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Global race for robotisation- Looking at the entire robotisation chain

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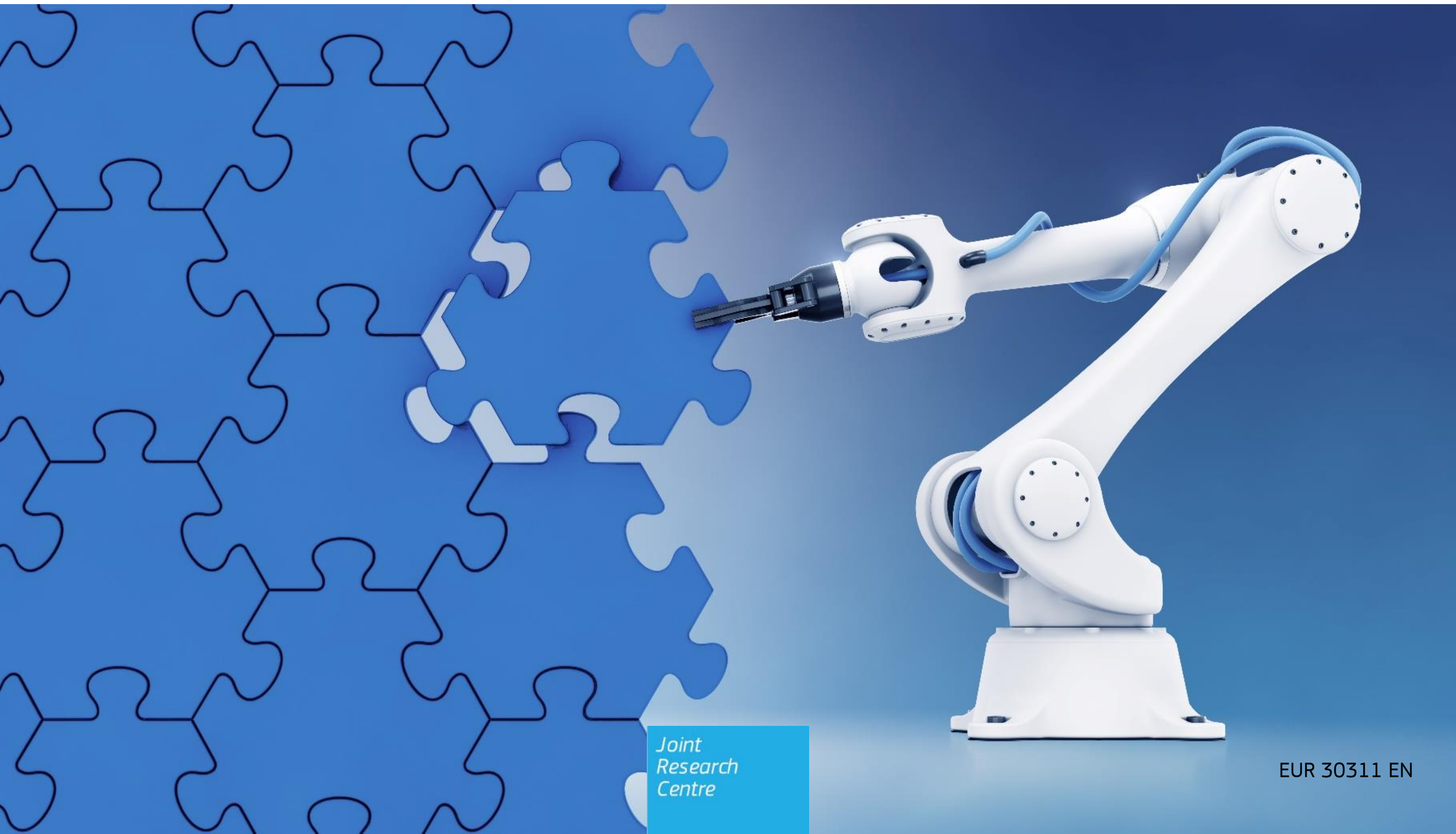

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Authors

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Abstract

Where does Europe stand in the global robotisation race? This paper aims to answer this question by developing a novel theoretical and analytical framework which applies the concept of a global value chain to robotisation. By doing this, we investigate in detail the entire robotisation chain, from robotics developers to robot manufacturers, and companies that deploy industrial robots. For the research and development (R&D)-intensive part of the chain (robotics development), we analyse the robotics patent data of the Worldwide Patent Statistical Database (PATSTAT) combined with ORBIS, while for the capital-intensive part (deployment of robots), our information is sourced from the International Federation of Robotics (IFR).

Our results show that although the ‘big five’ (Europe, USA, China, Japan, and Korea) dominate the global robotisation landscape they do not all hold equally strong positions across the whole robotisation chain. Japan and Korea are the early first-movers and today’s global leaders, as they are robustly engaged in every part of the chain. Europe is very strong in robot manufacturing and robot deployment, but is behind global leaders in robotics development. The USA has its firm competitive advantages in robotics development, while at present the latecomer China is a rival only in the industrial deployment of robots. Nevertheless, in Europe, some smaller and advanced economies are specialising in certain parts of the robotisation chain, as Austria, Denmark, France, the Netherlands, and Sweden are performing well in robotics development; not only this, Belgium, Italy, and Spain are making extensive use of industrial robots for various kinds of manufacturing. European economies which are lagging behind the rest – largely consisting of Central and Eastern European countries – are involved in the robotisation chain only insofar as they are involved in robot deployment.

Since there are only 43 countries globally who are taking part in robotisation, the eminent policy challenge remains to find ways for countries to become integrated into the robotisation chain, and for those countries already engaged in robotisation, the main focus is to create policies which support upgrading across the chain, as the reshoring of previously offshored production becomes more prevalent.

Keywords: robotisation, global value chain, robotics patent, industrial transformation, territorial development, Europe

Subject classification codes: O3, O14, O30, O25

Introduction: What is the robotisation race about?

While there is still no universally accepted answer to the question of where we currently stand in the series of industrial revolutions, scholars are largely agreed that robotisation and artificial intelligence are two key features of the current industrial transformation. The various suggestions for naming the current period include ‘the next production revolution’ (OECD, 2017), ‘the second machine age’ (Brynjolfsson and McAfee, 2014), and ‘globalisation’s second unbundling’ (Baldwin, 2016), while there is also debate as to whether we are currently in the third (Rifkin, 2011; Gordon, 2016), fourth (Schwab, 2016), or fifth industrial revolution (Perez, 2002; Bouzou, 2016). Scholars widely agree that not all innovations and technological improvements are equally important, and that only few of them could trigger long-lasting societal changes. Regardless of the types of innovation that we consider, be it basic innovation (Hall and Preston, 1988), general-purpose technologies (Bresnahan and Trajtenberg, 1995; Helpman (Ed.), 1998; Lipsey, Carlaw, and Bekhar, 2005), or key enabling technologies (European Commission, 2012; European Commission, 2016), all include robotisation, as it is one of the main drivers of the ongoing industrial revolution. This is particularly the case as robots are widely used across different industries and applied in various ways, making their economic and social consequences far-reaching. Consequently, the global race for robotised production is about the countries which are able to actively participate in the current industrial revolution, and whether their innovations in robotics could lead them to obtain the first-mover advantages in the principal technology of the not-so-distant future.

There is, however, more at stake than the technology of the future, since we have already been using industrial robots for at least three decades, which has profoundly shaped our economy and society. A growing number of studies look at the adoption of industrial robots as a predominantly positive development, with enormous economic benefits (OECD, 2017; UNCTAD, 2017; Manyika et al., 2017; IFR, 2018). According to these studies, the deployment of industrial robots increases productivity, and significantly contributes to economic growth, while the challenges of the labour market are manageable, and create the need for policymakers to develop appropriate policy responses (Craglia (Ed.), 2018; European Commission, 2018). Graetz and Michaels (2018) calculate that between 1993 and 2007, robot densification increased the annual growth of labour productivity by 0.36 percentage points across the 17 countries analysed; this magnitude is similar to steam engine technology’s contribution to Britain’s annual labour productivity growth during the first industrial revolution. The Centre for Economics and Business Research (CEBR) (2017) estimates that between 1993 and 2015, investment in robots contributed almost 10% of cumulative GDP per capita growth in the majority of the Organisation for Economic Co-operation and Development (OECD) countries, and the increase in robot density (number of robots per million hours worked) by one unit was associated with a 0.04% increase in labour productivity. Jungmittag and Pesole (2019) highlight that, in the 12 European countries analysed, the stock of robots per €1 million of non-ICT capital input significantly contributed to labour productivity throughout the period between 1995 and 2015, and in the transport equipment industry, a rise in robot stocks of 1% increased labour productivity by 0.1% on average. Dauth et al. (2017) found that in Germany, where almost one tenth of the world's robots are in use, every additional robot per thousand workers raised the growth rate of GDP per person employed by 0.5% over the period between 2004 and 2014. In addition to these papers with aggregate figures, recent studies at regional, industry, and firm levels (Koch, Manuylov, and Smolka, 2019; Ballestar et al., 2020; Kromann et al., 2020) also support findings that deploying industrial robots is associated with considerable gains in productivity. Thus, the global race for robotisation is also about which countries will benefit from such GDP growth and productivity increase.

