were better in using the machine at full capacity, they reached quickly economies of scale and this was reflected in the higher propensity and success to outsource part of the production processes.

complex to organise efficiently, they lose huge amount of time between different tasks and they present low capital utilisation ratios. This could suggest the necessity for a different kind of flexibility that allows for the production of different products, with fluctuating volumes quantities, thus implying the reduction of the dimension of the batches. Whether this is something the fourth industrial revolution technologies may fill, it is yet to be explored by the firms we interviewed.

An example in this sense is the supplier *Feltex* that produces a different set of products with different lines that are not flexible (because the financial investment in automation is not justified), thus leading to diseconomies. Almost the entire spectrum of the suppliers interviewed work under capacity and would increase the level of automation having the right amount of volume. Variety seems to be an issue for many suppliers, not because they would need more flexibility but as they would need more volume to have sufficient demand to run lines in a rigid way but at full capacity.

On the supplier side, our analysis suggests that there is a tendency to vertically integrate. At the time of the interview in South Africa, optimal plant scale did not seem to fall as a consequence of machine availability, instead a fair number of firms is characterised by an increase of batch sizes and, whenever possible, a diminishing of product variety.

The drivers presented at the beginning of these section vary, according to financial opportunity, to manufacturing philosophy, to specific conditions of the country, and they also vary according to different commodities that are characterised by different production processes and more or less stringent standards to comply with. Metal companies, such as *MA*, *Sodecia*, *Multitool Engineering* are highly conditioned by volume. Automated machines, especially new industrial robots, are still very expensive and they are worth the investment if volumes are high. At the same time, some OEMs may require specific procedures, such as the example we mentioned between *MA* and *BMW* with the use of a new laser welding robot, where the supplier was "forced" to undertake the investment to produce with a specific process technology. In this example, flexibility is not a concern, but something that they intend to avoid, as stated by our interviewee from *MA*, "*In our commodity it's extremely rigid, we don't need flexibility. 1 door in 184 seconds and that's it*". (MA General Manager, 3rd of April, 2019)

Another interesting aspect on different commodities was revealed during the interview with the South African company *Smith Manufacturing*. According to them, robotic cells can be flexible, but it depends on the commodity and task. For instance, with heating exchangers they have flexibility and variation, as the same line can do four applications. A similar flexible situation is with a quality check robot that does inspections for 28 different configurations; it needs to be reprogrammed quite often but it is not a big challenge as they are a highly flexible, and quite integrated company.

7.6 Technology adoption is also value chain-dependent: South African dynamics and global ties

The main focus of the research has been the technological change happening in the South African automobile context. There are some dynamics related to the OEMs-suppliers relationship and to the specificities of the South African context that are important to consider.

First, the reality is very far from the rhetoric that OEMs control only strategically important parts of the value chain (Sako 2003). The interviews in the South African context confirm that OEMs have a pervasive role across the entire value chain. Also, differently from common trend across other emerging economies where there is an increasing involvement of global suppliers in partnering design and product activities (Pagano, 2003), suppliers' involvement in South Africa is still low as reflected in the inverted pyramid of value adding activities presented in section 5.2.

In every case we analysed, international suppliers tend to have product design and very often even process requirements decided by the headquarters. This confirms what Bartlett and Ghoshal (1987) stated in a study on automation in South Africa more than two decades ago, that international expansion is highly monitored and directed by the headquarter, and local subsidiaries, and operational units tend to replicate the same organisational models of parent company. Moreover, as found also in subsidiaries located in other parts of the world, they have no say in determining the composition of the product they manufacture (Szalavetz, 2020 on Central and Eastern Europe subsidiaries), thus preventing the formation of product related R&D. In the same study it is found that despite achievement in the field of cost efficiency, operational excellence and functional upgrading, the value chain position (and the relative autonomy) of the surveyed subsidiaries have barely changed, and "*they remain manufacturing units within the global organization of their parent companies, subject to hierarchical governance that has not changed*" (Szalavetz, 2020:57).

A final note on the relationship between automation and job creation, despite not being it part of our research questions (section 4.2), nor it was an aspect that we emphasised during our fieldwork.

The issue came out often during our interviews especially in relation to the specificities of the country that still has 27% of unemployment concentrated in the youngest generations. On a general level there does not seem to be a substitution effect between machines and human labour, but most of the interviewees do not exclude that this could be the case in the future. This could also depend on the specificities that characterise the present global market; differently from the previous waves of automation (1980s-1990s) where demand for automobiles was growing 17-18% a year (Cole and Yakushiji, 1984*)*, global demand is expecting to fall by millions of units in the next years[102].

The digitalisation trend in South Africa comes with a series of challenges that are job-related, such as new type of skills, related to mechatronics and engineering, that are needed as much as lacking in the country. All our interviewees confirm that, also due to the policy at the country level, firms are encouraged to maintain a balance between profits and people development, with the need to maintain both high resource efficiency and an effective use of manufacturing equipment. In this sense our analysis also confirms that increasing robot density in South Africa does not reflect the level of automation, but rather the increasing complexity and sophistication of automation[103].

8. Conclusions and implications for policy and development

The results of this research on the adoption of new technologies contribute to shed some light on some of the mechanisms that matter, when discussing the entrance of new technologies in our societies and productive structures. It is clear that firms are in the process of increasing automation although, only a slight majority have succeeded at meeting their target, and most of the times we found more automation and more sophistication of what already automated few decades ago[104], rather than a complete process of digitalisation. At the same time, when the process of automation

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[102] https://www.forbes.com/sites/neilwinton/2019/06/12/world-car-sales-will-fall-more-than-4-million-in-2019-report/

[103] There is an interesting paper that compares two manufacturing cells in the South African automotive sector, monitoring them for four months: **A** (semi-automated cell); **B (**automated cell). **A**: someone needs to open and close the door, 7.5 hours for three turns; labour costs R45/hr -semiskilled worker; quantity 150/hr. **B**: bar feeder and robotic arm, 8 hours for three turns; labour costs R26/hr -unskilled worker to change the part boxes; quantity 220/hr. The study concludes that in order to achieve the same profit as the automated cell, without reducing labour, the company would need to increase the quality rate by roughly 20%. They conclude that: "To promote labour in South Africa the effective use of equipment must be prioritise rather than the efficient use of resources. If a 10% reduction in labour is substituted into the model, the result will only be a 20% increase in profit. However, a job could be lost, the work might not be performed correctly without a worker's input, and an annual reduction of 10% in labour is not sustainable for company growth" (Hegedorn-Hansen et al., 2017).

