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AI Watch
Evolution of the EU market share of robotics: Data and Methodology

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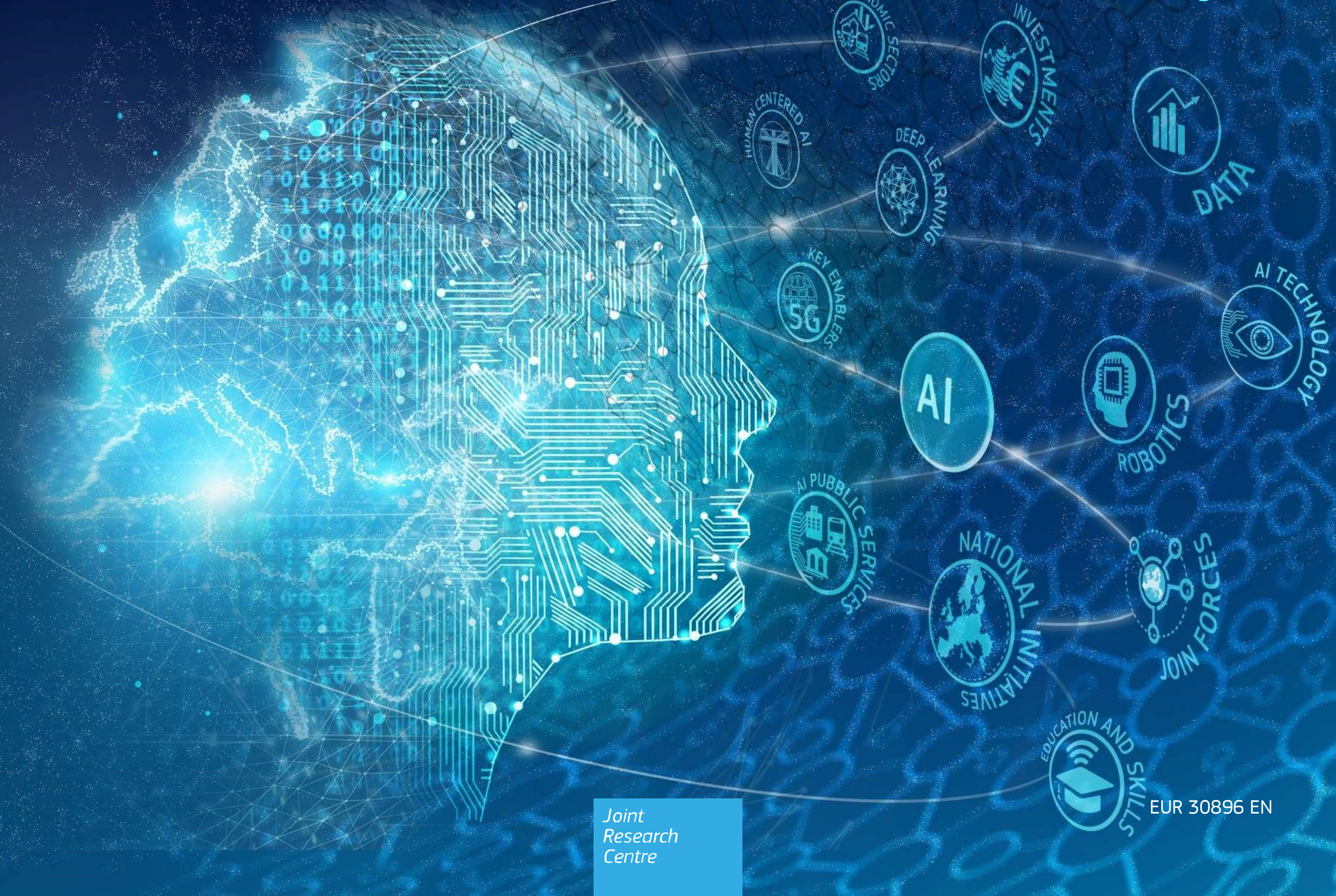

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Foreword

This report is published in the context of AI Watch, the European Commission knowledge service to monitor the development, uptake and impact of Artificial Intelligence (AI) for Europe, launched in December 2018.