Nevertheless, these two streams—innovation in robotics on the one hand, and deployment of industrial robots in production on the other—are treated in both the literature and in policymaking as two distinct issues. The interconnectedness of the two streams, however, is clear: innovation in robotics with growing application possibilities pushes the deployment of industrial robots, and conversely, manufacturers' demand for robots to be applied in various kinds of production processes pulls robotics innovation. A comprehensive theoretical and analytical framework of every element of robotisation, from robotics developers, to robot manufacturers, and companies which use industrial robots is something which is still largely missing in today's literature. Therefore, the present paper aims at closing this gap by developing a novel theoretical and analytical framework which primarily applies the concept of global value chains to robotisation. The main research questions addressed in this paper are as follows: *1) How is the global robot landscape evolving? 2) Where does Europe stand in the global robotisation race?*

In our quest to answer these questions, we largely rely on the concept of the global value chain, though we discuss and scrutinise in detail the fundamental differences between the robotisation chain and global production networks (Section 2.1). We go on to outline our novel analytical framework of the robotisation chain (Section 2.2), and analyse the factors which may influence territorial concentration across the robotisation chain (Section 2.3). The paper then briefly discusses the main data sources, the patent and company data from PATSTAT and ORBIS for the R&D-intensive part of the chain, and the International Federation of Robotics' (IFR) robot stock data for the capital-intensive part of the robotisation chain (Section 2.4). Based on the dataset, we provide a detailed analysis of the robotisation landscape, focusing both on the main regions of the world economy, and on countries within Europe (Section 2.5), and we also discuss the basic trends of the current global robotisation race (Section 2.6). Our concluding remarks (Section 3) offer further insights into related policy questions.

The conceptual framework of the robotisation chain, and its application to the global robotisation race

Robotisation chain versus global production network

Undoubtedly one of the greatest innovations of globalisation was the development of supply chains and value creation networks which span several countries and facilities. Baldwin (2016: 242) notes that this development triggered a genuine 'global value chain revolution'. During the 1990s, as the most recent wave of globalisation was in its beginning stages, the terms for such networks proliferated: 'value chains' (Porter, 1985), 'global production networks' (Dicken, 1998), or 'global commodity chains' (Gereffi and Korzeniewicz, 1994).Today, the expression 'global value chain' has become commonplace, (Rhodes, Warren, and Carter (Eds.), 2005; Gereffi, 2018; Ponte, Gereffi, and Raj-Reichert (Eds.), 2019) not least because it suggests that within a production network consisting of several companies, facilities, and countries, new value is added to the product at each stage —from design and purchasing through to parts manufacturing and assembly, and to sales and servicing—. Nowadays, ever-growing shares of products are assembled from components produced in different facilities and countries across the world (OECD, 2016; World Bank 2017a; WTO 2019), so much so that designations starting with 'Made in…' have become less and less meaningful. Within the chain, it is now not the place of assembly which is the main feature, but the location and quality of the value added. Meanwhile, labour, capital, and technology, being the key factors of production, are not distributed evenly across the various facilities and countries which make up the chain.

At first sight then, it seems obvious that the robotisation chain, revolving around a marketable product incorporating many intermediary components, might be analysed as a value chain. Robots are, however, also part of a broader process of industrial automation, and hence the robotisation chain is more than a new or unique global value chain. Thus, it is not our intention to describe the specific production network of robots, as a typical global production network analysis would do, but to apply the theoretical insights from research into global value chains to the robotisation chain.

We draw a clear distinction between the robotisation chain and the global value chain, because they differ from each other in at least four essential ways, namely their scope, intangible contents, maturity, and competition rules.

Firstly, robots are developed and produced for the market, but the end-users who purchase them are at the same time manufacturing companies themselves, and they put the robots to work in various automated production processes, while in traditional and consumer goods-oriented global value chains, the end-users are generally the final consumers. Therefore, the scope of the robotisation chain is much broader than that of global value chains, as the end-users trigger a new cycle in the robotisation process, creating economic and social consequences that are fiercely debated both in public and scientific discussions.

The issue which attracts the most attention is undoubtedly the impact that robots might have on employment. According to the most pessimistic assessments of the '*robocalypse*', almost one in two jobs will be replaced by robots for two decades to come (Frey and Osborne, 2013; Acemoglu and Restrepo, 2017; Chiacchio, Petropoulos, and Pichler, 2018; Lordan, 2018; Frey, 2019). More moderate assessments predict that one in eight jobs will disappear, and one third of all jobs will be significantly transformed (Arntz, Gregory, and Ziehran, 2016; Nedelkoska and Quintini, 2018), increasing the need for skills adjustments (Goos et al., 2019). Finally, the most detailed analyses of the past twenty years show a small but significantly positive effect of robotisation on total employment (Dauth et al., 2017; Klenert, Fernández-Macías, and Antón, 2020). In sum, these predictions and assessments are characterised by a high degree of uncertainty, and a number of theoretical and methodological drawbacks such as taking at face value what is technologically possible, focusing exclusively on the quantitative side of the implications for employment, and neglecting country-specific and industry-related factors (Cséfalvay, 2019a). By contrast, studies analysing productivity issues unanimously state that the deployment of robots has been accompanied by significant gains in productivity over the past two decades.

Yet, both studies on the potential impact robots have on employment, as well as analyses of past productivity growth caused by robots, have one point in common: they focus almost exclusively on the deployment of industrial robots, and pay much less attention, if any, to the route *prior* to robot installation, namely, robotics development, and robot manufacturing. It is, however, evident that these factors are the ones which, from the side of technology, push forward the deployment of robots. Cutting-edge robotics novelties offer an ever-expanding wide range of industrial application possibilities, while improvements in robot manufacturing could push down the price of robots. In other words, we simply cannot talk about robotisation without analysing robotics development and robot manufacturing, which are prerequisites for the deployment of robots; vice versa, we cannot talk only about the value chain of robots without analysing the possible economic and social impacts of deploying robots at the end of the chain.

Secondly, while in the past decade, new digital technologies have enormously transformed global value chains, value creation is now rapidly shifting towards digital contents and intangible assets (De Backer and Flaig, 2017; Haskel and Westlake, 2017; De Backer et al., 2018), and this phenomenon is particularly prevalent in the robotisation chain. Robots are 'intelligent machines', and their development, production, and deployment is inconceivable without extremely complex IT systems with sophisticated software, algorithms, applications, and big datasets. Moreover, the high number of digital contents and intangible assets across the robotisation chain, particularly in the development and design of industrial robots, means that opportunities for quick and global scaling are bigger in the robotisation chain than in traditional, consumer goods-oriented global value chains.

Thirdly, the majority of global value chains are developed for mature industries and products in the 'maturity stage' of their life cycle; in the robotisation chain, however, the products, i.e. industrial robots, are currently in the 'initial' or 'growth' stage. During the heydays of globalisation, value chains have gone global, moving especially towards developing countries with enormous labour reserves and exceedingly low wages, and offshoring often occurred at the point of the product reaching the 'maturity' or 'saturation' stage of its life cycle—a phenomenon described and theorised by Vernon (1966) more than half a century ago. Looking back over the past three decades, it seems that globalisation and offshoring of manufacturing from developed to developing countries were merely the necessary stepping-stones for large enterprises, enabling them to produce large quantities on a market which was becoming global. By contrast, robots are currently in the early stages of the product life cycle, and this enormously influences the robotisation chain's geographic pattern by paving the way for strong territorial concentration on the one hand, and weakening opportunities for regional convergences on the other.

— Finally, traditional global value chains and the robotisation chain are fundamentally different when it comes to governance issues, and the task is to assess the competitive positions of different countries. In global value chains, the most important governance question is about which countries and companies possess those key positions which allow them to control the whole chain (Gereffi and Korzeniewicz, 1994; Henderson et al., 2002; Gereffi, 2018). Although the outcome varies greatly according to the product in question, within traditional global value chains, the centre of power and profit is placed with the company who contributes the capital, the technology, or the market to the chain (Gereffi, Humphrey, and Sturgeon, 2005; Gereffi and Fernandez-Stark, 2016). By contrast, in the robotisation chain, the fundamental question is not about who has the most powerful control position in the chain, but who is able to concentrate all three of the most important elements of the chain: robotics development, robot manufacturing, and industrial robot deployment. Economic benefit and technological leadership are derived not from holding a single position, no matter how much control one could exercise from that point, but from active participation in each decisive part of the robotisation chain. Therefore, in the robotisation chain, the rule of competition differs from traditional global value chains, as countries which are strong at every point of the robotisation chain are the leaders and have the first-mover advantages, while those who are only integrated in some particular parts of the chain are lagging behind, and have the enormous challenge of upgrading across the chain and catching up with their competitors.