[104] McKinsey Global Survey

occurs, this increases the interdependencies between organisations, industries and geographical areas (Andreoni et al., 2018), thereby dividing even more industrial players and their slice of the cake.

First, this analysis shows that there are important infra sectoral dynamics that shape the adoption of new technologies. Contrary to the dominant narrative, which suggests a quick and homogenous adoption of 4IR technologies across countries and sectors, our analysis suggests that the diffusion of digital production technologies is a heterogenous and lengthy process. Questioning the dominant narrative on these matters is important, as the mere availability of the latest industrial robots, or the abstract capacity to install an AI system and to build the most sophisticated sensors are not relevant if they do not find a real, and economically feasible, applicability at the shopfloor level.

A redefinition of this issue would imply to look at the expanding literature on the 'robots substituting labour' phenomenon, and the statistics these are based upon, with different lenses. These studies neglect the role of the firm and its dynamics in the mechanisms of technological adoption, and also tend to underestimate the type of tasks that are substituted (Graetz and Michaels, 2017; Acemoglu and Restrepo, 2017; Chiacchio et al., 2018). For instance, in the example of the laser welding industrial robot adoption, the task performed by the robot was already automated; therefore, this new robot does not reflect more automation, but rather an increase in the sophistication of the current level of automation. On the contrary, it can happen that – as reported by the supplier *MA* - labour increased as more indirect jobs were required. Data are important and the few data available on new technologies, such as the International Federation of Robotics, are of crucial importance to understand the sectoral, country-level and type of application trends. Yet industrial robots are different, and they are used in different ways. On the pure basis of a dataset, a robot adopted in a German OEM is the same as one adopted in a Japanese OEM. Nonetheless, the fact that German OEMs change robots much more often would need to be considered in aggregate studies, as this quite considerably change the relations with labour and the reorganisation of production that are then given for granted.

Second, we found that digital production technologies are not widespread among automotive manufacturing firms in South Africa. The lack of diffusion finds a general exception on industrial robots that are fairly diffused in the automotive sector because they provide a wide range of benefits, and a series of complementarities. They also have some impediments such as costs, organisational bottlenecks, issues with skills and training programs that are often underestimated, but they are important obstacles for firms. Retrofitting emerged as a preferred way of implementing digital production technologies in Japanese OEMs, but also as the more viable way in which suppliers try to upgrade their production processes. Retrofit requires high productive capabilities that are not embedded in every firm we analysed, they rather come from pre-existing productive capabilities and a deep understanding of how machines and production processes work.

From a policy level perspective, promoting the adoption of 4IR technologies adds another layer of complexity to the following narrative. Once OEMs have been attracted to the country, and after the initial investment through the establishment of required skills, bulk infrastructure supply and the necessary support institutions, the government needs to push OEMs towards further deepening of their investment for the development of an actual automotive industry, with local production of high value adding activities. Upgrading the technological structure goes in the same direction and technology adoption should rather be viewed as an enabler of competitiveness (Kaziboni et al., 2018). When, for example, there is no stable Wi-Fi connection, 4IR technology upgrade, which depends on connectivity, is most likely a waste of money and time. These elements are highly interrelated as, eventually, it is the plant location that determines the level of automation of the assembly line. Moreover, automating in different firms may require a different set of instruments. OEMs and suppliers have different dynamics underneath their decision to adopt new technologies, as they tend to be characterised by different production processes, a more batch type of processes for the OEMs and more continuous type of processes for suppliers[105].

In addition, South Africa plant level studies found that reaching complete automation causes automation costs to increase exponentially while the personnel costs decrease only linearly, with higher total costs (Gorlach and Wessel, 2008). In a study by Kaziboni et al. (2018), on the adoption of predictive maintenance and monitoring systems, a number of issues emerged: (i) the cost and

[105] Alcorta (1995), expressed it in the following way: "*In the case of assembly [firms …] there is considerable evidence that under pressure to reduce costs final assemblers are requesting certain component manufacturers to undertake the production of a range of parts, sections or systems of a vehicle rather than having to put them together themselves. The idea is to have the component manufacturers delivering just-in-time whole sections or systems of the vehicle, reducing the number of final assembly steps and, as a result, easing significantly the assembly process. [Differently, for component producers] industrial automation would seem to be leading not so much to disintegration but, on the contrary, to vertical integration.*"

availability of bandwidth in South Africa lag behind most countries; (ii) operating this type of machines and analyse the data require specific skills that are scarce in South Africa; and (iii) there is an issue with data ownership. These challenges point to the fact that technology in itself does not provide a competitive advantage; rather, it is how it is applied that can lead to firms upgrading their production.

Third, the automotive sector is increasingly skewed in terms of power relations. South Africa represents clearly that “peripheral Fordism” highlighting the marginal place that many emerging economies continue to occupy in the international division of production and labour (Pardi, 2019). The situation emerging from the South African study told a story where OEMs have the power to dictate not only the number of cars and the model to produce - an aspect that already gives them a powerful role when sitting at the government table - but also where and how they source their material inputs and which types of technologies to adopt. These technologies are, in the majority of the cases, linked to the specific job performed by suppliers for the OEMs, confirming the role of South Africa as a “technology colony”. This element limits learning and knowledge spillovers that may come only after the production cycle and with complex retrofitting mechanisms (see also Durand and Milberg, 2018 for a similar argument on intellectual monopoly in GVCs).

