University of Oxford

ISSN 2045-5119

Department of International Development

TMCD Working Paper Series

No. 082

The diffusion of industrial robots
Contribution to the Routledge Handbook of Smart Technologies.

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This version Nov 2020

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Abstract: Over the last 20 years, industrial robots have become more flexible, adaptive and powerful. The worldwide diffusion of industrial robots increased significantly, especially after the global financial crisis of 2008/09. Despite this growth, industrial robots are unevenly distributed across countries, sectors and firms and still far from being a general-purpose technology. Today, firms in Asian countries install more industrial robots than America, Europe and Africa combined. China is the largest user of industrial robots. The manufacturing sector is by far the major application domain for robots, in particular the automotive and the electrical/electronics industries. Outside manufacturing, only few robots are installed. Robots are still an exception in small firms and for the production in smaller batches or single units. Evidence for an uneven diffusion of robots can also be found in comparisons of the intensity of robot use across countries which is very much driven by industrial structure.

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key concepts for the subject and name index

International Federation of Robotics

Evolution robots

Industrial robots

Diffusion

Manufacturing

European Manufacturing Survey

Europe

Asia

China

Korea

United States

Industrie 4.0

Productivity

Employment

1. Introduction

At the time of the publication of this book, robots will turn 100 years old. The term ‘robot’ was first used in 1920 by the Czech writer Karel Čapek to describe artificial people created to work. Over the last century, industrial robots have made an impressive career, from the theatre stage and the pages of science-fiction books to the shop floors of the world. The number of robots seems to be growing faster than other categories within information and communication technologies, in particular faster than personal computers (DeStefano et al., 2017). The International Federation of Robotics (IFR) reports that 303,847 robots were sold globally in 2016, up from 53,409 units in 1993.

This rapid diffusion can be explained by the decreasing price/performance ratio of robots, which is a result of performance increases in computing power, sensors, cameras, communication technologies, and energy storage (Pratt, 2015). New technologies such as collaborative robots and improved human-machine interaction have enlarged the potential application areas. Major advances in the future can also be expected from the combination of ‘machine learning’ (artificial intelligence) and robotics (IFR, 2019). However, productivity gains will also arise when firms learn to better integrate robots into their production processes. Another organizational innovation where the IFR sees potential for the future is “Robots as a Service”.

This chapter will provide an overview of the diffusion of robots in the economy and its economic effects. It is divided into eight sections: the next section discusses the characteristics of industrial robots. In the following sections 3 and 4, we will provide information on the diffusion of robots at country and sectoral level. Both sections will draw on data from the International Federation of Robotics (IFR). These data will be complemented with results from EUROSTAT and from the European Investment Bank in section 5. The sixth section will analyse the characteristics of firms using robots, including their size and the characteristics of their production processes. Besides country and sectoral differences, there is also a considerable heterogeneity in the use of robots among different types of firms. The seventh section will wrap up studies that investigated the economic effects of robots’ use in different countries. Section 8 closes with a summary and some conclusions.

2. The evolution of industrial robots

Before we look at the diffusion of robots in the economy, a few remarks are provided on the technology. The International Organization for Standardization (ISO, 2012) defines a robot as an "actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks". ISO also distinguishes between robots for industrial applications ("industrial robots"), and service robots, which "perform useful tasks for humans or equipment excluding industrial automation applications".

Robots are not a new technology. According to Mansfield (1989), the industrial robot was an American invention, and the first commercial robot was put into operation in 1961 by General Motors. The first industrial robots in Europe and in Japan were installed in 1967 (Scalera and Gasparetto, 2019). In the following years robots increasingly found applications in repetitive tasks such as welding, painting, bending or polishing. Major sectors making use of robots in the mid-1980s were the automotive and the electrical industries (Mansfield, 1989) – very similar to the specialisation patterns found today.

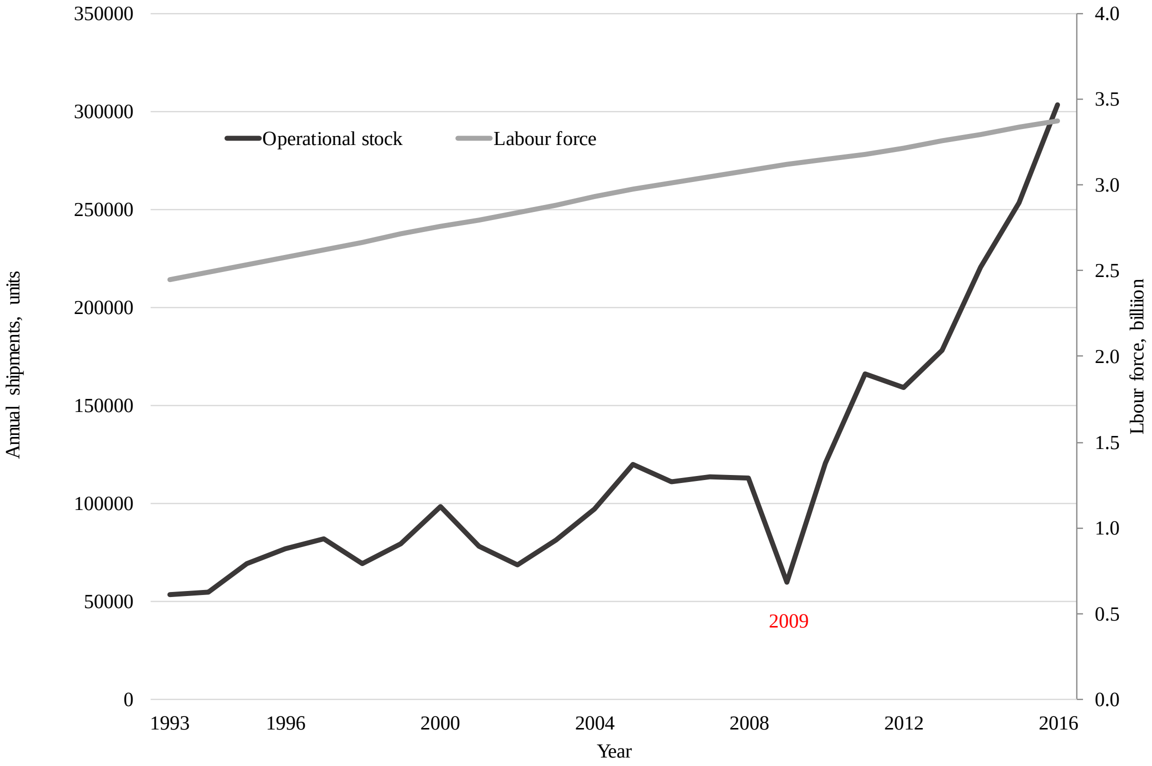
The evolution of industrial robots encompasses various generations (Hägele et al., 2016; Scalera and Gasparetto, 2019). While the first generation was little more than a programmable mechanical arm with no ability to move and no connection to the external environment, later generations became increasingly adaptive and autonomous due to increasing computing power and the use of various sensors. The second generation (between 1968 and 1977) was already programmable, used microprocessors and electric motors instead of hydraulic systems, had some limited capabilities to recognize their environment, and was able to carry out more difficult tasks. These abilities were further improved in the third generation (1978-1999), which also included limited adaptive capabilities and self-programming. Industrial robots for sorting, picking, and other complex tasks arrived in new application areas such as electronics, the food industry, or machinery.

The current generation of industrial robots is characterized by high computing capabilities, advanced sensors and intensive data exchange with their environment, including with other robots. Pratt (2015) identifies eight drivers determining the capabilities of today's industrial robots: (a) exponential growth in computing performance and (b) in global computing power; (b) improvements in electromechanical design tools and numerically controlled manufacturing tools; (c) improvements in electrical energy storage and (d) in electronics power efficiency; (e) exponential expansion of the availability and performance of local wireless digital communications; (f) exponential growth in the scale and performance of the internet; (g) and exponential growth of worldwide data storage. He predicts a "Cambrian Explosion" of robotics technology in the future, due to the combination of exponential growth in computing power ("Cloud Computing") and applications of artificial intelligence ("Deep Learning"), which will lead to a virtuous cycle of explosive growth.

3. The world-wide diffusion of robots

Prospects for robots seem bright, and the diffusion of robots so far may only be the prelude to things to come. Since the year 1993, annual shipment of industrial robots worldwide has grown from 53,409 units to 303,847 in 2016, which means more than a five-fold increase during a 23-year timespan. In particular, the shipment of industrial robots gradually increases, with some fluctuations, since 1993 and reaches its first and second peaks in 2000 and 2005 respectively (Figure 1).

Figure 1: Worldwide Shipments of Industrial Robots and Labour Force

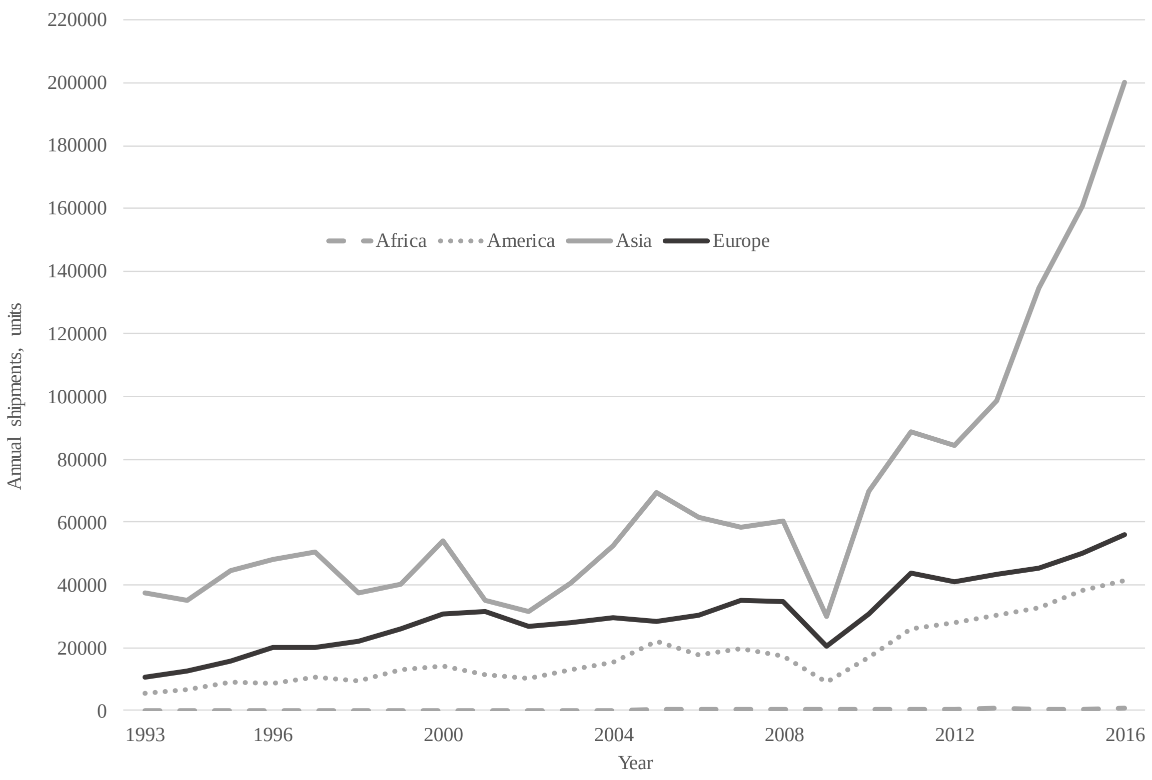


Source: IFR, World Bank

The annual shipment of industrial robots remains stable from 2005 to 2008 and is confronted with a sharp downturn to a level of 60,018 units in 2009 in response to the global financial crisis. Nevertheless, worldwide production of industrial robots recovers immediately after 2009 and starts to grow again with ever stronger momentum. From Figure 1, it seems that the global diffusion of robots starts to take off after the global financial crisis. The global labour force, on the other hand, increases more steadily from roughly 2.4 billion in 1993 to approximately 3.4 billion in 2016.