In short, the robotisation chain is larger and broader than a traditional global value chain which is developed for a particular product. Similarly, the robotisation chain is fundamentally different from traditional global production networks in many important respects, such as the scope, the intangible contents, the maturity of the product, and the competition rules. Nevertheless, the *concept* of the global value chain as an analytical approach could be beneficial for understanding and capturing the main features of the robotisation chain.

The analytical framework of the robotisation chain

Our analytical framework for the robotisation chain has been inspired by two main sources: the long-established literature on global value chains, and recent studies which explicitly analyse some particular part of the robotisation chain. For instance, Leigh and Kraft (2018) make a clear distinction between the 'suppliers', e.g. companies that design, produce, and sell industrial robots, and the 'robot-using manufacturers' (RUMs), e.g. companies which purchase, install, and deploy robots across various areas of manufacturing. Robot using manufacturers could purchase robots directly from suppliers that manufacture robots, or from specialised intermediaries, 'integrator' companies which provide specific expertise to install and customise robots, but large robot using manufacturers usually have their own in-house robotics integration capabilities or robotics development facilities. Forge and Blackman (2010) highlight that intermediary robotics companies, such as 'system integrator specialists' or suppliers of special components, are becoming important players, filling the space between robot manufacturers who supply branded products to the market, and companies that install and deploy robots.

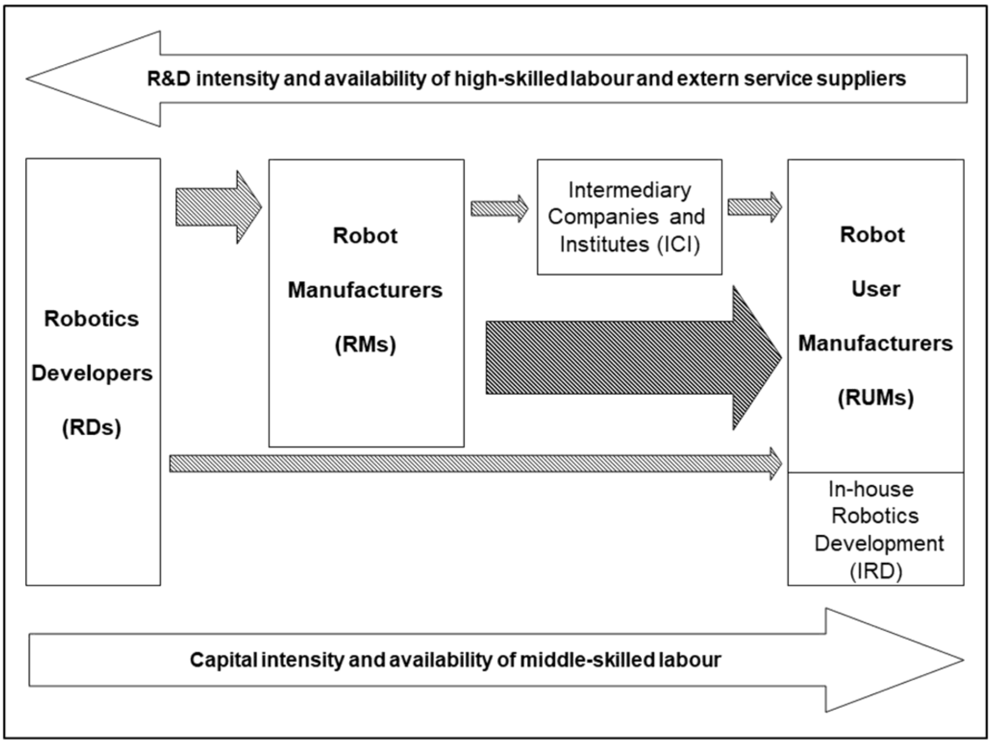
By combining this initial taxonomy with the concept of global production networks, the robotisation chain might be divided in three main parts, which together form the skeleton of our model (see *Fig. 1*):

— *Robotics developers* (RDs), who carry out cutting-edge research in this field, and develop new robotics technologies. These are big companies and small start-ups, university departments and research institutes, and it is evidently the case that enterprises which manufacture robots have their own extensive research facilities for robotics technologies.

— *Robot manufacturers* (RMs), companies for whom the design and production of robots is their main activity field, and who supply the market with robots on a large scale.

— *Robot user manufacturers* (RUMs),companies which purchase, install, and then deploy industrial robots to various kinds of production processes in order to supply consumers with products that come from automated production.

Figure 1. Model of the robotisation chain



Because of the highly complex and customised nature of robotics systems, there are also many mixed forms of companies and institutions within the robotisation chain:

- Large-scale robot manufacturers do not only produce robots for the market, but also carry out significant research in robotics, as RDs often have the ability to produce robots, albeit on a smaller scale or for purposes of experimentation.

- Most large RUMs, particularly in the automotive and electronics industries, have their own *In-house Robotics Development* (IRD) facilities, primarily for customising robots supplied by RMs to their specific production processes, or because of their particular requirements that emerge during automation.

- Finally, there are *Intermediary companies and institutions* (ICIs) which provide RUMs with vital expertise for installing and implementing robots to suit their specific needs.

At present in the literature, there are a growing number of studies which focus on a specific part of the robotisation chain, and pay particular attention to the global concentration of that part. For instance, in researching RDs, Keisner, Raffo and Wunsch-Vincent (2016) found that in 2015, four out of five companies and institutions in this field were home to only ten countries(Japan, USA, China, Korea, Canada, Germany, Italy, France, United Kingdom, and Switzerland). Unsurprisingly, between 1960 and 2011, applicants from these countries filed the vast majority of robotics-related patents, although in Europe, Denmark, Finland, the Netherlands, Sweden, and Spain also had a high number of innovative robotics firms filing for patents, relative to each country's GDP.

As for RMs, Leigh and Kraft (2018) note that the 28 robot-supplier companies which provide data for the IFR are headquartered in just 12 countries. Moreover, only four countries worldwide are home to three or more RMs; Denmark and Switzerland each have three, while Germany and Japan each have six companies. Forge and Blackman (2010) also highlight that in Europe, the major companies which specialise in developing and manufacturing industrial robots were located in only eight countries (Germany, Switzerland, Sweden, Italy, France, United Kingdom, the Netherlands, and Austria).

In respect to ICIs, Leigh and Kraft (2018) show that in the USA, they are always located in close proximity to RUMs. While 'supplier-dense regions' are placed in long-established high-tech clusters (e.g. Silicon Valley, Boston), with RDs specialising in research, design, and robot development , 'integrator-dense regions' where ICIs focus on implementing and customising robotics systems, are clustering in traditional industrial districts (e.g. the manufacturing belt around the Great Lakes).

Finally, RUMs are also strongly concentrated, and as Cséfalvay (2019b) highlights, around 1,600,000 industrial robots were deployed globally in 2015, but the overwhelming majority were at work in only five countries: Japan (18%), China (16%), USA (15%), Korea (13%), and Germany (11%). Adding all other EU member states with Germany's figure, Europe was heading with more than 400,000 robots (26%), and the combined share of the top five economies including Europe was 88% of the global robot stock, indicating an extremely wide gap between the few leaders and the Other Robotised Countries. Fernández-Macías, Klenert, and Antón (2020) also take note of this trend, as in Europe, robot deployment is largely specialised in few industries (car manufacturing, and the production of plastic and metal products), and in 2016, around 50% of European robot stock was put to work in a single country (Germany).

Thus, according to recent literature, strong territorial concentration seems to be the prevailing trend in each part of the robotisation chain, and only a handful of countries dominate the robotisation landscape. These studies, however, do not cover the *entire* robotisation chain, and do not deal with the interplay of different parts of the chain. Taking into account the complexity and dynamics of the robotisation chain, this trend is neither necessarily relevant to the same extent in every part of the chain, nor permanent in the long term.

Factors influencing concentration across the robotisation chain

Regarding the overall tendency for industrial-territorial concentration across the robotisation chain the literature offers two conflicting approaches. The first focuses on the territorial gap in robotisation, and as López Peláez (2014) highlights, this '*robotics divide'* includes economic, social, political, and even military aspects. As with the digital divide, there are deep issues between those states, companies, and individuals who have access to advanced robotics technology, and therefore to the benefits robotisation may offer, and those who do not have access and miss these opportunities. Bughin et. al (2018) also argue that today, an '*AI divide*' is emerging as Artificial Intelligence (AI) technologies (including robot-based automation) become more and more prevalent, and they estimate that AI leaders (primarily developed countries) could benefit from an additional 25% upside in GDP by 2030, while the followers (mostly emerging economies) may capture only half of this upside. The reasons for the AI divide are very diverse, ranging from the overall trend of increasing capital share in digital and highly automated industries since the 2000s (Aghion, B. Jones, and C. Jones, 2017), to the delicate interplay between innovation, and regulation which favours first-movers and deters followers (Aghion, Antonin, and Brunel, 2019), as well as unique factors such as the 'rise of superstar firms' (Autor et al., 2020), which could play an important role.