AI has become an area of strategic importance with potential to be a key driver of economic development. AI also has a wide range of potential social implications. As part of its Digital Single Market Strategy, the European Commission put forward in April 2018 a European strategy on AI in its Communication "Artificial Intelligence for Europe". The aims of the European AI strategy announced in the communication are:

- To boost the EU's technological and industrial capacity and AI uptake across the economy, both by the private and public sectors
- To prepare for socio-economic changes brought about by AI
- To ensure an appropriate ethical and legal framework.

In December 2018, the European Commission and the Member States published a "Coordinated Plan on Artificial Intelligence", on the development of AI in the EU. The Coordinated Plan mentions the role of AI Watch to monitor its implementation.

Subsequently, in February 2020, the Commission unveiled its vision for a digital transformation that works for everyone. The Commission presented a White Paper proposing a framework for trustworthy AI based on excellence and trust.

Furthermore, in April 2021 the European Commission proposed a set of actions to boost excellence in AI, and rules to ensure that the technology is trustworthy. The proposed Regulation on a European Approach for Artificial Intelligence and the update of the Coordinated Plan on AI aim to guarantee the safety and fundamental rights of people and businesses, while strengthening investment and innovation across EU countries. The 2021 review of the Coordinated Plan on AI refers to AI Watch reports and confirms the role of AI Watch to support implementation and monitoring of the Coordinated Plan.

AI Watch monitors European Union's industrial, technological and research capacity in AI; AI-related policy initiatives in the Member States; uptake and technical developments of AI; and AI impact. AI Watch has a European focus within the global landscape. In the context of AI Watch, the Commission works in coordination with Member States. AI Watch results and analyses are published on the AI Watch Portal (https://ec.europa.eu/knowledge4policy/ai-watch_en).

From AI Watch in-depth analyses we will be able to understand better European Union's areas of strength and areas where investment is needed. AI Watch will provide an independent assessment of the impacts and benefits of AI on growth, jobs, education, and society.

AI Watch is developed by the Joint Research Centre (JRC) of the European Commission in collaboration with the Directorate General for Communications Networks, Content and Technology (DG CONNECT).

This report addresses the following objectives of AI Watch: with the aim to study the evolution of the European market shares in robotics over the past ten years, this report i) offers a brief overview of the robotics industry; ii) reviews the scientific and institutional literatures looking at the economic impacts of robotics; iii) describes the available statistical data sources providing information about robotics installations, sales and companies; iv) provides an initial overview of the European robotics market shares from the different data sources identified; and v) proposes a methodology to compute the European market shares in robotics, and identifies its main challenges considering the data available and the objectives of the task.

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Abstract

One of the objectives of the AI WATCH is to calculate the EU robotics market shares over the past ten years. To this end, this report, first, provides a review of the robotics industry, and looks at the official definitions of both industrial and services robots. Second, the report offers a review of the scientific and institutional literature looking at the economic impact of robotics. Third, it describes the different statistical data sources, identified through a comprehensive search, offering relevant information about the robotics industry. Fourth, it provides an initial overview of the European robotics market shares from the different data sources identified. The identification of existing robotics data sources will contribute to the construction of a methodology to assess the EU shares concerning adoption and production of robots. The main objective is to establish the basis for a suitable database that will allow tracing the evolution of EU shares in the global robotics market over the past ten years, ideally disentangling between industrial and service robots. This report sketches such methodology, while it also identifies the main data gaps and challenges to integrating the heterogeneous information from different data sources into a coherent database, in order to derive consistent estimates of the EU market share in robotics. Such methodology will have to account for data challenges (e.g., missing data, development of sound merging techniques) so that the EU trends of robotics can be assessed along the most important dimensions (i.e. demand vs supply, industrial vs service robots), and aiming to provide relevant information to the policies of the European Commission for Robotics and Artificial Intelligence.