With regard to the geographical distribution of shipments of industrial robots, all of the four regions, i.e., Asia, America, Europe and Africa, witness significantly higher shipments in 2016 compared to those in 1993 (Figure 2). The sudden and dramatic downturn in the year 2009, when the impact of the financial crisis spreads to every corner of world economy, hits robot diffusion in all four regions. Throughout the whole period, annual industrial robot shipments in Asia outnumber those in the other three regions, and this gap further enlarges after the recovery from the global financial crisis. In 2016, Asia ends up with 200,042 units, almost twice the total shipments in the rest of the world. The shipment of industrial robots in Europe slightly exceeds those in America, with a similar annual change in both regions.

Figure 2: Worldwide Distribution of Industrial Robots

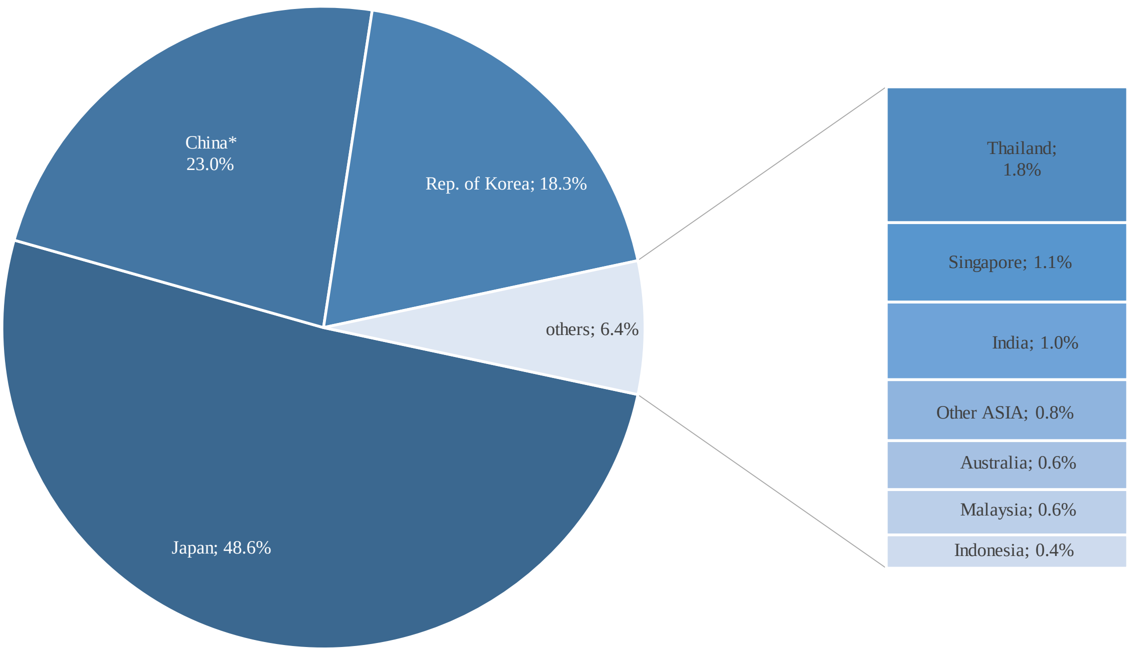


Source: IFR

Admittedly, Africa has the lowest volume of shipments, with no more than 5,000 units annually, even in 2016. However, the growth rate in this region exceeds that of the rest of the world by far, especially in the first decade of the 21st century. Before 1999, there are no shipments of industrial robots in Africa, while the stock almost triples in 2001 compared to the previous year. Since then, industrial robot shipments show a high growth rate overall until 2016.

The uneven geographical distribution of industrial robots is even more pronounced at the country level. Among the total shipments of industrial robots during the period of 1993-2016 in Asia, Japan takes up 48.6%, nearly equalling all the other countries and districts in Asia (excluding Hongkong, Macau and Taiwan); China comes in second place with 23%, followed by the Republic of Korea (Korea in the remainder of the text) with 18.3%. These three industrial economies together share 89.9% of Asian shipments of industrial robots, while the next seven countries in total account for 6.4%. Thailand, Singapore and India each account for 1~2% of the total shipments; for the other top ten countries, however, no single country takes up a share higher than one percent of total shipments to Asia. Indonesia has the fewest shipments of industrial robots among the Asian top ten countries, receiving only 0.4% of the total production. (Figure 3)

Figure 3: Shipments of Industrial Robots – Top 10 Countries in Asia, 1993-2016



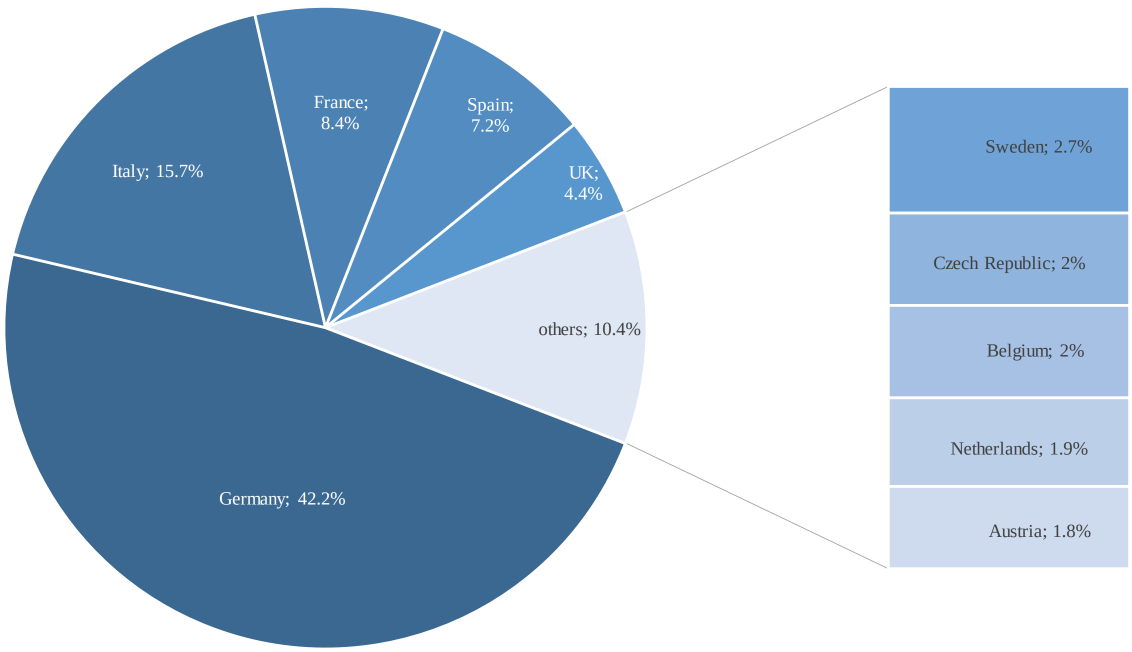
*excluding Hong Kong, Macau, Taiwan

Source: IFR

America displays a greater concentration of industrial robot shipments. The US alone is responsible for 87.7% of the total shipments across the continent, followed by Mexico with a share of only 4.8%. The remaining shipments go to Canada (3.3%) and other North and South American countries including Brazil (3.3%), Argentina (0.3%), Chile (0.02%), Columbia (0.01%), Puerto Rico (0.01%) and the rest of South America (0.7%).

By contrast, shipments of industrial robots are relatively evenly distributed in Europe with five countries taking up around 90% of total European shipments during the years 1993-2016 (Figure 4). Particularly, Germany stands out among European economies by receiving 42.2% of the total shipments, more than twice as much as Italy (15.7%) which ranks in 2nd place in the region. The share of shipments to France and Spain are similar, i.e., 8.4% and 7.2% respectively, followed by the United Kingdom as the fifth largest market with 4.4% of European total shipments. The remaining industrial robot shipments in Europe go to Sweden (2.7%), Czech Republic (2%), Belgium (2.0%), Netherlands (1.9%) and Austria (1.8%).

Figure 4: Shipments of Industrial Robots – Top 10 Countries in Europe, 1993-2016



Source: IFR

In a longitudinal perspective, the ranking of the ten largest markets worldwide remains relatively stable, with a few variations, as emerging economies and developing countries play an increasing role in technological development and industrialization. In 1993, all of the top ten markets were developed countries. China entered as the 10th market for industrial robots in 2001 and Thailand and Mexico joined the ranking in 2009 and 2016, respectively. It is worth noting that China rose to be the 5th largest market after the global financial crisis and leapt to replace Japan as the world's largest market in 2016. With 96,500 units, Chinese firms install more than twice the number of industrial robots as Korea, Japan, the US, and Germany. Countries such as Belgium and Sweden, initially in the list of top markets for industrial robots, gradually fade away from the list. (Table 1)

It is no coincidence that the largest users of robots in Europe and the world are also the largest car manufacturing countries. In regard to robot shipments, the top 10 countries very closely resemble the top 10 car producers worldwide, with the exception of India, which is not among the top 10 in the diffusion of robots. Thus, the rise of China, Korea, Mexico, and Thailand in the ranking of Table 1 is closely linked to the evolution of the automotive industry in these countries. The close relationship between robots and the automotive industry will be explored in section 4.