There are two key variables that are necessary to sustain the development of the automotive industry with the aim to upgrade the economic structure (Barnes et al., 2015): **(i)** the creation of domestic and regional market, whose advantages should derive from investing in an economy with increased market depth (see this point in the next section on conclusions and policy implications), i.e., market that have a horizon in terms of internal demand; **(ii)** the creation and upgrade of competitive capabilities that would encourage further investments. On the regional integration, there is a long way to go for South Africa especially considering its isolation from fast-emerging economies.

In 2018 there was an agreement to establish an African continental free trade area, with a recognition of the need to invest in the auto industry, as a sector that is scale intensive, and needs volume to justify investments especially by components suppliers (Black et al., 2017; Black et al., 2018). On the competitive capabilities, if South Africa was never fully able to leverage on exporting spillovers which are critical for synergies’ expansion and increase in productivity, and the close link between export activities and accumulation of knowledge still have to materialise

(UNCTAD, 2016). Particularly problematic in this sense is the lack of medium size manufacturing firms that are essential to bridge MNCs and SMEs locally, with the increasing phenomenon of the "missing middle" (Andreoni, 2019). These companies, such as Tier 2 and 3 in the automotive sector are not able to capture a high-value niche that are crucial to develop due to the lack of multiple sets of complementary production capabilities across and beyond the value chain.

To conclude, another crucial question that policy makers have to ask themselves is: "how much space really exists for emerging economies entering the automotive sector when global production overcapacity is in excess of 30% and the majority of vehicle assemblers are struggling to have the expected return on investments?". Whichever is the answer, selective industrial policies that may respond and apply to different circumstances are needed to support and drive upgrading (Wade, 1990). An industrial policy that shapes technological direction according to needs and obstacles of specific countries is of crucial importance, especially considering that many developing countries are still trying to cope with the third, when not the second, industrial revolution. Therefore, a gradual, incremental approach is necessary both for feasible investments and for the building up of productive capabilities (Andreoni and Chang, 2018), in the absence of which new advanced forms of technological and organisational integration will remain a technological mirage.

Appendix A

1. Questionnaire used during the interview

Technology

- What is the most important technology introduced in the last decade? And in the last five years?

- Did you introduce any of the technologies mentioned above? When? o Which was the main driver behind the adoption*? **(costs, standardization, flexibility, customization, new materials pull)***

- *In which step of the production process was the technology introduced?*

- How (If) did the increase in automation redefine the **tasks** performed in the manufacturing unit where it was adopted?

- Do you use any Enterprise Resource Planning system? When was it introduced? How does it benefit the firm?

- Are there any pivotal projects across manufacturing units testing system integration & IoT?

- In terms of flexibility of the production system, which one is the technology that had a stronger impact in terms of increasing flexibility? Relationship between product variety and product quantity

- Does, and in which aspects, the technological level of headquarters differ/push from/for the South African plants?

- Connectivity: are data coming from the final product already being used to improve the product/predict maintenance? How are these data integrated/received by the firm?

- Which is the main supplier of such technology? Any in-house development of automated devices?

- Did the increasing automation imply changes in product design or in product features and performance?

Organisation

- Are your suppliers using automated technologies (the three mentioned above)?

- In order to manage suppliers' relationships, which kind of technology do you use to place/receive orders? (manual purchase by phone, fax, email; electronic purchase EDI, Electronic handling of inventories, purchases and invoices, real time supply chain management...)

- What type of challenges do you have when engaging with your suppliers? Capabilities of suppliers to standardize/respond to customer

- Do you use any supply chain management software? Are suppliers a constraint/trigger for this?

Appendix B

1. List of OEMs interviewed.

1. **BMW** was established in January 1960 and changed its name into BMW (South Africa) (Pty) Ltd on 1975.
2. **Ford** South Africa (Port Elizabeth) (Pty) Ltd was registered in 1923. The name changed couple of times during the apartheid regime when the company disinvested from South Africa. The name was changed to Ford Motor Company of Southern Africa (Manufacturing) (Pty) Ltd in 2000 when Ford re-invested in South Africa.
3. **Isuzu** Truck South Africa (Pty) Ltd was registered in 2006 and a joint venture was established in 2007 between Isuzu Motors Ltd and General Motors South Africa. The company underwent a name change to Isuzu Motors South Africa (Pty) Ltd in July 2017.
4. **Nissan** (South Africa) (Pty) Ltd was established in 1963.
5. **Toyota** was established in May 1961 and underwent numerous name changes. At the end of August 2002, there was a takeover by Toyota Motors Corporation in Japan. As a result, there was a restructuring worldwide with the Toyota SA Manufacturing operations falling under Toyota South Africa Motors (Pty) Ltd.
6. **Volkswagen** South African Motor Assemblers and Distributors (SAMAD) was established in 1946 and in 1966, the company underwent a name change to Volkswagen of South Africa Ltd.

Name of the company	**Date**	**Person/s interviewed**
BMW	30th August 2019	Mrs. Zinhle Thela (plant manager) and Mr. Vincente Sigudhla (body shop manager)
Ford	29th August 2019	Mr. Ockert Berry (VP operations)
Isuzu	26th August 2019	Mr. Celestin Ndhlovu (Manager Business Strategy)
Nissan	2nd May 2019	Mr. Deve Revell (General Manager Purchasing)
Toyota	2nd September 2019	Mr. John Oliver (Vice President Production Planning and Logistics Operations) and Mr. Naven Govender (General Manager)
Volkswagen	26th August 2019	Mr. Thomas Schaefer (CEO) Mr. Ashwin Harry (Head of Production) Mr. Jens Bruecker (Director of Production)