Executive summary

One of the objectives of the AI Watch is to study the evolution of the European market shares in robotics over the past ten years. In order to achieve that goal, this report lays the foundations for the development of an appropriate methodology. The study presents a thorough revision of relevant elements of the robotics industry, and concludes that the best methodological approach would require the computation of an origin-destination-matrix of country-year-level robot trade flows providing detailed information on robot types, classifications and measurements. This would allow analysing the European market shares in robotics from both the supply and demand perspectives.

The report defines basic robot terminology by distinguishing industrial robots from service robots in line with international recognized standard (ISO) norms. The crucial difference lies in the applications the robots are designed and employed for. While industrial robots are mainly used in manufacturing industries for carrying out tasks, which are regarded dangerous, require high precision or exertion of great force, service robots are used in non-industrial environments such as offices or homes to conduct either monotonous tasks that can be routinized or tasks that involve humanized behaviour. Moreover, this report provides insight on use-cases and applications across economic sectors for which industrial and service robots are used and contrasts both types across a range of categories. A brief analysis of the main characteristics of industrial and service robot industries reveals that the market for industrial robots is consolidating, while the market for service robots is emerging and expected to grow further.

The existing literature on industrial robots is vast and mostly focuses on macroeconomic effects of robot adoption across different countries and industries. Of major interest are labour effects, effects on firm productivity, firms selecting into automation, and income distribution. Concerning labour market and income distribution effects, the reviewed literature is inconclusive. Depending on methods and setting, either job creating or displacing effects dominate. Industrial robot adopting firms tend to be larger and more productive than non-adopters. Further, robot adoption is associated with increases in firm productivity. The literature on service robots is comparably scarce, with very few sources investigating the economic impact of service robot adoption. One relevant finding indicates that the majority of empirical studies have relied on IFR data, meaning that all these papers and reports have looked at industrial robots from a highly aggregated perspective. Very few contributions have thus used other sources and in particular firm-level information.

Next, the report identifies and introduces the major sources of data on the international use of robots. Most importantly, the International Federation of Robotics (IRF) compiles data on industrial and service robots for a large number of countries, providing in-depth information on applications and industries from 1993 onwards. While the coverage of industrial robots is almost universal, pushing the quality and representativeness of these data to very high standards, this is not the case for service robots. From a different perspective, Comtrade provides robot trade data, mostly for the industrial segment. Collecting export data for service robots would require the adoption of assumptions about the proportion these robots represent in the corresponding classical categories (for instance, the proportion of robotic vacuum cleaners in total vacuum cleaners). On the other hand, Dealroom.co collects information about start-ups with a particular focus on technology-based companies; The Robot Report contains information on 6463 robotic companies worldwide. Other sources provide valuable but indirectly-related data, such as Eurostat, AngelList, Venture Source, Similarweb and Orbis. Moreover, several country-specific firm-level data sets exist.

In order to identify the most relevant data for the calculation of the EU robotic market shares, the report explores the identified data sources. Initial calculations show that, in the period 2009-2012, the EU-28 had the highest share in world industrial robot installations. From 2012 onwards the shares of the main economic areas of the world have converged, however China set itself apart by doubling its share in world industrial robots from 20% in 2012 to 40% in 2017 (IFR, 2019). The IFR data further shows that, in 2019, 55% of the sampled professional service robots were produced in Europe, but only 10% of personal/domestic service robots. Trade data shows that the EU-28 and Japan are the biggest exporters of industrial robots, while in parallel, the EU-28 is also the largest importer of these robots. An analysis of robot firms indicates that the creation of new robot companies peaked in 2015, both in the EU and worldwide. Firm-level data can be geo-coded to map the locations of these firms, and then be used to identify clusters of industrial and/or services robots, as well as clusters of ancillary businesses, research and educational hubs or agglomerations of integrators dedicated to robotics.