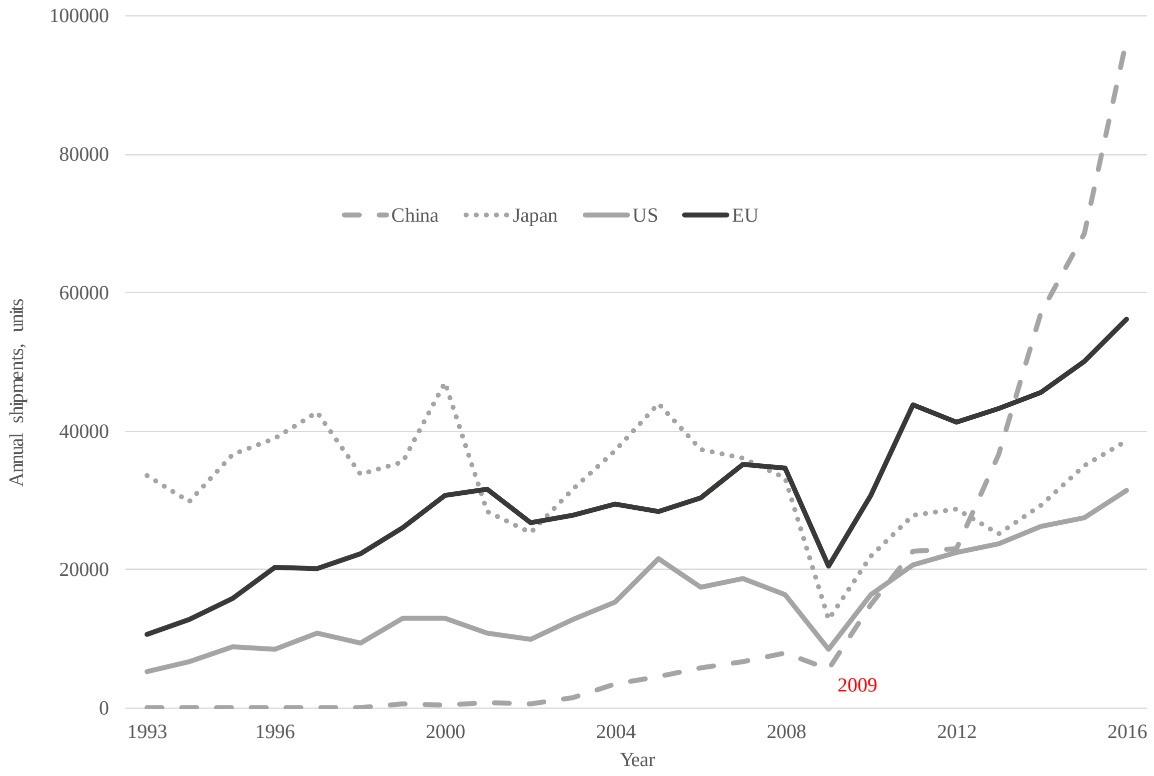
Table 1: Worldwide Shipments of Industrial Robots (Annually, '000 of units)

Rank	1993		2001		2009		2016	
1	Japan	33.5	Japan	28.4	Japan	12.8	China	96.5
2	US	5.2	Germany	12.7	Germany	8.5	Korea	41.4
3	Germany	4.3	US	10.8	US	8.4	Japan	38.6
4	Korea	2.7	Italy	6.4	Korea	7.8	US	31.4
5	Italy	2.5	Korea	4.1	China	5.5	Germany	20.1
6	France	1.0	Spain	3.6	Italy	2.9	Italy	6.5
7	UK	0.6	France	3.5	France	1.5	Mexico	5.9
8	Spain	0.5	UK	1.9	Spain	1.3	France	4.2
9	Singapore	0.4	Sweden	0.9	Thailand	0.8	Spain	3.9
10	Belgium	0.3	China	0.7	Belgium	0.7	Thailand	2.6

Source: IFR

Let us draw a focused comparison between the four leading economies where the adoption of industrial robots is concentrated: China, Japan, the US, and Europe. In 1993, Japan is the country adopting the most industrial robots (33,502 units), more than twice as many as the EU (10,509 units) and the US (5,246 units) combined. In contrast, there is no industrial robot adoption in China until 1999 (Figure 5).

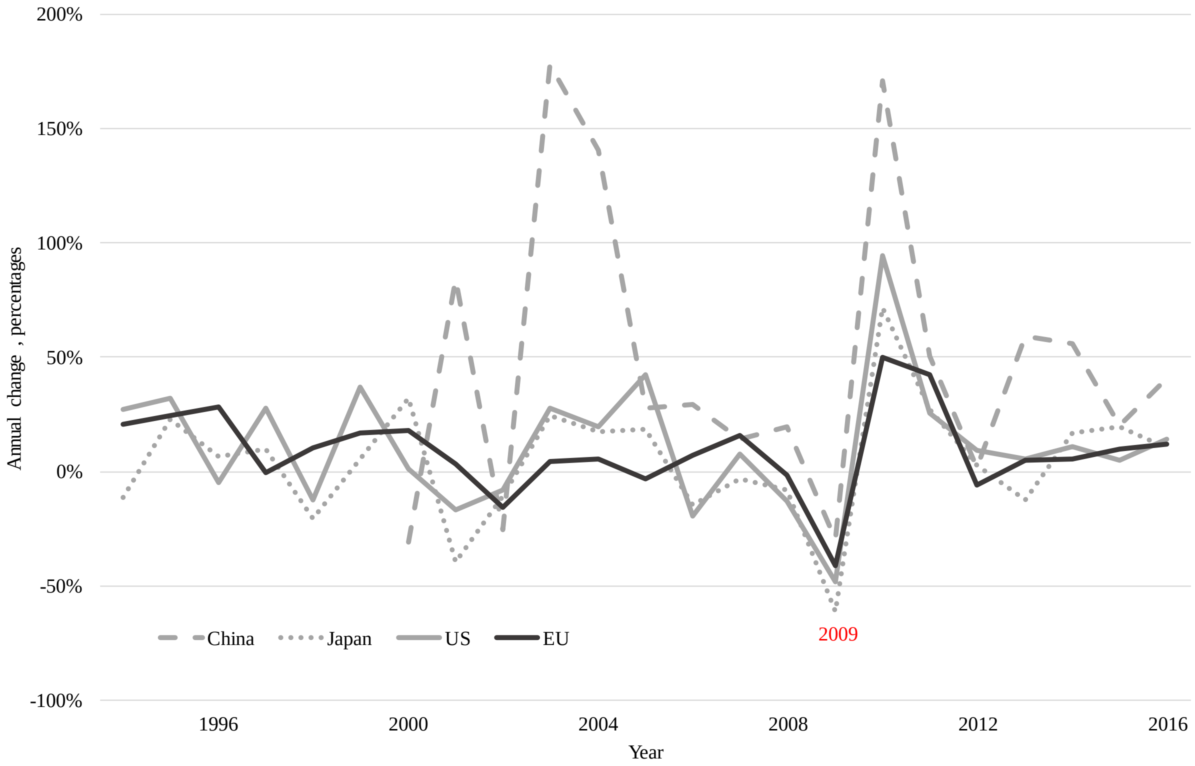
Figure 5: Distribution of Industrial Robots in Four Regions



Source: IFR

The diffusion of industrial robots is far from being a linear process. From 1993 to 2008, installations of industrial robots increase in the EU, the US and in China at different speeds. Figure 6 shows that positive growth dominates in these three economies, despite occasional declines before and after the millennium. Moreover, investment in robots is strongly affected by the business cycle. The economic downturns of 2001 and 2009 are clearly visible in the shipments of industrial robots, and this points to the importance of the business cycle for investment decisions in this technology. The fluctuation of shipments in China during the crisis is even more dramatic, with the adoption of industrial robots dropping 11% after an 84% surge in the previous year, and soon soars 178% in the following years. This pro-cyclical pattern of robot shipments indicates that firms consider robots as a long-term investment and do not expect short-term benefits like cost cutting; otherwise, investment in robots to reduce production costs would be an appropriate response to declining demand during a crisis. The slump in demand for robots can also be related to labour hoarding, the strategy of firms to keep their workforce stable and tolerate decreasing productivity as demand for their products falls into an economic crisis (Leitner and Stehrer, 2012). Thus, investment in robots is not the first priority for firms in a crisis.

Figure 6: Distribution of Industrial Robots in Four Regions, by Change Rate



Source: IFR

IFR does not provide data on the main producers of industrial robots at the country level. We also found no other public source for this information. However, from the world's largest firms in the robotics industry, we may infer that most robots are manufactured in Japan, Europe and China.

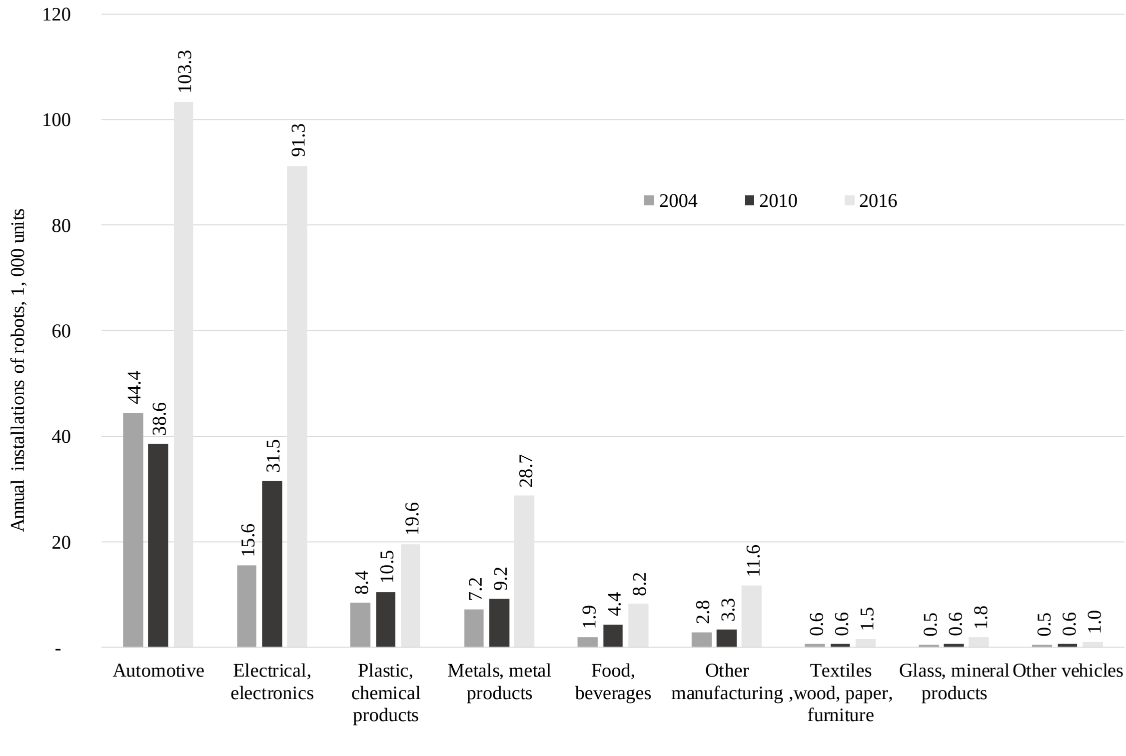
4. Sectoral patterns of the diffusion of robots

Apart from regional diversity, global industrial robot distribution also varies considerably between industrial sectors and sub-sectors. In all countries, industrial robots are predominantly installed by manufacturing firms, and only rarely distributed to other sectors, i.e. the education/research sector, agriculture, forestry and fishing industry, construction industry, electricity, gas and water supply industry, and mining and quarrying industry.