Company	Technology Introduced	Technology features	Drivers for technology adoption (and flexibility)
BMW	New line of industrial robots Increasing modularization in the body shop	Intention to use robots for two cycles now, but at the moment once dismissed they no longer keep spare parts They do not see major leaps forward in technology, it is incremental Jandamark – system integrator company - supports PLC better than Siemens, as they have great support for KUKA Every time that there is a new model, they build a new body shop. In the current the process is modularised with four buffers in four parts of the body shop They always have buffer apart from the assembly line, where a conveyor that moves with people Some robots with more than one arms, some robots can interchange arm Product changes are big, even materials, German big jumps vs Japanese kaizen approach (small incremental changes)	The main driver for technology automation is quality, safety and ergonomics. For other technologies like carbon fibre/water and laser cutting is just material driven (lightweight and strengths) The way in which a technology is used matters. If you use a technology for a full cycle with three shifts 7/7 then it cannot be re-used. Whether a robot is kept for another cycle depends also on design and space. Design is key, if the model is similar if we can use the same technology. As for space, it is better to have a new one that two old ones that can perform the same task – this is why with new products they changed all the robots in the bodyshop. Laser welding robot is about perceived customer quality and cost manufacturing Maintenance of the industrial robots. Two types: maintain to have the robot work or to make it last. Toyota has predictive maintenance; they invest because they want to keep robots longer Flexibility is about customization, but there is no customization, as the South African plant – like an increasing number of plants around the world- just produces one model. Adopting these new technologies is about volume, there is no flexibility as they do not want to reprogramme.
Ford	Factory Information System Global Data Information Analytics to track logistics 30 additional robots in the body shop and needed to reprogramme huge challenge	Technologies change with the product cycle, otherwise too much refurbish that is too complex. No variability and absolutely no variation in the body shop Rigidity is pursued within production: "*The more rigidity I have the easier is for me to put fingers in any issue. I can't deal with variability*" Increase modularization in the new plants, more buffers (for the New Ranger)	Drivers for technology adoption: • Consistency of the task performed is the main driver for production technologies. *(i.e.,* quality of the product*)* • Cost cutting, volume is key. • Ergonomics Product design and product technology are attached to the use of any type of robotics Drivers to change the robots are different also if maintenance capabilities are different: "The Japanese are very good in maintenance

			with the equipment, very meticulous, in the Western culture this piece of knowledge is not that good"
Isuzu	Pretty old body shop, the only recent introduction of new technologies relates industrial robots.	Technologies tend to be used with more variety. Japanese tend to be more creative, because they generally work at lower volumes and this pushes creativity In terms of machines flexibility, there is more of it when processes and products are similar. Flexibility a robotic cell can do more than one type of applications and along more than one production cycle (not easy there are overlapping, need to run both product lines for a period of time)	Investments in new technologies have to be justified, if there is no volume there is no justification, so volume is a very important aspect (similarly to Toyota). This also has a cascade effects with suppliers (e.g. with HESTO the two lines they have) Investment in new technology is purely driven by new models, as there is no single part that is shared, so there is a big investment in the tooling Drivers for automation: quality, safety/ergonomics and how strong is the business case. • Quality: where you need more repeatability (e.g., paint shop). In the paint shop the payback was not on the robotics, but we save paint and big efficiency transfer. This was a strong business case.
Nissan	Industrial robots ERP system SEP CX system to communicate/release orders to suppliers	Robots on the production of a ladder frame, for high level of accuracy New hand over robots (robots that inserts panels into the press) Paint shop robots, the line is automated the body is hanged	Strategy in terms of automation is to look at: *1) Employees safety* *2) Critical operations* Also, payback plays a role (economic decision). Retrofitting is difficult, testing phase difficult can take months; if you install robots in a close cell either you have a very sophisticated design or you need to build a new cell, duplication is costly. It's easier for us to bring a robot in an existing cell
Toyota	Industrial robots	Maintenance is critical They do incremental change in the *kaizen* way, thus new technologies for Toyota means retrofitting (which entails an entire set of different capabilities compared to the setting up of new body shop) Japanese work on a different cost structure to the rest of the world "if you can afford you can have it, otherwise no".	TMC system dictate around the level of automation Introduction of robots based on quality, safety (which is critical) and ergonomics For Toyota, there is a clear trade-off between flexibility and full utilisation; they can scarify the full utilization of the machine. Of course, robotics has increased flexibility! (flexibility for modules derivatives - single cab, double cab, SUV- not for other product)
Volkswagen	3DP in R&D	Planning investments on better predictive maintenance, "on the press shop if the press goes down we are dead"	The main reason to use classical robots is 1) geometrical accuracy (quality repeatability) 2) productivity (here the cost of labour matters)

(sister company in Pamplona, Spain) **Building two models, POLO and VIVO**	Project of using cobots Virtual training equipment to train people before getting them to the line New handling machine in the press shop (to eliminate fatigue)	The main challenge for their suppliers is volume, not productivity nor capacity (suppliers are very fragmented) In their shopfloor there are both stand-alone machines and conveyor/integrated and connected machines in the proportion of 60% *vs* 40%. In some areas this is problematic, as there can be obstacles for integration with tac time They use the cell in a very rigid way, they don't want to reprogramme, unless they change model. "*If you take an industrial robotic station you must consider availability and layout design - more or less decoupling, see example with the Japanese that have less decoupling, but they don't have 100% uptime*"	Another drivers for new technologies are new materials, that tend to increase complexity because of weight and other requirements The feeling is that to have more robots you have less flexibility, it's very difficult to set up industrial robots (*even if technically robotics increases flexibility because of the all reprogramming you have around it*). Men allow more tolerance, robot is more accurate It costs lots of money to create flexibility Considering product design, they are very technology driven and it creates complexity which leads to further investment. *There are smart ways of designing, Japanese keep the product stable for longer* (Don't automate waste)

Appendix C

List of suppliers interviewed

South African:

Name of the company	**Date**	**Person/s interviewed**
Feltex	2nd September 2019	Mr. Ugo Frigerio (Managing Director)
Trident Steel	31st of July 2019	Mr. Helgaard Meaker (Automotive Sales Director)
Silverton Engineering	6th August 2019	Mr. Boshoff Martin (Managing Director) and Mr. Von Nievwkoop (Plant Manager)
Multitool Engineering	6th August 2019	Mr. Orlando (General Manager)
Supreme Spring	26th April 2019	Mr. Mark Barley (Managing Director)
ATE	7th May 2019	Mr. Gary Ting Chong (General Manager)
Auto Industrial	7th May 2019	Mr. Mlondi Chiya (Lean Manager)
Smith Manufacturing	14th May 2019 and 2nd September 2019	Mr. Gerald Naidoo (Plant Director)