Finally, the report tackles the methodological challenges and goals, respectively. First, it assesses the data available for the task of calculating the EU market shares in robotics. Second, it describes the methodology proposed for calculating the origin-destination-matrix of cross-country robot trade, which can ultimately be

used for calculating EU market shares in robotics differentiating between supply and demand. Specifically, the supply of robots can be inferred from the information available on countries that produce and exports robots, whereas information on the demand of robots can be inferred from information available on countries that import, install and use robots. Despite the relatively large number of data sources, this first review and appraisal of the available datasets has revealed a wider availability of information on robot quantities (i.e. installed units) than robot values (i.e. economic value), as well as excellent coverage of industrial robots while service robots are under-represented. Moreover, the information available is often incomplete, lacking figures for some countries, sectors, types of applications, and years among others. These limitations will need to be solved through use of statistical imputation methods to reconstruct missing data wherever needed. The combination of different data sources, by year and type of robot, along with suitable imputation methods, will allow the calculation of the EU market share of robotics over the last 10 years.

1 Introduction

The idea of helping humans in heavy or repetitive work by artificial means has been observed since the beginning of humanity. Thus, tools and machines have been conceived, built and used as intermediate solutions with increasing performances over the time. The birth of the modern industrial robotics industry dates back to the early 1960s, when automotive manufacturers started to adopt machines developed to automate die casting, a complex and dangerous process. Since then, industrial robots have been transforming manufacturing processes by taking over hazardous and/or repetitive tasks previously performed by humans, and with increased efficiency. Until the 1990s, most robots –and robotics in general– were related to industrial applications, mainly aiming to streamline production at manufacturing sites.

It is difficult to specify when the first service robots appeared[1]. Machines helping or entertaining humans can be considered as its precursors. The first robots resembling humanoids were built in the beginning of the twentieth century for exhibitions and entertainment purposes. From this perspective, the history of service robots would be even older than the history of industrial robots. Joseph Engelberger[2], known as the father of robotics, predicted that service robots would one day become the largest class of robot applications, outnumbering the industrial uses by several times. Today, this is becoming a fact.

Recently, a new generation of service robots is becoming ubiquitous, with enhanced capabilities and robustness; and although still in an initial phase of development, designed with the aim to support, accompany and nurse humans. These robots typically share the human environment and exhibit basic intelligent behaviour to accomplish assigned tasks. The current trends are leading towards more complex, more personalized systems and robot services. This implies flexible systems that are able to perform tasks in an unconstrained, human-centred environment (Haidegger et al., 2013). At the same time, industrial robots are becoming more versatile and flexible, partially due to the improved cooperation with humans.

Technological advances are at the core of the evolution of the robotics industry. Robotics is a domain of technology which produces programmable machines that can perform a series of autonomous or semi-autonomous actions. Artificial Intelligence (AI) is a domain of computer science that seeks to develop computer programs that accomplish tasks normally performed by means of human intelligence. Within the AI WATCH[3], a recent report provides an operational definition of AI (Samoili et al., 2020). Therefore robotics and AI are different technology domains whose overlap produces 'artificially intelligent robots'[4] or AI-enhanced robots[5]. This report will look at AI only tangentially, when required for the description and the analysis of this report. A forthcoming AI Watch report will look at the landscape of the overlap of AI and robotics.

The main objective of this report is to provide a detailed inventory and description of the data sources available for analysing the evolution of the European robotics industry in detail. According to some sources, around a quarter of all industrial robots and half of all professional service robots in the world are produced by European companies[6]. Therefore, Europe should strive to keep its competitive advantage in robotics, in order to ensure the benefits of this technology for its economy and society. AI is of strategic importance for the European socio-economic development as it can help to address urgent challenges related to health or the environment, to take just two prominent examples. Yet, legal and ethical impacts should be carefully addressed too. It is essential to join forces in the European Union to maintain leading positions during this technological revolution, to increase competitiveness as much as to guarantee the presence of European values in the development and use of these technologies.