On the other hand, scholars of the second approach look at the geographic pattern in the context of interdependencies across the robotisation chain. As Ross (2016: 40) recognises, 'the countries that are best positioned are those that are developing and manufacturing robotics for export, that house the headquarters, the engineers, and the manufacturing facilities.' Those countries that only host RUMs without having robotics development and robot manufacturing facilities themselves possess the weakest positions across the robotisation chain.

In a similar manner, the United Nations Industrial Development Organisation (UNIDO) (2019) classifies countries in respect to their position in the development and deployment of advanced digital production (ADP) technologies (a category which includes robots). Based on patenting activities and trade relations in this field, UNIDO recognises the frontrunners who are leaders in all parts of the chain, in developing, producing, exporting, and deploying ADP technologies, although this group includes only ten countries globally. Follower economies are engaged in ADP technologies to a lesser extent, and the subcategory of ‘followers in production’ (23 countries) are countries which develop, produce, and export ADP technologies, while the ‘followers in use’ (17 countries) are economies which only import and deploy these technologies to various manufacturing industries. The latecomers’ group (28 countries) is also divided into producers and users, but in this case, engagement with ADP technologies is below the global average. All other countries in the world are not involved in the robotisation process.

Whether it is about the robotics/AI divide or interdependencies across the robotisation chain, these studies do not sufficiently explain why there is a strong tendency towards concentration. Although, having a certain amount of geographical understanding can help us to account for the fact that when new industries and technologies arise, there is initially a very strong territorial concentration, which only later will start to diffuse, with a considerable time lag, and regional convergence will begin. Furthermore, returning to the literature on global value chains, it is also widely understood that the relative importance of particular production and location factors varies significantly across production networks, and this enormously influences the geographic pattern of the chain (Kaplinsky, 2000; Kaplinsky and Morris, 2001; Humphrey and Schmitz, 2002; Henderson et al. 2002; Rhodes, Warren and Carter (Eds.), 2005; Gereffi and Fernandez-Stark, 2016). Drawn from these insights, we developed a matrix showing how different areas of the robotisation chain have varying needs regarding the most important production and location factors, such as R&D and capital intensity, skills held by the workforce, external services, and internal management (see *Tab. 1*).

Table 1. Relative importance of production and location factors across the robotisation chain.

	R&D intensity	Capital intensity	Scientific and highly qualified employees	Middle-skilled workers	External suppliers and services	Internal mana-gement
Robotics Developers	+++	+	+++	+	+++	+
Robots Manufacturers	++	++	++	++	++	++
Robot User Manufacturers	+	+++	+	+++	+	+++
In-house Robotics Development	++	+	++	+	++	+
Intermediary Companies and Institutions	++	+	++	+	++	+

It is easy to concede that while R&D is the dominant feature across the entire robotisation chain, its relative importance radically decreases from RDs to RMs, and finally to RUMs. Similarly, the availability of highly qualified and scientific workforces is vital for RDs and to a lesser extent for RMs, while RUMs primarily need access to middle-skilled workers who are capable of working with robots. In contrast, capital intensity shows a reverse direction, in that it is the highest for RUMs and the lowest for RDs, although for the latter, the risk of investment could also be significantly high. From an economic point of view, it should be noted that in most cases, the deployment of robots by RUMs is coupled with a broader system of production (e.g. assembly lines, hardware and software support, equipment, and data management). Hence, the purchase and instalment of robots is only a smaller fraction of the total capital-intensive investment in a newly established automated production system (OECD, 2019).

Based on this matrix of different location factors in the specific areas of the robotisation chain, some preliminary assumptions can be stated for territorial concentration. Firstly, because of the specific knowledge and expertise required, RDs might concentrate in countries and regions with high availability of scientific resources and workforces, universities and research institutes, and specialised suppliers and manufacturers. Moreover, there is evidence from agglomeration economies that when innovative regional clusters reach a certain scale and critical mass, they could become self-sustaining and self-reinforcing systems (Fujita and Mori, 2005; Glaeser, 2010; Fujita and Thisse, 2013), as was the case with information technologies (Saxenian, 1996; Castells, 2000). Thus, it is safe to say that in the case of RDs, the countries and regions that today possess the first-mover advantages could, over time, become robotics agglomerations with dominant positions.

Secondly, for RMs, it might be domain knowledge and expertise in advanced manufacturing, as well as market size, which could both drive and explain territorial concentration. Since, at the current technological level of robotics, companies in automotive and electronics industries deploy the majority of global robot stock, countries' specialisation in these industries might also offer a good basis and market scale for establishing RM companies.

Finally, the territorial pattern of RUMs is influenced by a number of economic factors, such as labour costs, the shrinking availability of the labour force in manufacturing, economic and employment structures, industrial dynamics and sectoral specialisation, and the countries' developmental stage and position in international division of labour. In this respect, there is a striking contrast between the current deployment of industrial robots and the ever-growing literature on the future of work. The latter in essence applies a comparison between the skills demands of the current jobs held by humans, and the (future) skills of robots, based on what is technologically possible today or what will be possible in the future. By doing this, studies predict and assess workers' risks of being displaced by automation (Frey and Osborne, 2013; Chui, Manyika, and Miremadi, 2015; Arntz, Gregory, and Ziehran, 2016; Nedelkoska and Quintini, 2018; Lordan, 2018; Frey, 2019), and calculate for instance that in the USA, each robot installed replaces six people (Acemoglu and Restrepo, 2017), while in Europe, each robot installed replaces three or four workers (Chiacchio, Petropoulos, and Pichler, 2018). At present, however, robots are overwhelmingly deployed in industries with middle or higher skills requirements (UNCTAD, 2017; OECD, 2019), and their penetration is exceedingly limited in those manufacturing activities where the majority of employees are classed as low-skilled workers, and the tasks carried out are easily replaceable by robots at current level of technology. Moreover, a recent study shows that in Europe, the adaption of industrial robots from 1995 to 2015 was linked to a small but significantly positive employment effect, as one additional robot per 1,000 workers was correlated with an increase in total employment of 1.3% (Klenert, Fernández-Macías, and Antón, 2020).

In real business life, for RUMS, the benefit of deploying industrial robots rather than employing human workforces lies primarily in different expenditure patterns, and to some extent, in the skills-biased opportunity of using robots instead of humans, as studies on the future of work suggest. Production processes with human labour are coupled with low capital expenditure (CAPEX) (e.g. for the recruitment of a labour force or for training) but very high operational expenditure (OPEX) (e.g. for labour costs), while in the case of automated production, the upfront investment in purchasing robots (CAPEX) is relatively high, and the OPEX is very low. As such, companies' choice between deploying robots and employing a human labour force is a trade-off in terms of different expenditure structures which may vary widely across industries and countries. Moreover, this trade-off could change over time, since in the past three decades, the performance and competence of industrial robots has steadily increased, while their price has continuously decreased. Chiacchio, Petropoulos, and Pichler (2018), CEBR (2017), and Melrose and Tilley (2017) all calculate that today, in countries with the highest robot penetration rates, robots have become around three times more efficient than those that were introduced in the 1990s, though their prices have halved in real terms; parallel to this, the cost of labour has almost doubled.

Similarly, recent studies indicate that in the context of falling robot prices and increasing wages, industrial robots are progressively deployed in industries and countries where wages are high relative to the price of robots, which means that these industries and countries benefit from a quick return of capital-intensive investments in robot-based automation. High labour costs might work as a strong incentive for companies deploying industrial robots; however, Atkinson (2018) shows that the intensity of robot deployment in the majority of European countries is lower than expected with respect to their high wages. Cséfalvay (2019b) also underlines the close link between high labour costs and intensive robot deployment, and argues that this link not only reflects, but also strengthens the already existing economic and geographic disparities across Europe. Using multivariate and econometric analysis, Fernández-Macías, Klenert, and Antón (2020) found that from 1995 to 2015, Europe's robot density grew more in industries and countries with higher wages than in sectors with higher routine and manual task content, and in economies with a higher risk of offshoring industrial production.

Because the specific production and location requirements that emerge at different parts of the robotisation chain are not ubiquitous or easy to reproduce, countries with these production factors could concentrate large shares across the robotisation chain. Though, while these factors might have some explanatory relevance, when looking at particular countries, further research might clarify the causality of the link between specific location requests and the countries' position in the robotisation chain.