International:

Name of the company	**Date**	**Person/s interviewed**
Atlantis Foundries	9th May 2019	Mr. Rautenbach (Senior Manager: Technical Engineering) and Mr. Gatenby (Senior Quality Manager)
MA	3rd of April and 30th of August 2019	Mr. Henk Van Der Merwe (General Manager)
Sumitomo	3rd of September 2019	Mr. Thomas Copley (Manager Divisional Head: IT)
Sodecia	7th September 2019	Mr. Jose Pereira (Logistic and Plant Supervisor)

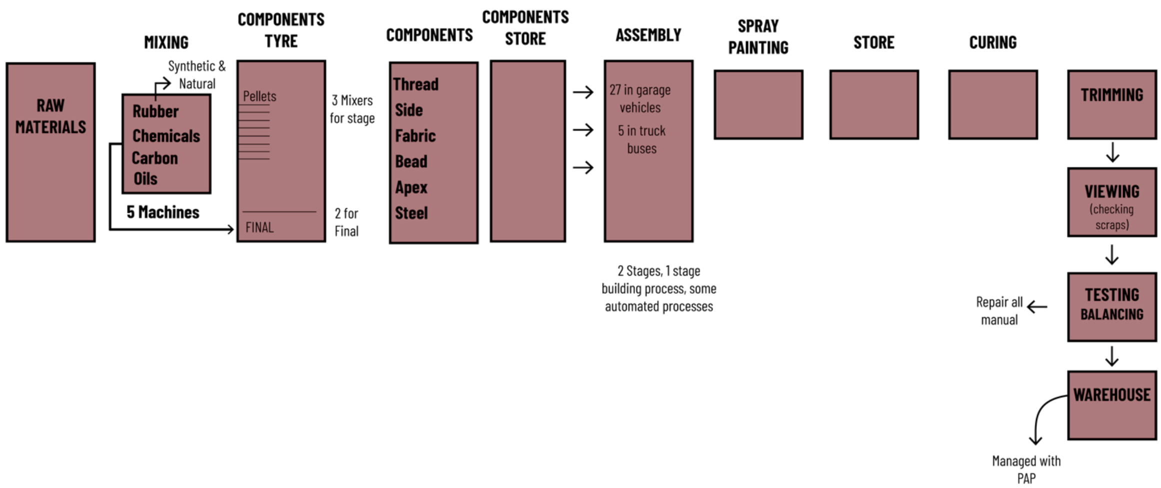
Appendix D

List of organisations and system integrator firms interviewed

Name of the company	Date	Person/s interviewed
NAACAM (National Association of Automotive Component and Allied Manufacturers)	12th April 2019	Mr. Renai Moothilal (Executive Director)
NAAMSA (National Association of Automobile Manufacturers of South Africa)	24th April 2019	Mr. Norman Lemprecht (Executive Manager)
AIDC (The Automotive Industry Development Centre)	2nd May 2019	Mr. Nkumbuzi Ben-Mazwi (Executive Strategic Projects)
Yaskawa	1st August 2019	Mr. Kurt Rosenberg (Customer Service Manager)
DESign	7th September 2019	Mr. Gavin Walter (Senior Manager Sales and Estimations)

Appendix E

The visits to the shopfloor included detailed explanations regarding the production processes with specific reference to the use of automated technologies and specific drivers. Below the production flow of Sumitomo production tyres is reported.



Conclusion and policy implications

Here, our ride into the realm of digital production technologies comes to an end. In retrospect, technological change, technological diffusion and technological adoption have been unpacked and observed undertaking two perspectives: a theoretical one, with a focus on the challenges regarding 4IR technological innovations; and an empirical one centred in the automotive industry, that studied both the diffusion of industrial robots through the use of econometric techniques, and the drivers for technology adoption at the level of the firm with the use of qualitative methods.

Conclusions presented at the end of each chapter contributed to developing a global picture of technology adoption challenges. The present section attempts to develop this picture further and to put forwards a series of policy implications, in a way that allows to reflect and triangulate the evidence from different chapters. Four main parts will follow: (*i*) the key messages from our research into technological change; (*ii*) a discussion on industrial policy implications based on the South African context; (iii) a reflection on the theoretical and empirical contribution of this work; (*iv*), the limitations of this research with a final consideration of the turmoil that will follow the covid-19 for industrial organisations.

1. So, how does technology adoption happen?

Technological adoption is a complex, multifaceted phenomenon, that presents different characteristics across countries, industries and firms. As technology moves between different stages - from invention to innovation to adaptation to modifications, as explored in Essay I - adopters experience different benefits and incur different costs. In other words, what represents a successful implementation depends on the stage of technology development. This thesis began by introducing the concept of technological change and continued by examining technology diffusion and adoption. Two interrelated perspectives were provided: the firm level and the GVC dimensions. Each of these perspectives was then unpacked and analysed along two dimensions of interest: technological change and the organisation of production.

In this process, the thesis emphasises the importance to consider each country's stage of development when assessing technological change - both in its form of technology adoption and diffusion - as the driving factors in adopting innovation also transform when innovation diffuses (Waarts et al., 2002).