One of the main objectives of the AI WATCH is to analyse the evolution of the European market share in robotics. Market shares are one of the most popular indicators in order to assess a country's (or region's) competitiveness[7] on a macroeconomic level. This is so because high market shares reveal a strong

1 See section 2 on the distinction between industrial and service robots.

2 https://en.wikipedia.org/wiki/Joseph_Engelberger

3 https://ec.europa.eu/knowledge4policy/ai-watch/about_en

4 https://blog.robotiq.com/whats-the-difference-between-robotics-and-artificial-intelligence

5 See the 2021 Review of the Coordinated Plan on Artificial Intelligence (https://digital-strategy.ec.europa.eu/en/library/coordinated-plan-artificial-intelligence-2021-review).

6 https://www.eu-robotics.net/sparc/about/robotics-in-europe/index.html. See also European Parliament (2018).

7 This corresponds to the OECD definition of competitiveness: "... a measure of a country's advantage or disadvantage in selling its products in international markets." See OECD Glossary of Statistical Terms at http://stats.oecd.org/glossary/detail.asp?ID=399

performance of a country's producers in international markets. Analysing changes in market shares –i.e., the evolution of competitiveness- is easy and straightforward if the appropriate data is available. However, it has also limitations because gains or losses in market shares only describe an outcome, while the driving forces behind underlying changes in competitiveness remain uncovered. An important condition to study market shares is the availability of appropriate data. However, as it will be evident throughout the report, with the volume and type of statistical information available today, the task of analysing the robotics industry, and obtaining relevant insights to inform policy makers, becomes quite complex. Hence, there is a clear need to develop an appropriate methodology to assemble a database describing the world robotics industry, particularly distinguishing industrial and service robots, with which it can be possible to calculate the EU market share in robotics and analyse its evolution for the past 10 years.

This report is structured as follows. Section 2 provides a brief overview of the robotics industry including definitions of robotics, classifications and sectors of application, and a summary of the main differences between industrial and service robots. It also offers a brief description of the European robotics market. Section 3 includes a literature review focusing on the economic impact of industrial and service robots and automation. Section 4 presents an outlook of the most relevant data sources that could contribute to the forthcoming investigation on EU market shares in robotics. These data sources provide data on the most relevant dimensions of robotics: its production and its adoption in different countries and regions. Section 5 provides insights into the main robotics databases by means of charts with selected information from each dataset. Section 6 lists the main challenges of each data source and of combining them together to calculate and track EU market shares. Section 7 delineates the main methodological goals to fulfil the objective to compute the EU market shares in robotics. Finally, section 8 draws the main conclusions.

2 The robotics industry

This section provides an overview of the robotics industry, its main segments and activities. The objective is to identify the main characteristics of the industry, its main trends and market structure, with a focus on the identification of the differences -in terms of technologies, applications and market structures- between industrial and service robots.

2.1 Definitions and types of robots

The International Federation of Robotics (IFR) is the main institution providing official definitions of both industrial and service robots. The IFR defines robotics according to an internationally recognised standard (ISO 8373:2012) that specifies the definitions for robots and robotic devices operating in both industrial and non-industrial environments. These definitions refer to both industrial and service robotics as they take into account the intended application of a robot. Accordingly[8]:

- A **robot** is an actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks. A robot includes the control system[9] and its interface.
- An **industrial robot** is an automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications[10]. The first column of Table 1 shows the main application areas of industrial robotics as considered by the IFR.
- A **service robot** is a robot that performs useful tasks for humans or equipment excluding industrial automation applications[11]. Service robots are further subdivided into professional and domestic robots.
    - A ***personal service robot*** (i.e. a service robot for personal use) is a service robot used for a non-commercial task, usually by lay persons. Examples are domestic servant robot, automated wheelchair, and personal mobility assist robot. The second column of Table 1 shows the application areas of personal service robots as considered by the IFR.
    - A ***professional service robot*** (i.e. a service robot for professional use) is a service robot used for commercial tasks, usually operated by a properly trained operator. Examples include cleaning robots for public spaces, delivery robots in offices or hospitals, fire-fighting robots, rehabilitation robots and surgery robots in hospitals. In this context, an operator is a person designated to start, monitor and stop the intended operation of a robot or robot system. The third column of Table 1 shows the main application areas of professional service robots as considered by the IFR.