Data and methodology

In order to capture the R&D-intensive parts of the robotisation chain (RDs, RMs, and IRDs), this study retrieved and analysed patent data from the PATSTAT 2019 spring edition, as maintained by the European Patent Office (EPO). It is definitely the case that the usefulness of patents as a measure of innovation at national, regional, and firm levels could vary greatly across industries (Fontana et al., 2013), and that there are extensive limitations to patent analyses (Archibugi, 1992), since not all innovations are patented, and not all patents lead to new products. Nevertheless, patents have a long and widespread history of being used to account for technological innovation which has been developed for commercial purposes, and the literature treats it as a 'tolerable assumption' that they measure commercially useful innovation (Griliches, 1990).

One main advantage of using patents to analyse technological developments relates to the International Patent Classification scheme (IPC), which is a hierarchical classification system used primarily to classify and search for patent documents including utility models[1] according to the technical fields. Cooperative Patent Classification (CPC) is an extension of the IPC, and jointly managed by the EPO and the US Patent and Trademark Office (USPTO). In this study, we focus on patent families pertaining specifically to robotics, following the methodology developed by the UK International Patent Office (UKIPO) (2014), and replicated by the World Intellectual Property Organisation (WIPO) (2015). More specifically, PATSTAT was queried for patent documents with IPC/CPC classes pertaining to robots, and the term 'robots' or 'robotics' in the title and the abstract of the document. Given that, documents from all intellectual property offices were retrieved, and in order to avoid double counting, the unit of our analysis was the extended patent family (International Patent Documentation (INPADOC)). The patent families in this analysis were fractionally counted according to their year of first filing worldwide, commonly known as the priority year, which is closest to the date of invention. Patent assignee data from PATSTAT were matched with data from ORBIS at the level of individual companies (including subsidiaries where available), using a series of probabilistic string-matching algorithms. ORBIS is a proprietary database maintained by Bureau van Dijk[2], which contains information on more than 365 million companies.

For the capital-intensive part of the robotisation chain (RUMs), the primary source of information came from the IFR. The IFR provides consolidated measures of industrial robot stock by country, year, and industry, based on the annual sales data of major RMs (IFR 2019). In addition, it calculates robot densities, measured as the number of industrial robots per 10,000 persons employed in respective industries, by using OECD's Structural Analysis Database (STAN) and International Labour Organisation Department of Statistics (ILOSTAT) data for employment.

In the detailed analysis of this report, we do not deal with individual companies and institutions, but with groups of entities who are active in some specific parts of the robotisation chain, and we analyse these groups by country breakdown. Nevertheless, the

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[1] Utility models are very similar to patents but have less stringent patentability requirements.
[2] A Moody's analytics company.

identification of the different parts of the robotisation chain, as it is shown in the theoretical model (see again *Fig. 1*) is limited at least by two main factors. Firstly, because robotics development and robot manufacturing are relatively new and very dynamic industrial activities, the industry classification of certain companies does not always follow the rapid changes in companies' profiles, and hence there are companies which are statistically classified to sectors other than robotics, although according to robotics patent figures, they are also active in robotics development. Secondly, in some highly robotised Asian countries, the economy is dominated by large industrial conglomerates (e.g. the *chaebols* in Korea, and the *keiretsu* system in Japan) which are at the same time working in a number of interlocking businesses and industries, and some of them are also active in robotics technologies and robot production. Bearing these limits in mind, and by using these datasets, for analytical purposes we classify the main parts of the robotisation chain as follows:

- We identify RMS as companies that are working according to ORBIS in robot manufacturing (NACE 28.22, 28.99). Because the robotisation chain contains a very high share of intangible assets, and due to robot manufacturing being in its early years, our analysis used the PATSTAT data, focusing only on the patent filing activity of this group of companies, in order to build a picture about its size and scope.

- Based on PATSTAT and ORBIS data, the IRD facilities of RUMs were identified by looking at robotics patents filed by automotive or electronics companies, since these are those two sectors where the overwhelming majority of global robot stock is currently deployed.

- Using the PATSTAT data, the group of RDs were treated as entities which filed significant numbers of patent families in robotics, the only exception being those entities which, according to ORBIS, are also classified as RMs or as automotive or electronics manufacturers (IRDs).

- For the classification of RUMs, we used the IFR data, particularly focusing on the operational stock of industrial robots, and robot density.

- Since the ICIs which help RUMs to customise robots to their specific needs generally do not have significant patent filing activity in robotics, we omitted this element of the robotisation chain from the analysis.

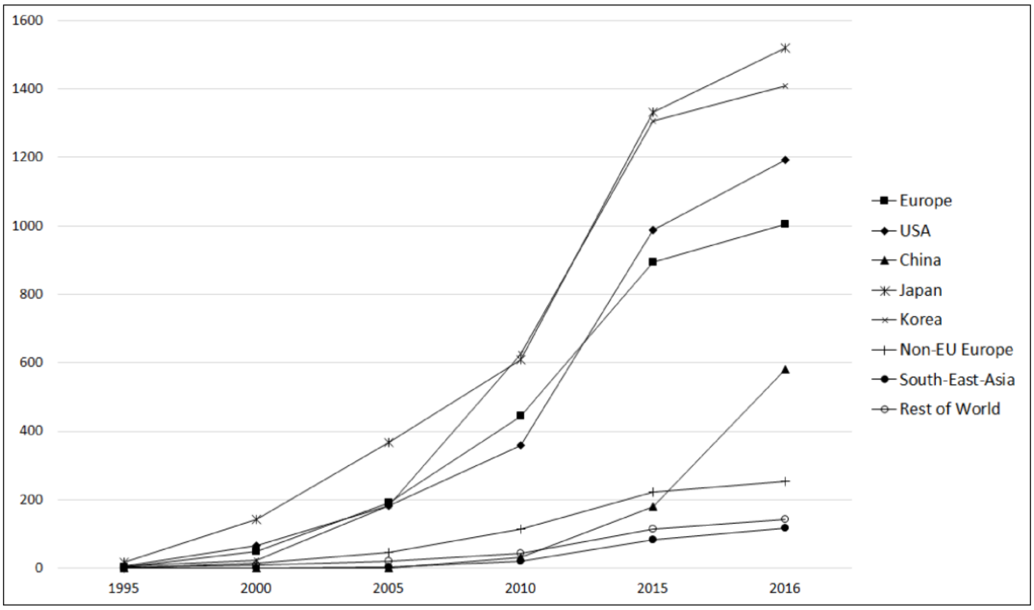
With regards to territorial scope, the present report applied a threshold that the manufacturing robot stock in a given country must have exceeded 1,000 robots in 2016, and as a sign of the strong territorial concentration worldwide, only 43 countries met this criterion. Using this threshold, 17 EU member states—Austria, Belgium, Czechia, Denmark, Finland, France, Germany, Hungary, Italy, the Netherlands, Poland, Portugal, Romania, Sweden, Slovakia, Slovenia, and Spain—have been analysed, and henceforward, the notion of *Europe* refers to these countries. *Central and Eastern Europe* comprises Czechia, Hungary, Poland, Romania, Slovakia, and Slovenia, while the category of *Non-EU Europe* includes those European countries that are not European Union member states, such as Norway, the United Kingdom, and Switzerland. For global comparisons, the analysis has been expanded to the USA, China, Japan, and Korea, as well as to *South-East Asian countries* (Honk Kong, Indonesia, Malaysia, Philippines, Singapore, Thailand, Taiwan, and Vietnam) and the group designated as the *Other Robotised Countries* (Australia, Argentina, Brazil, Canada, India, Israel, Mexico, New-Zealand, Russia, South Africa, and Turkey).

The data available do pose clear limits to the scale and scope of our analysis, as well as to the interpretation of the research results. Nevertheless, even with these limitations, our analysis could still be relevant to geographic differences, and hence might be informative for capturing the territorial pattern of the entire robotisation chain.

The global landscape of robotisation

Both robotics development and robot deployment belong to the most fast-growing global markets. Between 1995 and 2016, the number of robot-related patent families worldwide increased exponentially; it almost doubled every five years over this period, and while in 1995 only 35 patents families were filed, this figure jumped up to more than 1,100 by 2016. In total, 6,210 robotics patent families were filed between 1995 and 2016 in the 43 countries analysed, and their global distribution straightforwardly corresponds to the strong territorial concentration that we expected, as the 'big five' countries (Europe, USA, China, Japan, and Korea) possess the overwhelming majority of global patent stock (see *Fig. 2*).