Five key messages can be distilled from this research:

i. Technological change is the result of an incremental, rather than disruptive, type of process. The sequence of incremental innovation is most often more important in terms of its economic consequences than individual technological breakthrough. Within this process, basic and intermediate pre-existing capabilities discussed in Essay I play a crucial role.

ii. In the automotive sector, industrial robots are not determined by the presence of FDIs per se, and they better diffuse in countries that have more active local ecosystems (i.e., that innovate more and that export more in the same automotive sector). Industrial robots' diffusion depends also on different segments of the value chain, as presented in Essay II.

iii. In the automotive sector, there are three main sets of drivers for technology adoption: volume, quality and ergonomics. Flexibility does not appear to be a driver for technology adoption, rather a way in which different companies use technologies. Once adopted, digital production technologies are used in different ways: whether they are used at full capacity, thus in a more rigid way, or they are rather implemented in a more flexible manner. These features affect economies of scale and innovation processes (Essay III).

iv. The path towards the fourth industrial revolution presents several challenges. An increase in the level of automation is simply one facet of it; the other -probably more relevant in terms of disruptive impacts - is the full digitalisation of production systems, which requires a high number of sophisticated infrastructures, a highly skilled working force and a wide set of dynamic and productive capabilities.

v. The GVC perspective – in the automotive sector – sheds further lights on how big MNCs shape the direction and intensity of technologies' adoption. The complex power relationship between governments and MNCs shapes the possibility and opportunities for local production ecosystems to link up to the GVC and to nurture the domestic ecosystem.

2. The space for industrial policy and fourth industrial revolution technologies in South Africa

The fourth industrial revolution is an incremental change towards the digitalisation of entire ecosystems; this increases the challenges for countries that are not technologically advanced, and that may suffer from the lack of the necessary capabilities to integrate new technologies. New technologies mean different things, as they highly differ across countries, and they depend on the skills level, industrial policy, FDIs policy, and local institutional engagement with MNCs.

Our study of the literature and our empirical analysis during the period of fieldwork, shed further lights on a series of challenging elements for South Africa, that could serve as a tool to examine countries at similar stages of development:

a) **Local capabilities are essential to GVC integration; they should increase not be eroded**. South Africa is characterised by very peculiar historical and institutional trajectories. After the end of the apartheid regime in 1994, there was a progressive erosion of local capabilities in the automotive sector, and more generally, in the manufacturing sector (Barnes et al., *forthcoming* 2021). In a similar way to what happened to other peripheral countries, such as Slovakia, South Africa has been characterised by

> *"export-oriented foreign-owned factories* [that] *often assemble high-tech, high-quality goods with a relatively high value-added from components that are either imported or produced locally by other firms"* (Pavlinek, 2016 in a study on Slovakia).

The erosion of productive capabilities went in parallel with the erosion of R&D, as discussed in Essay III. In South Africa, the international configuration of the automotive value chain did not include R&D development, that was rather kept outside of the country. In a sector where the technology-intensive and R&D driven character is evident, having a decreasing level of R&D capabilities means that both the value addition and the innovation potential are happening elsewhere.

R&D is extremely concentrated globally; in 2017 over 75% of R&D investment was made by only ten countries[106]. Only a few developing economies have developed into 'R&D powerhouses', such as China and South Korea. For some of these countries, the process took around two decades points in the direction of incrementality: productive capabilities require time and continuous efforts. Building up such capabilities and vital ecosystems are even more essential today when it appears as if a 'glass ceiling' separates the R&D leaders from the rest of the world. Therefore, under industrial policy lenses, participation in GVCs – and therefore channels that contribute to attract FDIs - must come with participation in R&D networks to climb up the innovation ladder.

b) Investing in human capital and organisational capabilities remains crucial.

It is important to invest in skills, as human inputs are crucial for the use of technology. Since the early times of industrial policies, the transfer of skills (i.e., personnel) has been crucial. The economic historian David Landes (1969) remembered the British skills workers in the United States providing the indispensable assistance in adopting newly developed techniques; if this applied to countries that were apparently "close together", emerging economies would need this even more (Rosenberg, 1970) Below a reference to an example between the skills' transfer between Britain and the United States.

[106] UNCTAD calculations based on UNESCO Institute for Statistics (2020), https://sdgpulse.unctad.org/sustainable-industry/

Investing in human resources is also fundamental since firms need to develop multiple set of complementarity production capabilities across the value chain (Andreoni, 2019). GVC is an essential channel for industrialisation, but it is likely to remain a mere unexplored channel without the implementation of consistent industrial policy measures. Policy measures in this sense need to look at filling the gap, and fostering the society towards those basic and intermediate capabilities that are crucial to engage with future technologies.

c) Government and institutions matter

Industrial transformations are complex, and so are the effects of structural changes. Within these change mechanisms, the relationship between institutions and stakeholders, between structure and agency, is highly relevant. Especially, in light of the fact that government can act as a catalyst of changes towards desirable paths while avoiding lock-ins and at the same time paving the way towards learning processes (Colander and Kupers, 2014)

In this sense, institutions have to pursue a balanced policy to attract FDIs while fostering the development of local productive ecosystem[107]. In the export-orientation process, the assimilation of advanced technologies is fundamental, and it has to be balanced against a complete openness to inwards FDIs. The government's role would differ along the integration process; in this sense, different authors suggest that in the process of development and GVC participation, successful countries would follow a 'in-out-in again' process (Lee et al, 2017; Andreoni et al., 2021)[108].

Within these processes, learning targeted policies are essential. As Alice Amsden (1989) explained, in the XIX century technological change happened through invention, in the XX it emerged through innovation, and in the XXI century it reaches emerging countries

[107] For example, in Thailand, demand and supply policies have been combined in a way where technological skills push met demand pull in a country where firms have been 'accompanied' by fiscal incentives to recent digital production technologies (see Andreoni, 2019). Moreover, a wide range of enabling institutions and infrastructures permitted the Thai government to provide the right set up for firms both local and international (Barnes et al., 2016). For other examples see Taymaz and Yilmaz, 2017 for Turkey (although they state that the success is mitigated by the lack of organizational capabilities); Hill, 2007 for Czech Republic.

[108] At the beginning countries tend to prioritize the engagement with GVC and the access to global market demand. In the 'out' phase, countries focus their efforts on substituting some imported intermediate goods with domestic produce (Kee and Tang, 2016). Both processes are made possible by an expansion of domestic supply-chain linkages. The last phase 'in again' countries benefit from cumulative dynamics of trade capacity and domestic production expansion (Andreoni et al., 2021).

through learning and imitation processes. The latter also requires the adaptation to local conditions, and it could involve a substantial amount of innovation (Khan, 2013).