Within the manufacturing sector, the automotive industry displays the highest adoption of industrial robots with 44,400 shipments in 2004, followed by the electrical and electronics industry with 15,600 units, which is only slightly more than one-third of the former. The shipment of industrial robots to the automotive industry dropped to 38,600 in 2010, two years after the global financial crisis in 2008. It is worth noting that the decline in robot shipments during the global financial crisis was due to a drop in demand in the automotive industry, as this is the only industry that has experienced a downturn in the adoption of industrial robots between 2004 and 2010. Despite the shock, the annual use of industrial robots in the automotive industry soon recovers, rising to 103,300 units by 2016 - more than twice as many as in the years 2004 to 2010.

The electrical and electronics industry is the second largest user industry of industrial robots. However, the gap to the automotive industry is large: in 2004, only 15,600 units were applied in this industry. The number doubled in 2010 compared to 2004 and tripled in 2016. Since 2010, the gap between the electrical/electronics industry and the automotive industry has been narrowing (Figure 7). This indicates that, over time, more application areas for robots outside the automotive industry have emerged. Examples for such new application areas of industrial robots outside the automotive industry are the manufacturing of metal products, of plastic products, the chemical industry and the manufacturers of food and beverages.

Figure 7: Industrial Robots Installed in Manufacturing Industries World-wide



Source: IFR

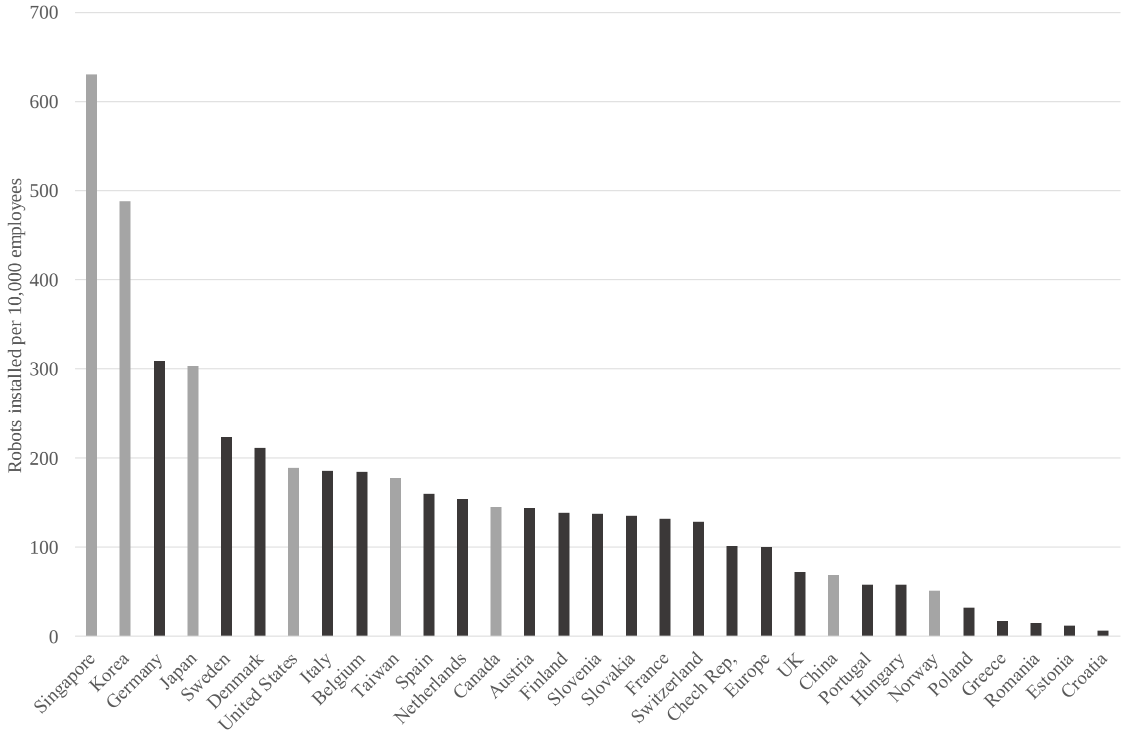
In most industries, industrial robot adoption accelerates over time, just like in the automotive and in the electrical and electronic industry. Medium and high technology-intensive industries use more robots than low-tech branches, disregarding the difference in the size of the sub-industries. For example, 7,200 units of industrial robots were installed in the metal products industry in 2004, and only 2,000 more units joined the stock in 2010. However, six years later, the annual adoption of industrial robots has more than tripled, reaching a total of 28,700 units. This is the same for plastic products and for the chemical industry, the 4th highest adoption branch in manufacturing sectors, where the use of industrial robots nearly doubles in the second period. Similar trends can be observed in industries where robots are only applied to a limited extent, such as the industries of wood and furniture, paper, textiles, other vehicles, glass, ceramics, stone, mineral products, and all other manufacturing branches. For these categories, there are hardly any scenarios for the use of industrial robots. For instance, even in the year 2016, only 300 units are adopted in the textiles industry. The only exception is the food and beverage sector, where growth in the adoption of industrial robots doubles in the second period (Figure 7).

5. Robots' intensity across countries

In a discussion about the diffusion of robots, not only should absolute numbers be considered, but also how intensively firms in different countries use robots. Intensity is usually measured by the number of installed robots per 10,000 workers or the ratio of firms using robots to all firms in a country.

The ranking of the countries according to robot intensity clearly differs from that in Table 1. Singapore is the country with the highest robot density, followed by Korea and Germany. Here, some small countries have a much higher weight, while neither the US nor China are in the leading positions. Given the sheer size of these economies, a massive investment in robots would be required to achieve such a position. Europe (dark grey bars in Figure 8) lags behind Japan, the US and China, although some European countries, especially Germany, Sweden and Denmark, reveal high robot intensities. The countries with the lowest robot intensity in Europe are Eastern-European countries including Estonia, Romania, and Croatia.

Figure 8: Number of Robots per 10,000 Employees in Manufacturing, 2016



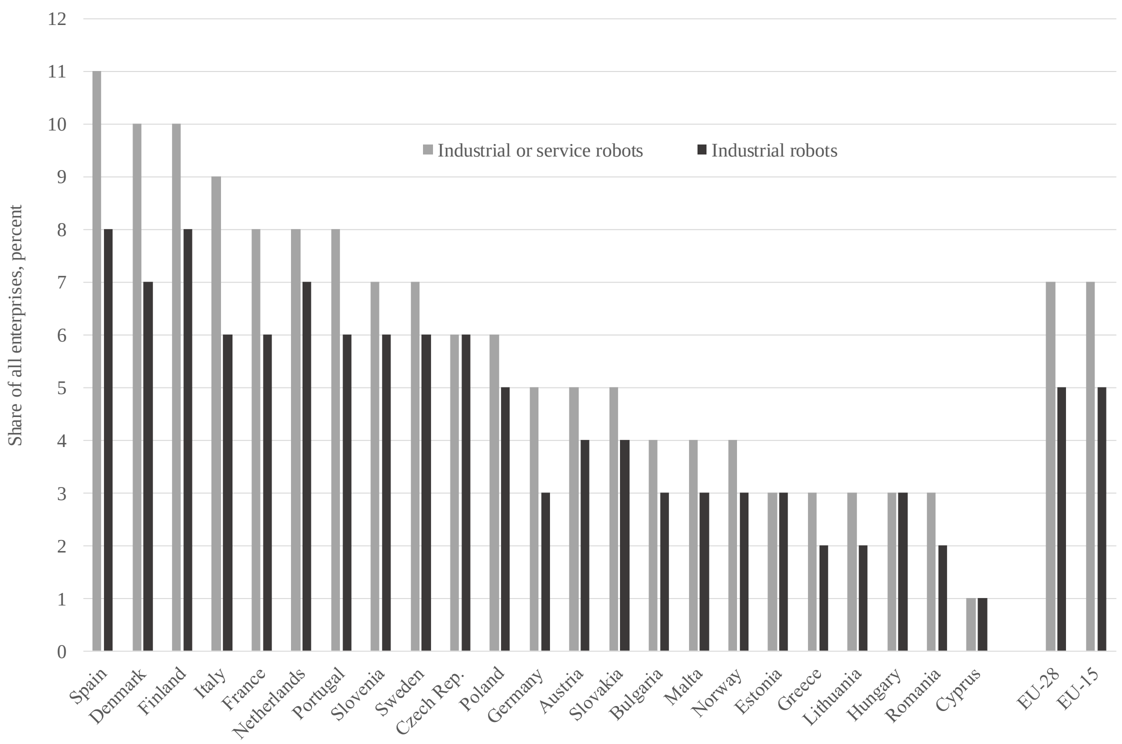
Source: IFR

Evidence on robot intensity is not only provided by the IFR, but also by the European national statistical offices in cooperation with EUROSTAT, as well as by the European Investment Bank in its annual Investment Report (EIB, 2019). Unfortunately, this information is only available for European countries, and in the case of the EIB data, only for European countries and the US.