Figure 2. Development of robot-related patent stock by macro regions of the world, 1995-2016 (number of patent families)

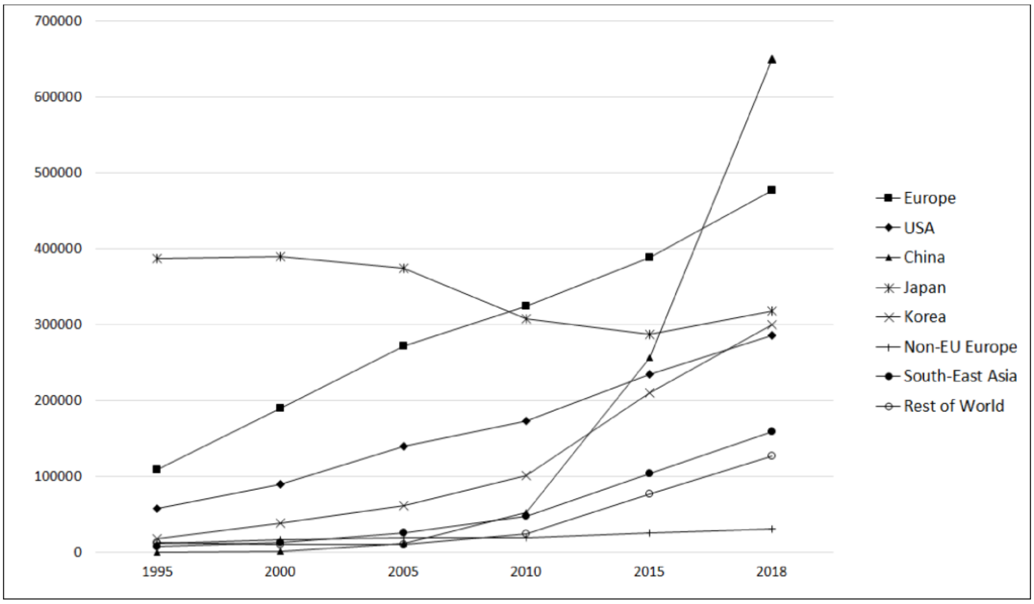


Source: authors' calculation based on data from PATSTAT and ORBIS

The first movers in robotics are Japan and Korea, and these countries together now own almost half of the robots-related patents worldwide. Overall, the USA and Europe followed the growth trend of the global leaders, and while the USA surpassed Europe in the last couple of years, the number of patents in both the USA and Europe were considerably lower than in Japan and Korea throughout the period analysed. In Europe, however, robotics development is limited to a small fraction of countries, and almost 60% of the patents filed were in Germany (576 patens). Germany, together with France (133 patents) and Sweden (121 patents), concentrate more than 80% of Europe's total robotics patent stock, and when we consider Austria, Denmark, Italy, and the Netherlands alongside the aforementioned countries, this figure becomes over 90%. The non-EU member European countries—Switzerland with almost 200 patents, and the UK with 58 patents—are also performing well. By contrast, China, with an almost insignificant number of robotics-related patents up until 2010, seems to be a latecomer, and their rapid catching-up process only began in the past couple of years. South-East Asia is clearly lagging behind, and robotics development is represented by almost a single country, as the region possesses less than 120 patents, but more than 100 of those were filed in Taiwan. Countries from the Other Robotised Countries filed less than 150 robotics patents, with Canada (57 families) and Israel (44 families) being responsible for the vast majority of these.

Similarly, the number of industrial robots increased exponentially between 1995 and 2018, from 600,000 robots deployed worldwide in 1995 in the 43 countries analysed, up to 1,600,000 in 2015, and to 2,350,000 in 2018. Beyond this expressive global rise of industrial robots there has been, however, a significant reshuffling process in the 'big five' (see *Fig. 3*).

Figure 3. Development of industrial robot stock by macro regions of the world, 1995-2018 (number of industrial robots installed)



Source: authors' calculation based on data from IFR (2019)

Firstly, in Europe, the USA, and Korea the steady growth of robot stock was coupled with a relatively persistent global share over the period from 1995 to 2018, and now one in five robots are deployed in Europe, and around one in eight in Korea and in the USA. Secondly, in Japan, who were early frontrunners in robotisation , and who concentrated around two thirds of the global robot stock in 1995, the number of robots has drastically decreased over the past two decades. Only in recent years has this number started to rise again, meaning that today, Japan's global share has plummeted to the level of the USA and Korea. Finally, the most stunning development is in China, where until 2010, industrial robots were almost non-existent, but since then the number of industrial robots has skyrocketed by a factor of 12, and now China has become the global leader in robot deployment, with 650,000 robots installed – a global share of 28%.

Looking at the R&D-intensive parts of the robotisation chain in more detail, the majority of robotics-related patents (61%) have been filed by RDs, followed by IRDs with 32%, while RMs own only 7% of the patent families globally. The leading role of the 'big five' countries also remains incontestable in this perspective, although their position varies greatly at different parts of the chain, both in respect of global share and density (see *Tab. 2*).

Table 2. Global distribution of the main activities across the robotisation chain, and their densities (robotics patents per 100,000 employees in manufacturing (2016), industrial robot stock per 10,000 employees in manufacturing (2018)).

	Robotics Developers (patents)		**Robot Manufacturers (patents)**		**In-house Robotics Development (patents)**		**Robot User Manufacturers (industrial robots)**	
	Global share (%)	Density	Global share (%)	Density	Global share (%)	Density	Global share (%)	Density
Europe	14.1	0.6	57.8	1.3	10.7	0.5	20.3	-
Germany	6.2	1.5	45.7	1.3	7.0	0.8	9.2	338
USA	22.0	2.4	11.9	0.2	15.3	0.9	12.1	217
China	12.8	0.2	1.7	0.1	4.2	0.1	27.7	140
Japan	22.3	3.7	7.8	0.2	32.4	2.7	13.6	327
Korea	17.2	7.6	17.8	0.9	34.4	7.8	12.8	774
Big Five	*88.4*	-	*97.0*	-	*97.0*	-	*86.5*	-
Non-EU Europe	1.5	-	2.2	-	0.8	-	1.3	-
South-East Asia	3.4	-	0.6	-	1.4	-	6.8	-
Rest of World	6.7	-	0.2	-	0.8	-	5.4	-
Total	100.0		100.0		100.0		100.0	

Source: authors' calculation based on data from PATSTAT, ORBIS, and EUROSTAT for robotics patent stock and density, and from IFR (2019) for robot stock and density.

For instance, while China currently deploys more than one quarter of the global robot stock, their portion of patents filed by RMs and IRDs is extremely low, and their share in the patents of RDs is the lowest among the 'big five'. In contrast, Japan and Korea are the global leaders for IRD, and these countries together concentrate around two thirds of all patents of this kind, a phenomenon which can be traced back, at least partially, to their industrial conglomerate structure. In addition, Japan and Korea concentrate considerable shares of the patents filed by RDs, and their RUMs also deploy a high number of robots in different industries.

Undoubtedly the biggest strength of the USA is in the high number of patents filed by RDs, but it is also the case that companies within the USA which deploy industrial robots have significant robotics patent filing activity. Finally, while RMs own only a small fraction of the global robotics patents stock (7%), Europe concentrates more than half of these patents. Among the patent assignees, there are many European and Japanese companies which are present in Europe via overseas subsidiaries[3]. In addition, Europe is also well positioned in robot deployment.

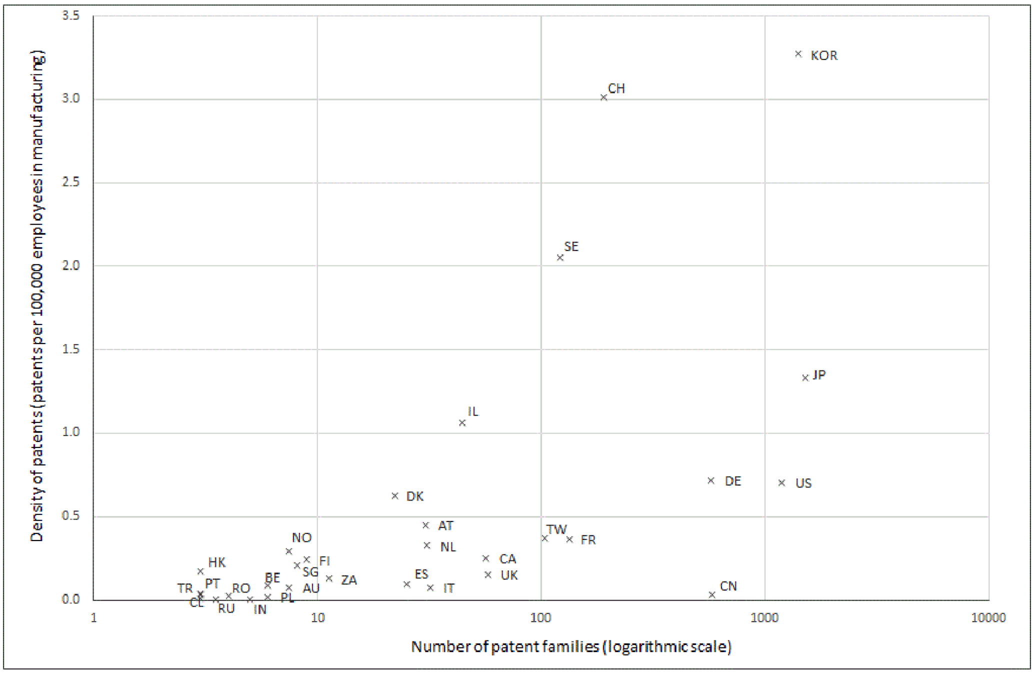
High global shares in some parts of the robotisation chain, however, have not gone hand in hand with high densities (measured as robotics patents per 100,000, and industrial robots per 10,000 employees in manufacturing). Although, density values show in a more precise manner how deeply robotisation transforms the economy in question, as when calculating density, the economy's size and the particular role of manufacturing in the economy must both be taken into account.