If it is true that present times are characterised by more explicit scientific content and improved channels for technology transfer, targeted industrial policies remain essential to stimulate learning and imitation processes. The main goal when designing industrial policy in an emerging economy has to be the development of basic and intermediate organisational capabilities, without which the current innovation opportunities created by the new technologies will not be captured, thus leading countries and sectors locked in past technological paradigms.

Industrial policy targeted to the digital industrialisation needs to consider the value creation space and opportunities in specific local contexts. We discussed in Essay I the importance of pre-existing capabilities when analysing technology adoption and the relative industrial policies. As such, if a country is between the second and the third industrial revolution – considering the level of infrastructures and capabilities present in the country - policies would need to consider this and would not design jumps to the fourth industrial revolution. Instead, they have to be tailored in such a way to take into account the different interests, capabilities, and distribution of power within and among different organisations. Besides, policies need to be specific because structural transformation cannot be achieved using generic policy frameworks. Strategic choices have to be made to unleash industrial renewal of existing sectors, and the emergence of new competitive players in the productive structure (Andreoni, 2020).

d) Industrial policy for the automotive sector

Automotive was at the centre of a series of successful experiences of industrial development. Investing in such an industry is a strategy followed by many countries because of the unique properties that the automotive sector has. For example, rapid technological changes have been spawning dramatic changes in other industries, such as robotics application to heavy industries that is still receiving primary stimulation from automotive manufacturers and suppliers. Thinking about replicating models from the past is worthless but considering some elements from those experiences may be interesting also for today's industrial policy.

Generally speaking, the development of this industry coincided with protectionist and subsidised policies around the world. For example, if we look at the rise of the Japanese experience, apart from the pre-existing manufacturing capabilities they had at the country level[109], at least two factors are very different from the present situation. First, significant barriers were erected by the Japanese not much in terms of tariffs, commodity taxes, and non-tariff barriers, but mostly through the prohibition of foreign equity investments in Japan-based companies. Numerous policies are hard to adopt today, but some could be considered, for instance, the restrictions of foreign-owned firms. Second, other "external factors" complemented industrial policies in Japan, such as the extent of the market: the total value of motor vehicle production grew 17-18 % a year, thus providing a massive demand-pull during the Japanese expansion period (Cole and Yakushiji, 1984).

Another example is the United States, as they entirely relied on government assistance on every possible level: from lower fuel taxes to enormous investment in building ever-better roads and highways, to large quantities of cheap consumer credits – to stimulate the purchasing of motor vehicles – and low sale taxes and registration fees for motor vehicles (Cole and Yakushiji, 1984).

Furthermore, industrial policy for the automotive sector cannot neglect the role that market access plays. In this sense, demand from big market is important considering that successful experiences were based on either a big internal market (the case of China, India or Brazil), or a potential market emerging from regionalisation dynamism that could lead to a similar market pull opportunity (e.g., the Mercosur, the ASEAN[110], the NAFTA, the European market). Automotive GVCs are in fact a regional, rather than a purely global, type of production. Besides, regionalisation and the access to big markets lead to dynamic

[109] These capabilities at the supplier level were crucial, early development of the steel industry was a top government target, and inexpensive, high quality Japanese steel has been an important input for automobiles.
[110] ASEAN countries had a real, but slow, process of regionalisation that benefited enormously the area. See Amighini and Gorgoni (2014) on the structural change in the auto industry

economies of scale, productivity growth and specialisation, that implied "dynamic increasing returns to scale" and "circular and cumulative causation" (Myrdal 1957; Kaldor, 1972).

South Africa's scenario for regionalisation appears more challenging than the cases mentioned above. However, a significant regional market to access seems still an essential element for success, indispensable to induce localisation and to retain some bargaining power with foreign firms (Barnes et al., 2021).

e) **The FDIs receiving model should shift from a headquarter-centred model to a domestic centric one**. Local institutions should foster the multi-domestic decentralised firm model[111]. This model is a strategy based on the decentralisation of engineering, which encourages the development of local innovations (bottom-up) and leads to the internationalisation of R&D (Pardi, 2019). In this model, global best practices have less influence and platforms are designed locally – as they start with the idea of looking at potential consumers to design a platform that may become multiregional[112].

   Such a model is essential to have a continuous swinging between demand and supply inputs that call for more locally based innovation. It is only through the bottom-up pressure of local companies that they could reach "the gold at the base of the pyramid" through their own innovations (Nadvi, 2014). A higher level of integration of the domestic ecosystem could also result in an advantage for MNCs that could better use their resources, generating higher economic and social spillovers.

3. Contribution to theoretical debates on technology adoption

[111] Pardi (2019) individuates the dominant model of the global and centralized firms and the multi domestic and decentralized firm model.

[112] For example, the case of Renault Kwid in India was a successful case of multidomestic and decentralised firm model, where 98% of suppliers are Indian. If international standards were followed, all of them would have been cut out (Pardi, 2019).

This study makes two main contributions to the technology adoption literature in the context of the 4IR. As the first contribution, this thesis proposes a method to capture and study heterogeneity by demonstrating that technology adoption varies considerably even across the same manufacturing sector, i.e., automotive, and sometimes even within the same firms' organisational units. Our method achieves novel insights by focusing on: (i) unpacking the stages of production of specific industries and firms; and (ii) digging into the peculiarities that different products, different materials and different processes may present for technological change. Furthermore, this thesis builds a framework of drivers for technology adoption, such as volume, quality and ergonomics. To the best of our knowledge, this is the first systematisation of these drivers (table 5).

As the second contribution, we bridge the topic of technology adoption with industrial policy. Through a close analysis of the 4IR, which examined what is really intended with this new wave of technologies and studied technology adoption dynamics in a specific country (i.e., South Africa), we provided further evidence on how industrial policy should direct industrial ecosystems upgrade towards digital technologies. The incremental nature of these changes, and the high reliance on sophisticated tangible infrastructure and tangible - and intangible – capabilities call for small but continuous incremental steps, rather than big jumps ahead. Along these lines, our research also suggests more consideration of different business model strategies as firms are far from operating in a standard way. This is relevant because each driver for technology adoption plays differently within different business models; thus, organisations and policymakers will need to emphasise different benefits and develop different strategies to cooperate with incentives.