According to EUROSTAT, the highest shares of enterprises with 10 or more employees using robots are found in Spain (11%), Denmark and Finland (both 10%), and Italy (9%). In contrast, the IFR sees Germany, Sweden and Denmark as the countries with the highest robot intensity in Europe, based on the number of robots installed per 10,000 manufacturing employees (see Figure 8). The difference between the two rankings can be explained by a few large firms in Germany, Sweden and Denmark which invest heavily in robots. We find these firms in the automotive industry. Finland - with no automotive industry - is the country where the rankings according to IFR and EUROSTAT differ the most. EUROSTAT finds the lowest shares of firms using robots in Cyprus (1%), Estonia, Greece, Lithuania, Hungary and Romania (Figure 9 below), which is consistent with IFR data.

Another interesting result from EUROSTAT data is that there is no difference in the diffusion of robots between Western European member states and the EU-28 average (two right-hand columns in Figure 9). This is in stark contrast to many other indicators of innovation and technology diffusion, which still show a considerable gap between EU member states in Western Europe and in Central and Eastern Europe. One explanation is the strong manufacturing base in some of the Central and Eastern European member states. The Czech Republic, Poland, Hungary, Slovakia and Slovenia have large automotive and metal products industries, which manifests itself in a higher share of firms using robots.

Figure 9: Share of Enterprises in Different European Countries that use Industrial or Service Robots, 2018

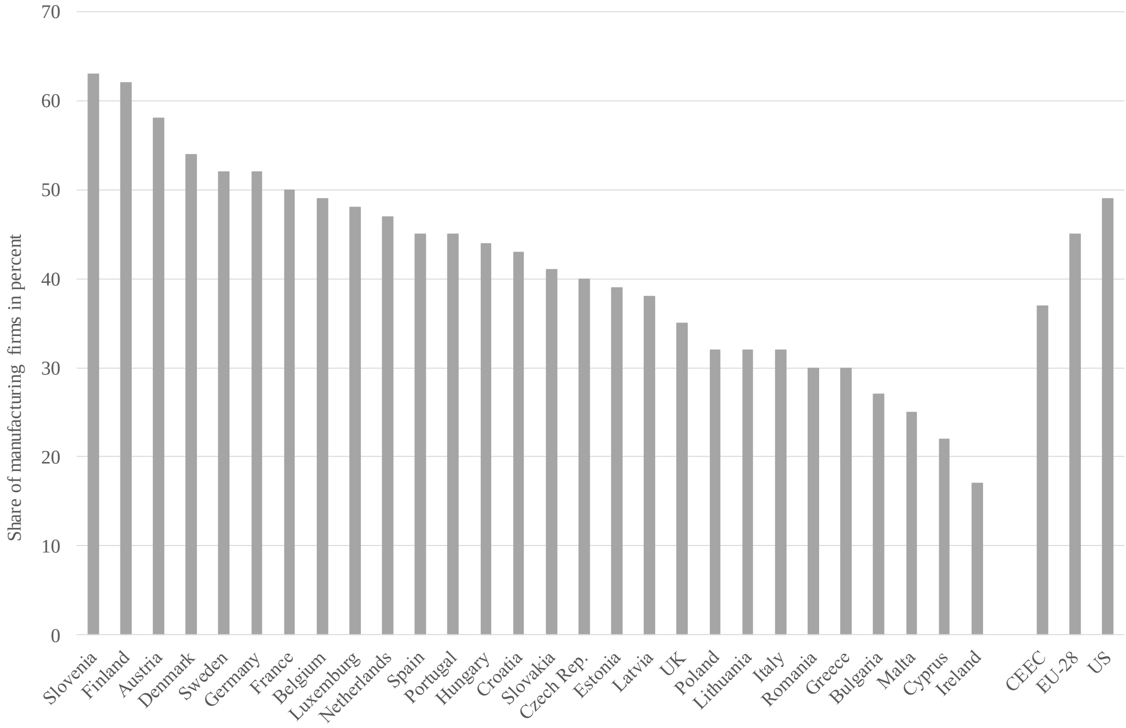


Source: EUROSTAT, ICT usage in enterprises

Robots are also covered in the Investment Survey 2019/20 by the European Investment Bank (EIB, 2019). A total of 12,672 European firms participated in this survey. The EIB notes that the diffusion of advanced robots in the EU manufacturing industries is highest in small countries: Slovenia, followed by Finland, Austria, Denmark and Sweden. In contrast, however, Malta, Cyprus and Ireland are lagging behind (Figure 10).

A major advantage of the EIB Investment Survey is that it allows a comparison of the European Union with the United States. According to the EIB, the diffusion of robots in the US is slightly higher than in the EU. However, the gap between the US and the EU is much smaller in EIB data than in the IFR data, which shows an average intensity of 114 robots per 10,000 employees in European manufacturing compared to 217 robots in the United States. Overall, the EIB (2019) concludes that a deficit of European firms in digitalisation is more likely to be observed with the adoption of the Internet of Things than with the adoption of industrial robots.

Figure 10: Share of Manufacturing Firms that use Advanced Robots, 2018



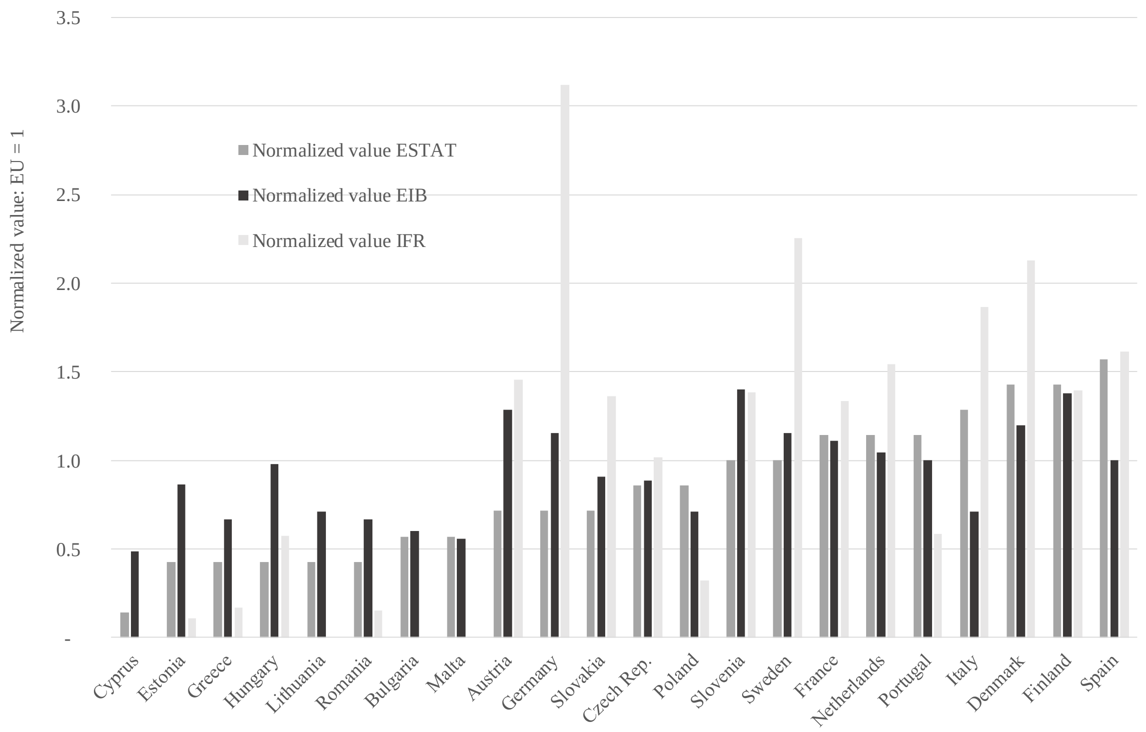
Note: CEEC are Central and Eastern European Countries

Source: European Investment Bank, Investment Survey 2019/20

Obviously, the EIB results differ from EUROSTAT as well as from the IFR data. Readers will also find that the numbers reported by the EIB are considerably higher than those reported by EUROSTAT, although both surveys cover the year 2018. The most likely reasons for these discrepancies are different survey techniques and different questions about robotics' use. EUROSTAT's survey asks whether the firm uses industrial or service robots, including some potential applications. The questionnaire used by the EIB is not yet available online, so a comparison is not possible. Moreover, as the diffusion of robots increases with the firm size, the share of small firms in the EIB survey may be lower compared to the EUROSTAT survey. The IFR is based on actual shipments, which is a different concept than the robots installed in firms. Shipments may go to intermediaries or be forwarded from the headquarters of multinational firms to subsidiaries in other countries.

To compare IFR, EUROSTAT, EIB data, we normalize the country values to the EU or European average, so that countries with a higher diffusion than the EU average have a value larger than one and vice versa (Figure 11). The country rankings are quite inconsistent between the three surveys. Only five countries (Finland, Netherlands, France, Sweden and Denmark) are at or above the EU average in all three surveys. These countries can be regarded as the leaders in the application of robots in Europe. Germany is difficult to include, as the divergence between IFR and the other two datasets is largest here. Germany scores well on the IFR and the EIB data but is below EU average in the EUROSTAT data. A careful examination of the data would be necessary to understand the reasons for these differences. However, it seems conceivable that German firms are among the most sophisticated users of robots worldwide. Poland, Romania, Hungary, Greece and Estonia rank below the EU or European average in all three surveys, so it seems fair to say that these countries are lagging behind in the diffusion of robots.

Figure 11: Normalized Values for IFR, EUROSTAT, and EIB Data on Robot Diffusion, 2016 and 2017.



Source: IFR, EUROSTAT, EIB, own calculations

With a Spearman correlation index of 0.63, the EIB and the EUROSTAT survey are the most comparable, followed by EIB-IFR (correlation of 0.62) and EUROSTAT-IFR (correlation of

0.6). However, some small EU countries are not included in the IFR data, which makes the comparison difficult. Nevertheless, due to their methodology, the data on the diffusion of robots at country level reveal large differences. From a methodological point of view, for a number of questions, a survey at the firm level, such as the EIB or EUROSTAT surveys, is preferable to shipment data because it is easier to match with other data at the firm level. This also puts some question marks against cross-country studies using IFR data because they cannot take into account the concentration of robots in some very robot-intensive firms and industries (see section 7).