Firstly, while it is the most striking development that in recent years, the number of industrial robots in China has skyrocketed up to 650,000 robots, the Chinese robot density remained relatively low compared to its peers, and the densities regarding patent filing activities are at the lowest in China. Secondly, the USA concentrates more than one fifth of all RDs' patents globally, though their density rate is lagging behind. Thirdly, and in contrast to this, Japan and Korea have not only high global shares, but also high densities of RD and IRD patents, and these countries have very intense robot deployment too. Finally, Europe, and particularly Germany, has a very high share and high density in the patent filing of RMs, as well as in the deployment of industrial robots.

Moreover, despite the strong concentration of every part of the robotisation chain in the 'big five', some smaller economies are performing and converging surprisingly well. Regarding robotics patents, in Europe, densities in Sweden and Denmark are well above the global average, while Austria, France, and the Netherlands have just below global average densities (see *Fig. 4*). Within the Non-EU Europe category, Switzerland excels with the world's second highest robotics patent density, within the group of other robotised countries Israel shows also globally very strong position in robotics development, and within the South-East Asia group, Taiwan has a good performance rate, while from the Other Robotised Countries group, Israel's patent density is well above the global average.

Figure 4. Robotics patent stock and patent density, selected countries worldwide (global average=0.525 patents per 100,000 employees in manufacturing, Pearson's r=0.5452).

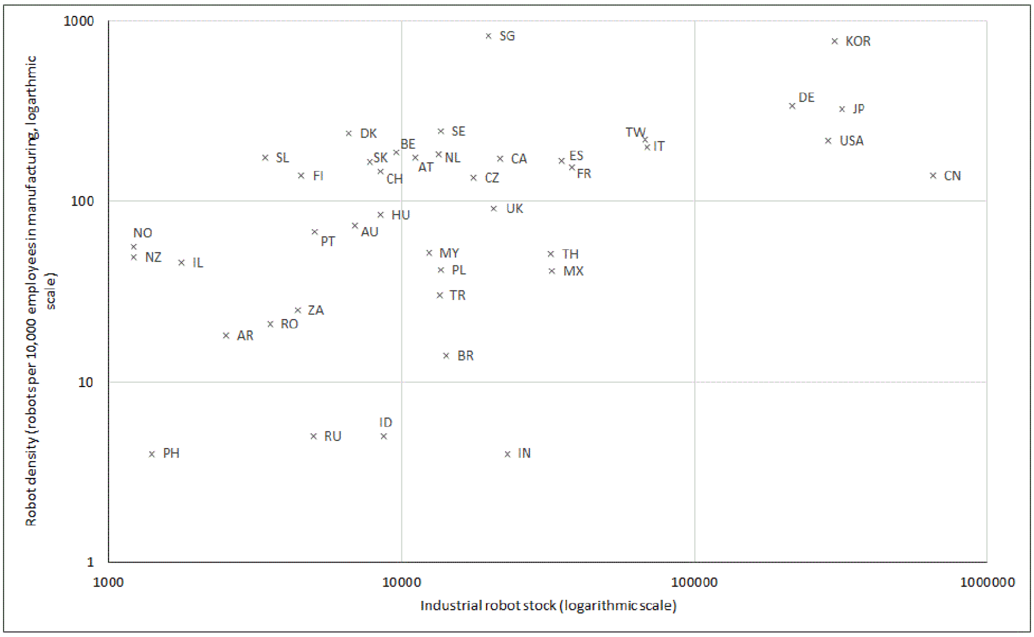
[3] Companies usually own other smaller companies (subsidiaries), which may be located abroad. Mother companies and their affiliates are organised in a tree-like corporate structure. This information is available, but was not used in the present geographic analysis, because the industrial classification is not necessarily common between the subsidiaries and the mother companies (mother companies not classified as RMs).



Source: authors' calculation based on data from PATSTAT and ORBIS for patent stock, and EUROSTAT for employment.

In respect to robot deployment, in most of the smaller European economies, rising robot stocks were associated with rising density figures and now, a sign of convergence is that robot densities are clearly above the global average (see *Fig. 5*). South-East Asia is lagging far behind both the average number of robots installed and robot density; however, Singapore currently has the world's highest robot density with 831 robots per 10,000 manufacturing employees, and Taiwan is yet again seen to fare well in global comparison. Finally, in the Non-EU Europe group, Switzerland's robot density is above the global average, and within the Other Robotised Countries group, this is also the case for Canada.

Figure 5. Industrial robot stock and robot density in manufacturing, selected countries worldwide, 2018 (global average=99 robots per 10,000 employees in manufacturing, Pearson's r=0.3458).



Source: authors' chart based on data from IFR (2019).

Main trends of the current global robotisation race

Based on the detailed analysis of the robotisation chain, the following four major trends of the current global race can be observed:

- Firstly, large and advanced economies, the 'big five' countries, dominate the global robotisation landscape with an extremely strong concentration across the entire robotisation chain.
- Secondly, within the 'big five', the particular economies differ significantly with regard to the scale and scope of their engagement in robotisation, and very few of them have equally strong positions at every point of the robotisation chain.
- The third trend shows that smaller and advanced economies are engaged in robotisation to a lesser extent, but are successfully specialising in some specific part of the robotisation chain.
- Finally, despite the strong concentration in the 'big five', it is possible for latecomers to join the robotisation chain and work their way up it, although at present, their convergence process is limited to industrial robot deployment.

With regards to the first trend, the current territorial pattern of the robotisation chain supports the old wisdom that size really matters, as the 'big five' countries concentrate an overwhelming majority in every area of the chain. This is partly because of the fact that at the current technological level, industrial robots are used for a relatively small and well-defined scope of tasks, such as assembling and disassembling, processing (e.g. cutting and grinding), dispensing (e.g. panting and spraying), material handling (e.g. picking, placing, packaging, measuring, and testing), and welding and soldering (IFR, 2019). Similarly, the industry structure of global robot stock is characterised largely by only four industries: automotive, electronics, metal products, and rubber and plastic. Thus, these limited application possibilities greatly favour large-scale mass production which is driven by global companies, and by countries with large internal markets and/or strong export-oriented economies. Large economies have significantly higher resources for investment in new production technologies, as well as more advanced innovation systems, larger R&D capacities for robotics development than their smaller counterparts, and—perhaps most importantly— higher economies of scale to make robotics development and the deployment of industrial robots efficient.

Nevertheless, the second trend is such that not all of the 'big five' countries possess an equally strong position in every part of the robotisation chain, as the early frontrunners and today's global leaders, Japan and Korea do. For instance, Europe, and particularly Germany, is very strong in robot manufacturing and robot deployment, but needs to catch up with the global leaders for RDs and IRDs. The USA has its firm competitive advantages in robotics development, and yet industrial robots are not deployed in manufacturing as intensively as in other ‘big five’ countries. China is currently a strong competitor in the deployment of industrial robots only —following the spirit of the age-old phrase that ‘if you can’t prevent change, embrace it’—because this is the way to maintain and improve its position as a ‘world factory’ (Zhang (Ed.), 2006) in this technological transformation.

The third trend, the specialisation of smaller advanced economies in some specific areas of the robotisation chain, is a more pronounced development in Europe. While Austria, Denmark, France, the Netherlands, and Sweden may not engage in every part of the robotisation chain to the same extent as the ‘big five’ countries, they do have well performing RDs, and in addition to this, Belgium, Italy, and Spain make extensive use of industrial robots in various kinds of manufacturing. The majority of Central and Eastern European countries, however, are lagging behind, and are integrated into the robotisation chain almost exclusively by robot deployment. Within the Non-EU Europe group, Switzerland is one of the global leaders in robotics development, and within the South-East Asia group, Singapore and Taiwan are also successfully specialising in robotics development, as well as in the deployment of industrial robots.

Finally, the development of the robotisation chain has its own dynamics as it allows for convergence; the quickest and easiest path of convergence is the deployment of industrial robots in various kinds of manufacturing, particularly when the country belongs to multiple global production networks. Within the ‘big five’, over the course of only a couple of years, China has become a global leader in industrial robot deployment, and within Europe, the countries which are categorised within the Central and Eastern European group are also showing signs of convergence through industrial robot deployment. Most of these countries, however, are lacking when it comes to robotics development and robot manufacturing, and they are currently struggling to converge within these areas of the chain. Moreover, in many countries, the intensity of robot deployment is also around or below the global average, which increases the risk that they might be trapped in this stage.