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8 These definitions can be found in the following link: https://www.iso.org/obp/ui/#iso:std:iso:8373:ed-2:v1:en

9 The control system is the set of logic control and power functions which allows monitoring and control of the mechanical structure of the robot and communication with the environment (equipment and users).

10 The IFR 2020 industrial robots report offers the following clarifications of the terms from this definition (see page 23):
- **Reprogrammable**: designed so that the programmed motions or auxiliary functions can be changed without physical alteration;
- **Multipurpose**: capable of being adapted to a different application with physical alteration;
- **Physical alteration**: alteration of the mechanical system (the mechanical system does not include storage media, ROMs, etc.);
- **Axis**: direction used to specify the robot motion in a linear or rotary mode;
- **Fixed in place or mobile**: The robot can be mounted at some other stationary point but it can also be mounted to a non-stationary point, e.g. railways. Note: In the past few years, the combination of robot arms (articulated robots) and Autonomous Mobile Robots (AMR) became popular. This is a system of two robots. In compliance with the definition above, the articulated robot is counted in this statistic, while the AMR is counted in the service robot statistic (see World Robotics Service Robots).

11 Industrial automation applications include, but are not limited to, manufacturing, inspection, packaging, and assembly.

Table 1: Application areas of robots

INDUSTRIAL ROBOTS	PERSONAL SERVICE ROBOTS	PROFESSIONAL SERVICE ROBOTS
Handling operations/machine tending: - Handling operations for metal casting - Handling operations for plastic moulding - Handling operations for stamping/forging/ bending - Handling operations at machine tools - Machine tending for other processes - Handling operations for measurement, inspection, testing - Handling operations for palletizing - Handling operations for packaging, picking and placing - Material Handling not elsewhere classified.	***Robots for domestic tasks***: - Robot companions / assistants / humanoids (mobile manipulation) - Vacuuming, floor cleaning - Lawn mowing - Pool cleaning - Window cleaning - Home security & surveillance	***Field robotics:*** - Agriculture (broad acre, greenhouse, fruit-growing, vineyard) - Milking robots - Robots for livestock farming - Other robots in agriculture - Mining robots - Space robots
Welding and soldering (all materials): - Arc welding - Spot welding - Laser welding - Soldering	***Entertainment robots***: - Toy/hobby robots - Multimedia, social - Education and research	***Professional cleaning:*** - Floor cleaning - Window and wall cleaning (including wall climbing robots) - Tank, tube and pipe cleaning - Hull cleaning (aircraft, vehicles, etc.)
Dispensing: - Painting and enamelling - Application of adhesive, sealing material or similar material - Other dispensing/spraying	***Elderly and handicap assistance***: - Robotized wheelchairs - Personal aids and assistive devices - Other assistance functions	***Inspection and maintenance systems:*** - Facilities, plants - Tank, tubes, pipes and sewers
Processing: - Laser cutting - Water jet cutting - Mechanical cutting/grinding/ deburring/ milling/polishing		***Construction and demolition:*** - Nuclear demolition & dismantling - Building construction - Robots for heavy/civil construction
Assembling and disassembling: - Assembling - Disassembling		***Logistic systems:*** - Autonomous guided vehicles (AGV) in manufacturing environments - AGVs in non-manufacturing environments (indoor) - Cargo handling, outdoor logistics - Personal transportation
Others: - Cleanroom for Flat Panel Display - Cleanroom for semiconductors - Cleanroom for others		***Medical robotics:*** - Diagnostic systems - Robot assisted surgery or therapy - Rehabilitation systems
		Rescue und security applications: - Fire and disaster fighting robots - Surveillance/security robots (no UAV)
		Defence applications: - Demining robots - Unmanned aerial vehicles - Unmanned ground based vehicles (e.g. bomb fighting) - Autonomous ships - Unmanned underwater vehicles
		Autonomous ships and underwater vehicles (civil/general use)
		Powered Human Exoskeletons
		Unmanned Aerial Vehicles (general use)
		Mobile Platforms (general use)
		Public relation robots and joy rides: - Hotel, restaurant and bartender robots - Mobile guidance, information robots, telepresence robots - Robots in marketing - Robot joy rides - Others (i.e. library robots)