6. Robots in manufacturing: some firm-level evidence

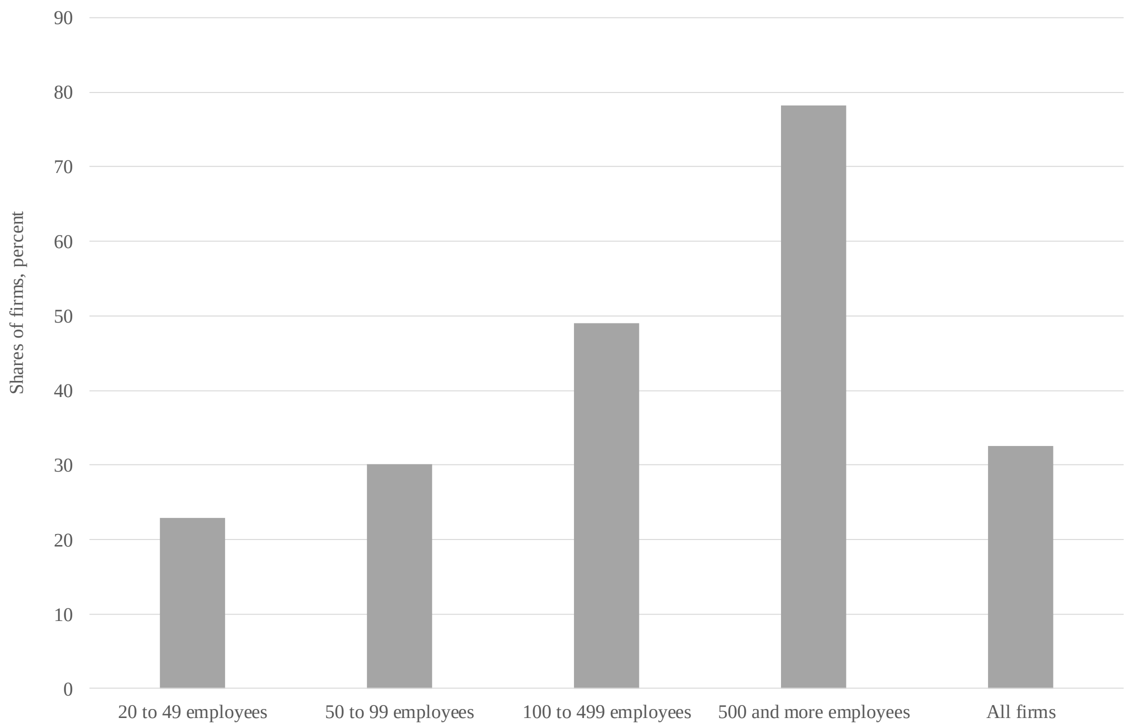
In manufacturing, robots are applied in many different processes and production contexts. The IFR data provides insights from the perspective of robot producers and indicates who buys these robots. Thus, IFR data offer an interesting insight into the robot market but provide only little information about the users of industrial robots, i.e. those companies that purchase the robots. When discussing the diffusion of robots, it is also of great interest to place the firms that use robots into the context of their non-using counterparts. Therefore, we add an additional perspective by analysing the use of industrial robots in manufacturing at firm level. This approach allows us to clarify structural barriers and delivers an insight from the perspective of robot users.

The *European Manufacturing Survey* (EMS) provides this perspective. EMS investigates the use of techno-organizational innovations in manufacturing at the level of individual manufacturing sites (Jäger and Maloca, 2016). In each country, the survey comprises a large random sample of manufacturing firms with at least 20 employees covering the entire manufacturing sector. EMS is organized by a consortium of research institutes and universities from across Europe. The EMS 2015 data includes information from Germany, Austria, Spain, Croatia, the Netherlands, Slovenia, Switzerland, and the Republic of Serbia, containing a sample of over 2,750 manufacturing companies. Thus, EMS enables us to draw a reliable picture of industrial companies that use robots.

On average, one third of all manufacturing firms with at least 20 employees in these eight European countries uses industrial robots either for manufacturing processes (e.g. welding, painting, cutting) or for handling processes (e.g. depositing, assembling, sorting, packing processes) in 2015 (Figure 12). This indicates that despite the impressive total number of robots in manufacturing, industrial robots are far from being standard tools in production but are used by a significant sub-group of manufacturers in Europe.

One important sub-group is large firms. According to Figure 12, large companies with 500 and more employees are by far the most active users of robots on their shop floor (78% of all companies in that size class). This share decreases considerably with firm size: companies with 100 to 499 employees are still quite active with nearly 50 percent of all companies of that size using industrial robots. Among industrial companies with 50 to 99 employees, 30 percent are using industrial robots, whereas in small firms with fewer than 50 employees, this share drops to 23 percent.

Figure 12: Share of European Manufacturing Firms that use Robots in Different Firm Sizes, 2015



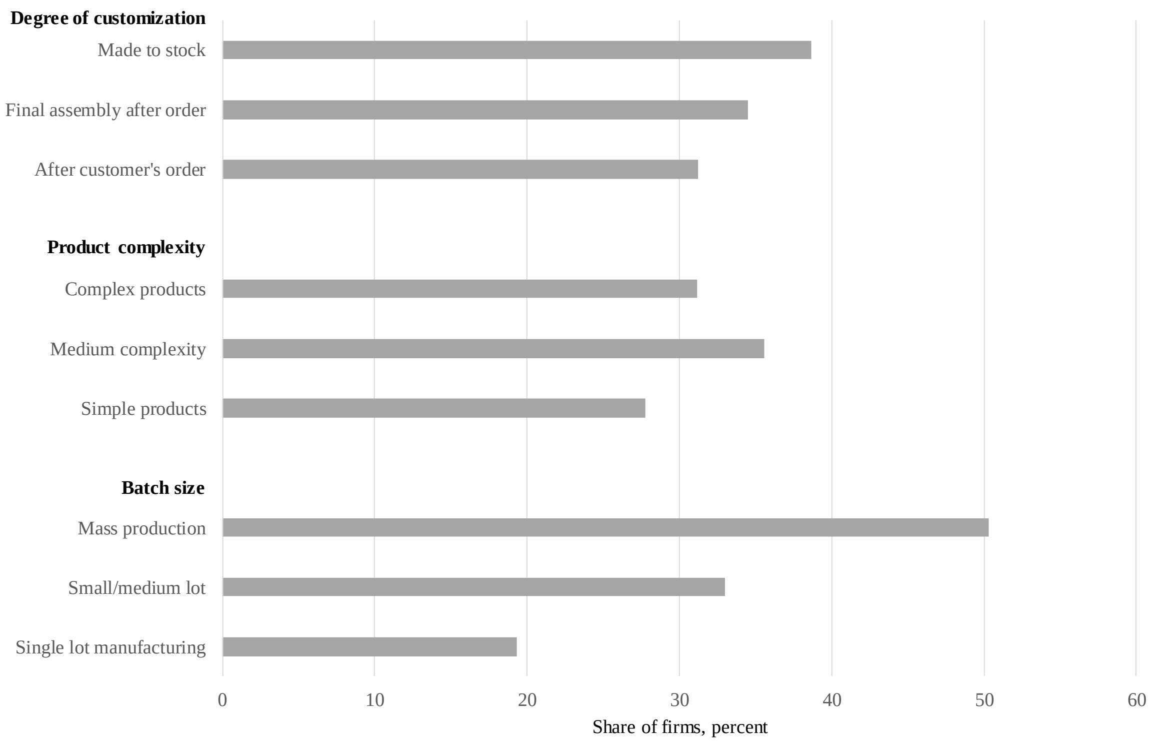
Source: *European Manufacturing Survey* 2015, eight countries, compiled by Fraunhofer ISI, weighted data.

The use of industrial robots therefore differs considerably depending on firm size. In larger firms, the use of industrial robots is rather common; robots can be considered a standard tool. Larger companies have more opportunities and higher economies of scale to use industrial robot systems efficiently, have more experiences with the introduction of advanced production technologies and can find more robot models that meet their needs and resources (Jäger et al., 2016).

When looking at the production characteristics, the batch size is the most important determinant of robot use. Mass producers display a significantly higher propensity to use industrial robots than companies producing in small batches or single units. Economies of scale are easier to realise under the conditions of larger batch sizes, enabling productivity growth through the automation of repetitive tasks.

Slight differences can be found regarding the product complexity and the degree of customization. Figure 13 shows that 36 percent of all companies that produce medium complex products use industrial robots, while this share is only 30 percent and 33 percent for producers of simple or complex products, respectively. Medium complex products with high volumes have more handling and assembly tasks that are suitable for automation but also contain a sufficient number of repetitive tasks to be automated (Jäger et al., 2015). Moreover, as displayed in Figure 13, firms that produce after a customer's order or finish the prefabricated product after receiving a customer's order are significantly less likely to use robots than firms that anticipate customer demand and produce to stock.

Figure 13: Share of European Manufacturing Firms that use Robots by Production Characteristics, 2015



Source: *European Manufacturing Survey* 2015, eight countries, compiled by Fraunhofer ISI, weighted data.

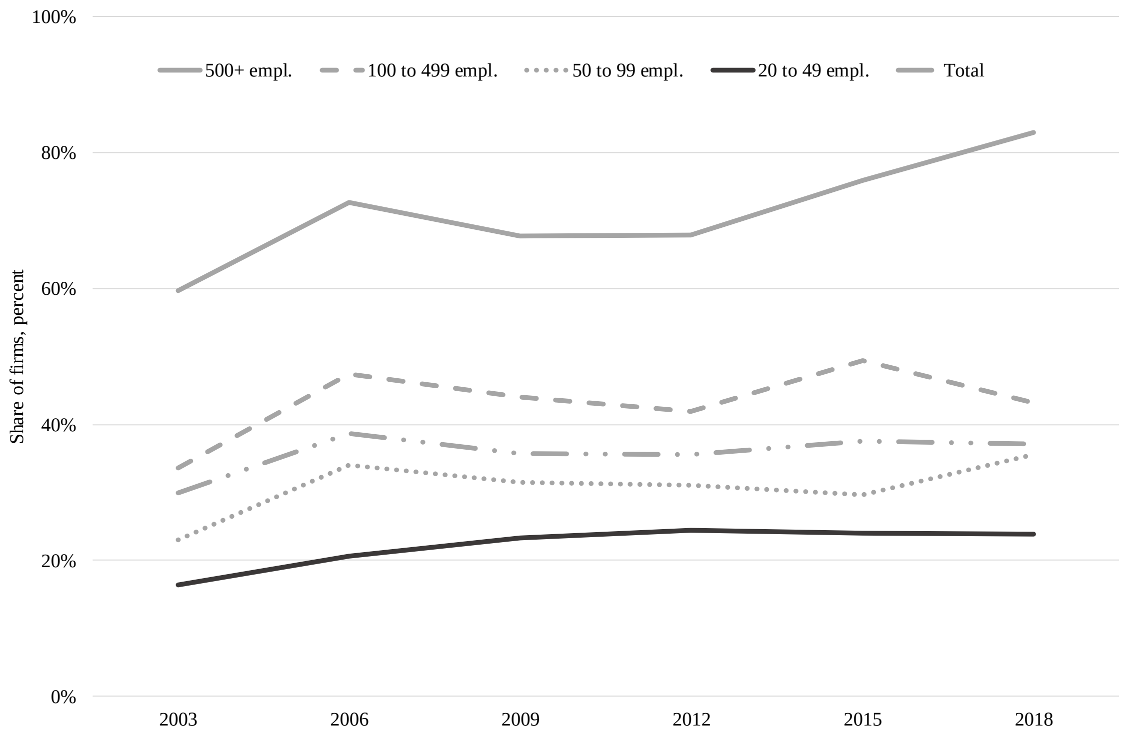
These structural differences, together with sectoral affiliation and location, are of great importance in determining the chances of using industrial robots in a manufacturing firm.