For instance, to stimulate the adoption of technologies in the early stages of development, policymakers may choose to emphasise the innovations' direct benefits and provide subsidies, thus aiming to reduce the cost of development and capital costs involved in technology adoption. In contrast, to stimulate the adoption of more mature technologies, more significant efforts will be needed in both communicating information about indirect benefits and designing and providing subsidies that reduce initiation and indirect implementation costs.

Our framework lays the foundations for further research on the dynamics of technology adoption drivers. Future research will need to explore specific features that characterise different sectors in terms of 4IR technologies adoption, thereby overcoming the static approach where technology adoption is treated as a freely available black box.

The level of heterogeneity emerging from this study imposes a methodological shift in this subject. Important factors to consider are: (i) the ways companies incrementally integrate the last generation of technologies to execute several production tasks within existing production systems, and (ii) how such integration requires a continuous process of retrofitting of these same production systems, and the development of new capabilities to run them effectively. Such a shift in the approach to the 4IR has profound implications for industrial policies. A more targeted and grounded visions of what is feasible incrementally in different countries and sectors is set to replace futurist and less-grounded discussions around technology.

4. Limitations and future areas of research

Whilst we aimed at providing a comprehensive study of technology adoption, some limitations are still present. First, a limitation directly derives from the research design, specifically in the unit of analysis considered. The focus on industry and firm-level adoption, rather than organisational-level adoption implies that the study does not consider sectoral differences that may affect our implications on technology adoption. In order to address this shortcoming, future research should aim to identify a range of industries, beyond automotive, which are major early adopters of 4IR technologies. Although this research primarily intended to give a full picture of 4IR technology adoption, industrial robots inevitably became its main focus, as they are the only widely-diffused technology belonging to the 4IR.

Second, and relatedly, the qualitative research design, although appropriate for an evolutionary process as technology adoption, limits the generalisations of findings to other firms and sectors. As the technology matures, a quantitative approach, coupled with case studies, would be important to investigate the dynamics associated with 4IR technology adoption across a range of different application settings. This approach would offer the best - yet the most resource-intensive - approach to studying the change at the organisational and industry-level, and it would enable researchers to account for sectoral differences in the patterns of adoption.

Table 1 presents a roadmap for future research, with the possibility to extend our work to other industries, different organisational innovation stages and other technologies.

Roadmap for future research

Extension of findings to…	**Research design**
Other industries	1) Comparative case studies of different industries in the process of 4IR technologies adoption (to understand and identify whether the pattern is similar and/or in what differs) 2) Longitudinal survey of 4IR technologies adoption at organizational level across different industries and across time (to clarify the role of organizational/sectoral/stage of diffusion differences in shaping the magnitude of costs)
Other organizational innovation stages	Comparative case studies of technology adoption at organizational level measuring the magnitude of costs and benefits as the technology diffuses throughout the organization
Other technologies	Longitudinal case studies of technology adoption and diffusion, focusing on identifying technology drivers at different stages of diffusion

Table 1. Source: Author

5. COVID-19, which prospects for international development?

Although this research started more than three years ago, when nothing even remotely similar to COVID-19 was expected nor foreseeable. The world has rapidly changed in an uncontrolled way and the seismic changes happened in the last year will reverberate in the fields of technology adoption, as well as 4IR and FDI.

More importantly, for a thesis that discussed GVC and production dynamics at the MNC level, global trade decline is destined to impact international production organisation significantly. As far as FDI is concerned, they are expected to contract between 30% and 40% in 2020/21 (UNCTAD, 2020). The cyclical consumer industries, such as airlines, hotels, restaurants, and the manufacturing and energy sectors will be among the most affected sectors. Global trade is expected to fall between 13% and 32% in 2020-2021 (WTO, 2019). Within this scenario, costs and advantages associated with the GVC approach may change considerably (see Strange, 2020).

Second, as this thesis looked deeply into an emerging economy like South Africa, it is crucial to consider that financial and production flows have changed in the last year. According to the International Monetary Fund (2020) [113], from the beginning of the Covid-19 crisis until late March 2020, developing countries experienced the largest capital outflow ever recorded, with investors removing US$ 83 billion from emerging economies. Nonetheless, these changes could enhance innovation dynamics in emerging economies that could be less dependent on developed economies (Andreoni et al., 2021).

Third, the forced move to "working from home" is perhaps one of the most significant organisation design shock that occurred in our lifetime. How would this influence the way firms work and innovate? Will creativity suffer from remote working? Will it require more or less modularisation of work? Some industries may quickly shift to remote forms of collaboration, but what would happen to sectors, such as the automotive one, where asynchronous tacit coordination may not be a viable alternative (Srikanth and Puranam, 2014)?

All these questions cannot be answered yet, but they are important to consider in the next future of industrial policies design and implementation, especially because - at least in the present time – the vast majority of innovation infrastructures required to make scientific

[113] https://www.imf.org/en/News/Articles/2020/03/23/pr2098-imf-managing-director-statement-following-a-g20-ministerial-call-on-the-coronavirus-emergency

breakthroughs, cannot be virtualised (George et al., 2020). The physical infrastructure has been the dominant model for over a century, and important questions are raised in terms of how labs, buildings, and social ecosystems, might change (George et al., 2020).

Fourth, the profound implications of industrial organisation evolution will also affect how production systems innovate, which is even more relevant in light of the special role that innovation will have in recovering from the pandemic. Studies are called for in order to analyse how ecosystems innovate, and firms resist, react and adapt to changes in situations with a high degree of uncertainty, such as the pandemic and post-pandemic times (Doern et al., 2019; Ratten, 2020; Sherma et al., 2020).

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Conclusions

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