Source: IFR, 2020.

In addition to robots, the corresponding ISO standard also defines the following categories:

- A ***robotic device*** is an actuated mechanism fulfilling the characteristics of an industrial robot or a service robot, but lacking either the number of programmable axes or the degree of autonomy. Examples of robotic devices are power-assist devices; tele-operated devices; and two-axis industrial manipulators.
- A ***robot system*** is a system comprising robot(s), end-effector(s)[12] and any machinery, equipment, devices, or sensors supporting the robot performing its task.
- A ***robot cell*** refers to one or more robot systems, including associated machinery and equipment and the associated safeguarded space and protective measures.
- A ***robot line*** is composed of more than one robot cell performing the same or different functions and associated equipment, in single or coupled safeguarded spaces.

Robots can vary in design, functionality and degree of autonomy. For instance, one alternative typology[13] distinguishes the five types of robots described below.

Pre-programmed Robots

Pre-programmed robots operate in a controlled environment where they do simple, monotonous tasks. An example of a pre-programmed robot would be a mechanical arm on an automotive assembly line. The arm serves one function — to weld a door on or to insert a certain part into the engine, for instance — and its job is to perform that task faster, more efficiently and for longer than a human.

Humanoid Robots

Humanoid robots are robots that look like and/or mimic human behaviour. These robots usually perform human-like activities (like running, jumping and carrying objects), and are sometimes designed to look like humans, even having human faces and expressions.

Autonomous robots

Autonomous robots operate independently of human operators. These robots are usually designed to carry out tasks in open environments that do not require human supervision. They use sensors to perceive the world around them, and then employ decision-making structures (usually computer-based artificial intelligence solutions) to take the optimal next step based on their data and mission. An example of an autonomous robot would be the Roomba vacuum cleaner, which uses sensors to roam freely throughout a house.

Tele-operated Robots

Tele-operated robots are semi-autonomous robots that use a wireless network to enable human control from a safe –short or long- distance. These robots often work in extreme geographical conditions, weather, or circumstances. Examples of tele-operated robots are the human-controlled submarines used to fix underwater pipe leaks or drones used to detect landmines on a battlefield. In tele-medicine, for instance, tele-robotic systems are classified into short- and long-distance, depending on the distance from which they are operated (Avgousti et al., 2016).

Augmenting Robots

Augmenting robots either enhance current human capabilities or replace the capabilities a human may have lost. Some current examples of augmenting robots are robotic prosthetic limbs or exoskeletons used to lift hefty weights.

2.2 Sectors where robots are applied

Robots were once considered capable of handling only the simplest repetitive tasks. In recent years, improvements in sensors, motion control, and machine learning have made robots and cognitive systems

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12 An end-effector is a device or tool that is connected to the end of a robot arm where the hand would be. The end effector is the part of the robot that interacts with the environment.

13 https://builtin.com/robotics

more flexible. They are already helping human users in many activities such as manufacturing, precision agriculture, and disaster recovery. In addition to hardware and software improvements, automation is benefiting from the ability to collect, analyse, and share big data through cloud computing and the Internet of Things. Below are some of the sectors that are using robots most intensively.