However, there are some changes in these determinants over time. Producers of discrete parts, i.e. plastic products, metal products, electrical and electronic products, machinery, or automotive and transport equipment are a good example. Together, these sectors account for around two thirds of all firms in manufacturing. The shifts over time can be assessed based on EMS data from Austria, Germany and Switzerland from 2003 to 2018 in the figure below. Data for the other five countries are not available for the full period.

Section 3 showed an impressive increase in the number of installed robots in all countries. This trend can be observed in the EMS as well. However, the increase in the number of firms using industrial robots is rather low compared to IFR data. The share of firms using robots grew much more slowly than the number of installed robots in manufacturing (Figure 14). This indicates that the boom in installed robots is a capital deepening rather than broadening issue.

Figure 14 also shows that the increase of firms using robots can mainly be related to large firms; the share of robot users in this group rose from 60 percent to over 80 percent between 2003 and 2018. The expectation that robots will become more common in manufacturing over time and that the gap will decrease between larger and smaller firms in the diffusion of robots has not been fulfilled. On the contrary, the advantage of larger firms has become even greater. The diffusion among small firms remains weak.

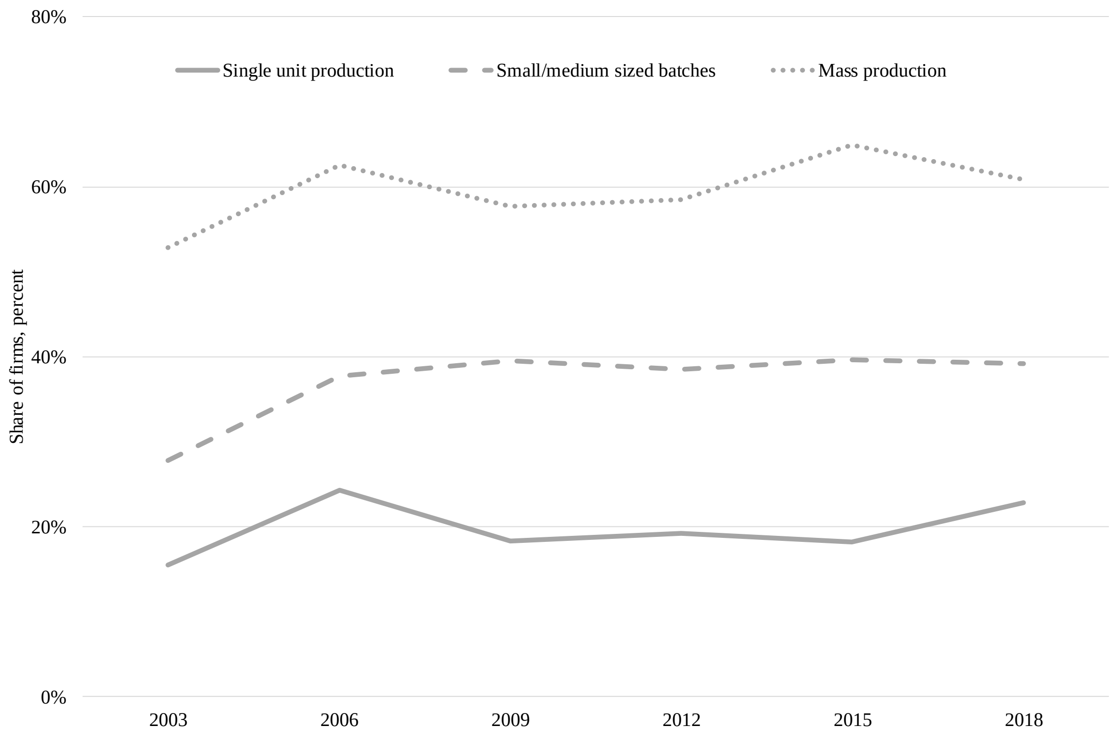
Figure 14: Share of Robot Users among Austrian, German, and Swiss Manufacturers of Discrete Parts, Differentiated by Firm Size Groups, 2003-2018



Source: *European Manufacturing Survey* AT, CH, DE - 2003-2018, compiled by Fraunhofer ISI.

Another difference in the diffusion of industrial robots, which persists over time, is between firms producing single pieces, small batches and mass production (Figure 15). Mass producers use industrial robots much more frequently than manufacturers with smaller batches, and this gap does not narrow over time. Between 2003 and 2009, the use of industrial robots increased among manufacturers producing small or medium sized batches, but the diffusion stagnated after 2009, indicating that the promise of flexibility given by Industrie 4.0 is still not fulfilled. The development of industrial robots that are easier to program and more flexible to integrate into not (fully) automated systems has been successful to some extent (Kinkel and Weißfloch, 2009). Nevertheless, the use of industrial robots by companies producing single units remains fairly constant at around 20 percent.

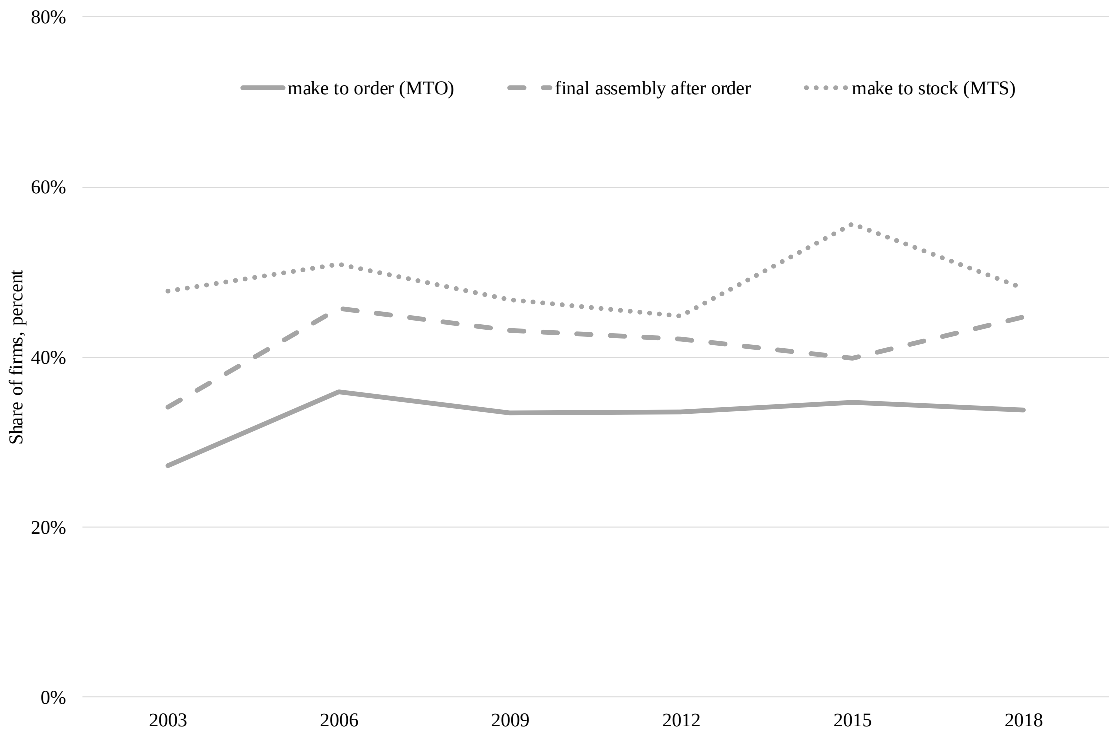
Figure 15: Share of Robot Users among Austrian, German, and Swiss Manufacturers of Selected Core Sub-sectors, Differentiated by Batch Size, 2003-2018



Source: *European Manufacturing Survey* AT, CH, DE - 2003-2018, compiled by Fraunhofer ISI.

A similar trend can be observed among firms that produce in varying degrees of customization (Figure 16). A larger share of companies that produce to stock still use industrial robots in their production, as opposed to companies that start production only after receiving the customers' order. However, it appears that manufacturers that only perform final production steps after receiving customer orders and use pre-fabricated parts from stock have been able to benefit more from robots in the last 15 years. The distribution among those producers increased disproportionately by 10 percentage points.

Figure 16: Share of Robot Users among Austrian, German, and Swiss Manufacturers of Selected Core Sub-sectors, Differentiated by Degree of Customization, 2003-2018



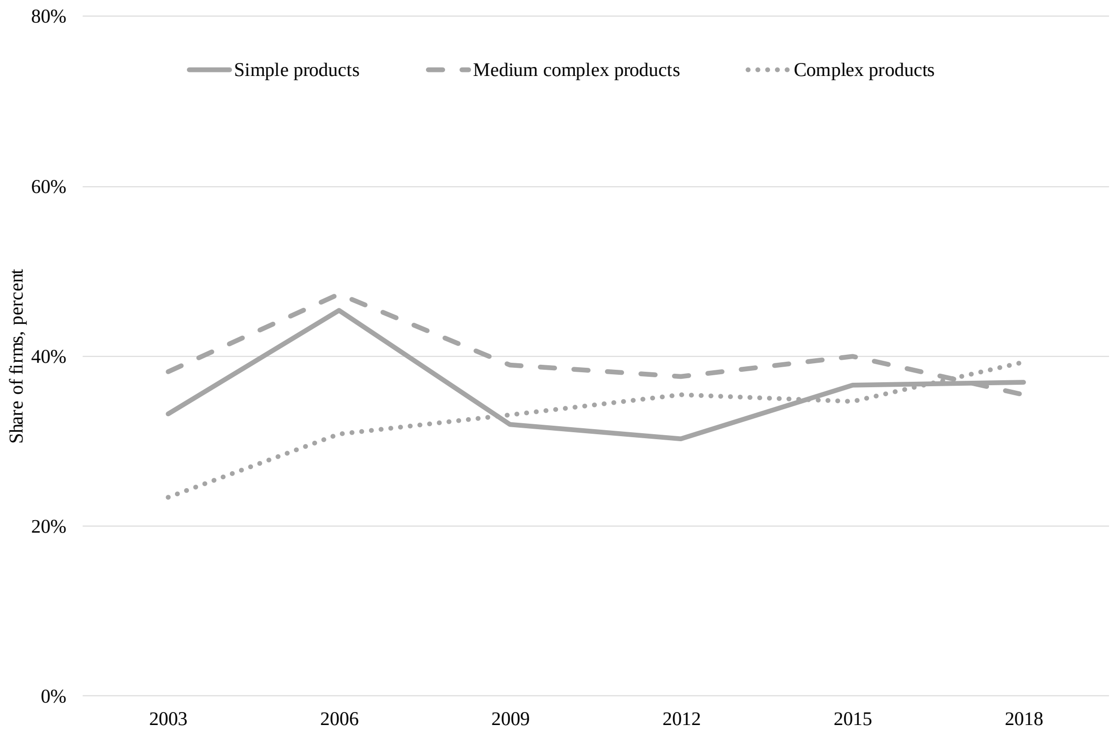
Source: *European Manufacturing Survey* AT, CH, DE - 2003-2018, compiled by Fraunhofer ISI.