Concluding remarks: Policy challenges

Evidently, these four trends are about the first and current snapshot of the global robotisation race, which taking into account the strong dynamics and the complexity of the robotisation chain, might change rapidly in the years to come. These trends, however, raise three fundamental policy questions:

- the first question relates to the *integration* of countries into the robotisation chain;
- the second question is about the *upgrading* of economies along the chain;
- while the third policy challenge is regarding the *reshoring* of previously offshored production processes, made feasible by advances in robotisation.

The vast literature on global value chains consistently highlights that while the integration of less developed countries into the global value chains drives globalisation, this integration could also contribute enormously to their economic catching-up process (Kaplinsky, 2000; Kaplinsky and Morris, 2001; Henderson et al., 2002; Baldwin and Lopez-Gonzales 2013; Taglioni and Winkler, 2016; World Bank 2017a; Gereffi, 2018; UNIDO, 2018; Ponte, Gereffi and Raj-Reichert, 2019; Raei, Ignatenko, and Mircheva, 2019). Similarly, at present, an overwhelming majority of the world's countries are excluded from the ongoing wave of robotisation, as the present report also covers only 43 countries which are engaged in robotisation with a stock of at least 1,000 industrial robots. Moreover, most of these countries are integrated into the robotisation chain only via robot deployment, without having robotics development at all. Hence, the policy challenge can be distilled into a single question: *What factors support the integration of a country into the robotisation chain?*

There are many issues in integrating countries into the robotisation chain, such as development levels, industrial structures, the availability of skilled labour forces, innovation systems, the openness of the market, and economic policy. However, recent studies show that countries which engage in the various production networks of global companies have better chances of deploying industrial robots than those economies which are less globalised. For instance, in the 37 emerging economies covered by the European Bank for Reconstruction and Development (EBRD), a regression analysis suggests that 1% increase of foreign direct investment in a given sector and a given country is coupled with a 12% increase in industrial robot stock (EBRD, 2018). Eséfalvay (2019b) also highlights that the recent increase of robot stock in Central and Eastern Europe is partly a result of the nearshoring of Western European car manufacturers in the region. Once again, because at the current technological level, the application of industrial robots is limited to few industries and a relatively small number of production processes, this fact favours mass production driven by global companies. Therefore, the decisions of global firms about how to develop and configure the territorial structure of their supply chains across different economies have an immediate impact on the adoption of robots in the affected countries. This is, however, not without the risk of *dependent robotisation*, both in terms of a sectoral dependence from few industries, or a single industry from which global companies locate automated production, and in terms of structural dependence, meaning that robotisation in these countries is excessively relying on the localisation decisions of global firms.

Once a country is integrated into the robotisation chain, typically by robot deployment, its economy faces a new and more difficult *challenge of upgrading along the robotisation chain*, and the difficulty lies in the availability of different location factors at certain parts of the robotisation chain (see again *Tab. 2*). Robotics development (RDs and IRDs) is extremely R&D-intensive, and requires highly skilled labour to be available, as well as for there to be a supportive ecosystem of universities and research institutes. Robot manufacturing (RMs) requires not only domain knowledge in advanced manufacturing, but also for the internal market to be a specific size, allowing for upscaling, while the deployment of robots (RUMs) is highly capital-intensive, and requires middle-skilled labour. In short, and in contrast to those strategies that proved to be sufficient to attract robot-based manufacturing supported by foreign direct investment (FDI) streams (relatively well-skilled labour at low wages, good infrastructure, open economy, and trade liberalisation), the countries which are lagging behind need new policies for upgrading along the robotisation chain, policies which focus much more on improving their R&D capacities. As the example of some small and advanced economies in Europe and South-East Asia shows us, countries which do not have the market scale that makes robot manufacturing and robots deployment efficient, are able to move upwards along the robotisation chain by specialising in robotics development. For this purpose, a flourishing ecosystem of research institutions and universities seems to be a necessary prerequisite, but also targeted innovation policies and collaboration between the public and the private sectors in R&D might have a positive effect.

Moreover, upgrading along the chain is a fundamental issue when it comes to the employment impacts of robotisation. There are two channels through which robotisation could contribute to job creation, and it is the biggest drawback of studies on the future of work that they almost entirely exclude these channels from their assessments of how the labour market might be impacted. The first channel is productivity gain, as deployment of robots increases productivity, and increased productivity could push down prices; lower prices could boost demand, and enhanced demand could have a positive impact on jobs across the whole economy. However, in light of our model of the robotisation chain, it is easy to see the second channel: the parts of the robotisation chain *prior* to the instalment and deployment of industrial robots by the robot using manufacturers (RUMs). In particular, robotics development (RDs and IRDs) and robot manufacturing (RMs) create new jobs and generate trade, and this fact must be considered when assessing the impact of robotisation on employment.

Indeed, this is the point where the engagement of various countries in particular parts of the robotisation chain come into play again. The net employment effect across the whole robotisation chain might be significantly different in countries that have strong positions in all the three important elements of the robotisation chain than in countries that only deploy industrial robots and lack the job-creating parts of the robotics chain. In other words, the employment impact of robotisation depends not only on the skill-biased factors highlighted by studies on the future of work, but also on countries' integration and position in the robotisation chain.

Yet, both integration into the robotisation chain and upgrading along the chain is to some extent hampered by the fact that robotisation has an immense power to redraw the current picture of the international division of labour. One the one hand, with robots, it is possible to produce the product parts in a more compact structure, and this could drastically diminish the number of components and intermediaries which are currently assembled in traditional manufacturing. On the other hand, robot-based automation and the application of digital and data-based technologies in manufacturing (Industry 4.0) increases opportunities for producing geographically closer to the consumer markets of the developed countries (Propis De and Bailey (Eds.), 2020). Consequently, the third policy challenge is such that companies may reconsider their supply chains and production networks, and this could result in the *reshoring of previously offshored production processes*, which depending on reshoring choice and geographical distance, could take on different forms, such as back-shoring, home-shoring, or near-shoring (Pegoraro, Propis De, and Chidlow, 2020).

1 Although longitudinal analyses are sparsely available, and studies are varying greatly according to timeframe, methodology, and data, they indicate that reshoring has already been started in Europe (Gray et al., 2013; Dachs and Kinkel, 2013; Fratocchi et al., 2014; De Backer et al., 2016; De Backer and Flaig, 2017; Mauro et al., 2018; Dachs et al., 2019; Kinkel, Pegoraro, and Coates, 2020), as the gap between offshoring and back-shoring activities has become smaller over the past two decades. For instance, in the European countries studied between10% and 22% of companies reported offshoring activities in the mid-2000s, and between 3% and 7% experienced reshoring (Kinkel 2012; Dachs and Kinkel 2013). Though, almost a decade later, on average only 12% of companies offshored their activities in 2015, while more than 4% of the European firms analysed have moved production back to their home country (Dachs et al, 2019). Similar processes evolved in Germany, where the share of companies that reported offshoring ranged between 17% and 27% in the mid-1990s, and where there was a significantly higher level of offshoring than there were firms which moved back activities (4-6%) (Kinkel, 2014). In the mid-2010s, however, Germany's offshoring dropped to 9%, while back-shoring remained stable at 3% of the companies analysed (Kinkel, 2019). Consequently, according to Kinkel (2020:202), in Germany 'there is currently one back-shoring company for every three offshoring companies.' Nevertheless, in Europe, the average share of companies active in reshoring at all manufacturing companies varies widely from 3% in Germany to around 6% in Belgium and France, and up to 9% in Sweden (Kinkel, Pegoraro, and Coates, 2020).
As these studies on reshoring highlight, the latest digital technologies and robot-based automation may reintroduce industrial production to developed countries, or help to maintain the manufacturing base at home. However, due to robotisation-driven reshoring, it is not the jobs that will return, but the production, with automated plants and robotised factories requiring fewer, but higher-skilled, workers. To put it plainly, the jobs that were relocated from developed countries to developing ones in the course of globalisation will never return.

In fact, new jobs will only be created in industrial production if workers are able to compete with the requirements of operating robotised plants through training and skills.

2 Therefore, the policy challenge is twofold: highly developed countries with advanced manufacturing and innovation systems face a trade-off between the expected job losses in low-skilled activities that may be caused by robot deployment and the relatively small increase in higher-skilled jobs, and the significant productivity gains made feasible by reshoring with robotised factories. By contrast, countries which are currently excluded from robotisation, or are less involved in robotisation, have to confront the problem that back-shoring industrial production from less developed countries to developed economies might block the way for integration and upgrading.
Whether a country faces the issue of integration into robotisation, the challenge of upgrading along the robotisation chain, or the reshoring of previously offshored production, it is clear that further analyses, particularly at firm-level, will contribute to the appropriate design of targeted and country-specific policies. Similarly, while this study is based on aggregate data, further research using microdata could reveal a more detailed picture of the robotisation chain. Finally, while this report focuses on industrial robots, the development and widespread deployment of service robots may in the future trigger significant changes in the global robotisation race.

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