In contrast, the convergence in the use of industrial robots between manufacturers of products of varying degrees of complexity, as shown in Figure 17, indicates a clear technological shift during the last 15 years. At the beginning of the century, industrial robots were mainly used by producers of simple products, but not by producers of complex products. Today, the differences between manufacturers of products with different degrees of complexity have disappeared. In 2003, the share of robot users among producers of complex products was much lower. Since then, robots have been used quite consistently by companies producing simple products, complex products, or products of medium complexity. All in all, the potential of automation today is less determined by the complexity of the manufactured or assembled product.

These results show that industrial robots became more flexible and functional during the last 15 years. Today, robots are used both by manufacturers of complex products as well as by producers of simple products and are equally suitable for customer-specific assembly processes based on prefabricated pieces as well as for make-to-stock production. These seemingly minor changes should not be underestimated, as they were only possible due to significant technical developments in the manufacturing of industrial robots on the one hand and in pricing and thus dimensioning of industrial robots on the other.

However, robots are still far from being a general-purpose technology. In light of the results of this section, industrial robots still look like a tool for automated mass production in the paradigm of the Third Industrial Revolution, rather than a tool of Industrie 4.0 with its promise to combine customization with the cost advantages of mass production (Lichtblau et al., 2015). The vision of a new generation of universally applicable industrial robots, which act as a “third hand” of the workers and can be easily programmed for very different tasks by non-professionals, has not yet been realized (Kinkel and Weißfloch, 2009). Robots continue to be specialized in individual tasks, and their main application area is still production processes in which a large number of similar products are manufactured, benefitting from economies of scale. The applications of robots for production in smaller batches or single unit production processes is still considerably less common.

Figure 17: Share of Robot Users among Austrian, German, and Swiss Manufacturers of Selected Core Sub-sectors, Differentiated by Product Complexity, 2003-2018



Source: *European Manufacturing Survey* AT, CH, DE - 2003-2018, compiled by Fraunhofer ISI.

Moreover, in the last decade, smaller companies have not introduced robots on a larger scale, despite the consistent findings and assumptions of a positive impact on productivity even when all costs are taken into account (Horvat et al., 2019). The gap between large and small companies in the use of industrial robots has not (yet) been diminished by the high edge innovations of mobile, collaborating, autonomous robots nor by a decade of digitization of production processes. The barriers for SMEs to adopt robots remain high: investment costs, uncertainty about the potential economic effects, and a lack of skilled personnel (Kroll et al., 2016).

7. Economic effects of robots: some results from recent studies

Robots have existed for more than 50 years, but their capabilities have only grown exponentially over the last 10 years due to rapid improvements in their components. Thus, we ask whether the economic impact of robots is already visible in the economy and what effects can be observed through the use of robots. Information and communication technologies (ICT) have made important contributions to aggregate productivity growth in the last decades (Brynjolfsson and Hitt, 1996; Oliner et al., 2008; van Ark et al., 2008), and we may observe similar effects as a result of the exponential growth of robots.

The paper by Acemoglu and Restrepo (2020) has perhaps received most attention so far. They estimate the impact of industrial robots on wages and employment for local US labour markets between 1990 and 2007 using IFR data and find a robust negative effect of robot intensity on employment and wages. One additional robot per 1,000 employees reduces employment by 0.2 percentage points. Acemoglu and Restrepo point out that this effect is distinct from the impacts of foreign trade, offshoring, the decline in routine jobs, or the effects of other types of ICT. Productivity effects of robots are an implicit part of the model, since a high productivity growth from robots would compensate for the negative employment effect. However, the productivity gains from robots are too small to compensate for such an effect. Using the same methodology and data, Giuntella and Wang (2019) find a large negative effect for China as well.

Dauth et al. (2018) apply the analysis to data from Germany. In contrast to Acemoglu and Restrepo, they do not find a negative effect on employment. The authors explain this result with the tendency of German workers to accept wage cuts in order to stabilize jobs in the light of the threat from automation. In a later version of the paper (Dauth et al., 2019), they observe a substantial shift in employment away from manufacturing towards business services. Hence, productivity improvements in their core business might be outweighed by the expansion of firms to lower productivity activities such as administrative or other service activities and a higher demand for these activities.

Graetz and Michaels (2018) investigate the impact of robots on employment at the industry level for the period 1993 to 2007 for 17 countries with IFR data. They find a positive effect of the increased use of robots on productivity, wages and subsequently on GDP growth, but find no evidence of a negative effect of robots on aggregate employment. The exceptions are low-skilled workers and a weaker negative effect for middle-skilled employment.

Fu et al. (2020) offer some consistent evidence based on an industry-level and cross-country panel dataset of 74 economies between 2004 and 2016. The paper concludes that the adoption of industrial robots is related to significant gains in labour productivity and total employment in developed economies, whereas increased robot adoption decreases the share of labour and GDP in developing economies. Increased robot adoption is linked to significantly higher income inequality in both developed and developing economies, although there is no evidence of technological unemployment over the same period.

The World Bank (2019) concludes that most studies on the employment effects of robots overestimate the adverse effects, and that robots are hardly responsible for job losses during the past years. The World Bank mentions that the US and the UK have lost industrial jobs due to robots, while the growth of manufacturing in East Asia has more than compensated for this loss. Flexible skills and less specialisation in individual tasks or narrow industries are key to making robots more employment-oriented, but much of the aggregate effect of robots remains uncertain. Another recent paper (Berg et al., 2018) is more pessimistic. The authors investigate the effects of robots in a dynamic general equilibrium model and find that robots put pressure on real wages, substantially decreasing the labour share, and consequently increase overall inequality.

A main drawback of the studies mentioned above is their level of aggregation. Restrictions in the data force the authors to investigate the effects of robots at the sectoral or economy-wide level and ignore the heterogeneity in the diffusion and the effects of robots, as well as selection effects in robot use. One exception is Koch et al. (2019) who use firm-level data on robot adoption from Spain. They show that firms with robots expand employment and turnover, while non-adopters shrink and destroy employment by shifting business to adopters. Moreover, Koch et al. (2019) find ex-ante selection effects – firms that adopt robots are already larger and more productive than non-adopters. Südekum and Woessner (2019) reveal that the top 20% of firms in manufacturing benefit disproportionally from robots, while the other firms show no effect. This is in line with an earlier paper by the OECD that demonstrated that the productivity gap between frontier firms and laggards has widened, possibly due to the use of ICT (Andrews et al., 2016). It is also in line with insights from firm-level evidence from Shi et al. (2020) which show that innovation in digital production technologies (robotics included) tends to increase wages on average, and this wage-boosting effect tends to be particularly significant in the high-tech manufacturing sectors.

The considerable variability of the results suggests that the final verdict on the economic effects of robots has not been decided yet. New data sets will enlarge our understanding of these effects in the future. Moreover, there are still considerable blind spots in the literature. Micro studies on the effects of robots, for example, are largely absent in the literature. In addition, the economic policy literature on Industrie 4.0 suggests that flexibility and customization are the main effects of these technologies – a claim that has not yet been empirically investigated. A better understanding of these effects will also shed some light on the overall productivity effects of robots - one can assume that more flexibility and a higher degree of customization will eventually turn into higher productivity. It may therefore be a fruitful way to break down overall productivity into its sub-effects at the firm level. Additionally, robots are just one of several technologies known under the common heading of “Industrie 4.0”. These technologies may reveal substantial cross-fertilization when they are employed together – for example, modern logistics and seamless data exchange can multiply the productivity of robots by enabling firms to synchronize their production with suppliers and customers. Such cumulative productivity effects are not yet considered in the literature.

8. Conclusions

Over the last 20 years, robots have made an impressive career from the pages of science-fiction books to the shop floors of the world. Industrial robots have become more flexible, adaptive and powerful, and have moved into new application areas. New developments such as mobile, collaborating, and autonomous robots, as well as the convergence of robotics and artificial intelligence will provide further stimuli for their diffusion.

From 1993 to 2016, the worldwide diffusion of industrial robots increased significantly, especially after the global financial crisis of 2008/09. Despite this growth, industrial robots are unevenly distributed across countries, sectors and firms. Asian countries install more industrial robots than America, Europe and Africa combined. In 2016, China was the world’s largest market for industrial robots, followed by Korea and Japan. The manufacturing sector is by far the major application domain for robots, in particular the automotive and the electrical/electronics industries. This uneven distribution suggests that robots have not yet emerged into a general-purpose technology that can be applied in all sectors of the economy. This is also evident from data at the firm-level: the main application of robots is still the mass production of goods with a low degree of customization. Firm size is still an important determinant of robot use, and robots are only slowly diffusing among small firms.

Evidence of an uneven diffusion of robots can also be found in comparisons of the intensity of robot use across countries. Country rankings based on the share of firms using robots lead to results that differ from rankings based on the absolute number of robots per 10,000 employees in manufacturing, since robots are concentrated in large firms and in a few manufacturing sectors. This makes the number of installed robots a somewhat misleading indicator for comparisons between countries and challenges the results of some of the empirical analyses on robots, productivity, and employment.

Firm-level data on the diffusion of robots as well as other new technologies are also better suited to analyse the economic effects of robots. Results to date on the employment and productivity effects of robots are mixed; some studies find such effects, while others fail to establish a link between employment, productivity and the use of robots. This is a gap in the literature that needs further research.

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