Manufacturing

The manufacturing industry is probably the oldest and most consolidated user of robots. These robots and co-bots (i.e. robots that work alongside humans) work to efficiently test and assemble products, such as cars and industrial equipment. Industrial robotics is being used in many aspects of manufacturing to help increase productivity and efficiency and reduce production costs. Many robots in manufacturing collaborate with workers to perform repetitive, monotonous or intricate tasks under the guidance and control of the worker. With these machines, accuracy is valued more than speed, as is the ability to be reprogrammed for specific tasks of varying complexity. Robotic manufacturing technology is also becoming safer to operate, namely through the use of cameras, sensors and automatic shutdown capabilities which allow robots to detect and keep away from humans in the workplace.

Agriculture

To help increase productivity while reducing overall costs, the agricultural industry has actively worked to adopt different forms of robotic technology. Farmers have been using automated tractors and combines, that are guided by GPS, for precision agriculture. Recently, there has been an increase in the experimental use of autonomous systems that automate operations such as pruning, thinning, mowing, spraying and weeding. Sensor technology is also being used to manage pests and diseases affecting crops.

Public safety

In the military and public safety sectors, robotic technology is being applied in many areas. One of the most visible is that of unmanned drones. These machines can be used for surveillance and support operations on the battlefield. Military drones flying over war and conflict zones, in hostage situations and for natural and man-made disasters are capable of assessing danger levels and providing soldiers and first responders with real-time information.

Logistics

Shipping, handling and quality control robots are becoming a must-have for most retailers and logistics companies. Because consumers now expect packages arriving at blazing speeds, logistics companies employ robots in warehouses, and even on the road, to help maximize time efficiency. Currently, robots can take items off the shelves, transport them across the warehouse floor and package them. Additionally, a rise in last-mile robots (robots that will autonomously deliver packages to the buyer's door) will ensure more frequent human-robot interactions in the near future in this sector.

Home

Today robots can be seen all over the homes, helping with chores, reminding us of our schedules and even entertaining kids. The most well-known, and with highest volume of sales, example of home robots is the autonomous vacuum cleaner Roomba. Additionally, robots have now evolved to do everything from autonomously mowing grass to cleaning pools. Smart, automated robots are expected to be able to take over more complex tasks like cooking in the near future.

Transport

Self-driving cars are no longer just imagination but a reality through a combination of data science and robotics. Several car manufacturers (Tesla, Ford, Waymo, Volkswagen and BMW, among others) are all working on the next wave of travel that will completely change the sector. In addition, rideshare companies like Uber and Lyft are also developing autonomous rideshare vehicles that do not require humans to operate them.

Healthcare

Robots have made enormous advances in the healthcare industry. These mechanical solutions have uses in just about every aspect of healthcare, from robot-assisted surgeries to robots that help humans recover from injury in physical therapy. Examples of robots at work in healthcare are exoskeletons, which can help people regain the ability to walk, and robots designed to autonomously move throughout a hospital and deliver everything from medicines to clean linen. Advances in robotics have the potential to change a wide variety of healthcare practices, including surgery, rehabilitation, therapy, patient companionship, and activities of daily living. In addition, besides the fact that robots have been used by pharmaceutical companies in labs, recently they have also employed robots to help speed up the fight against COVID-19. These robots are now being used to fill and seal COVID-19 testing swabs, and are also being used by some manufacturers to produce personal protective equipment (PPE) and respirators.

2.3 Industrial vs service robots

Both industrial and service robots are manufactured according to the same ISO standards, those published by the different robotic industries associations and other regulatory bodies. Both robot types must adhere to a set of safety standards aimed at preventing or minimizing injuries to humans in their area of operation. Both service and industrial robots may sometimes use the same design principles with regard to operation, construction and sensing abilities. For instance, it is not rare to see both industrial and service robots using bionics –i.e. mimicking living organisms- in the way they operate or in their design.

However, there are important differences between industrial and service robots. While industrial robots are highly used in manufacturing industries and factories for carrying out dangerous tasks, service robots are mostly used in offices and homes for carrying out human tasks. Table 2 provides a detailed comparison of the two main classes of robots.

Table 2: Differences between industrial and service robotics

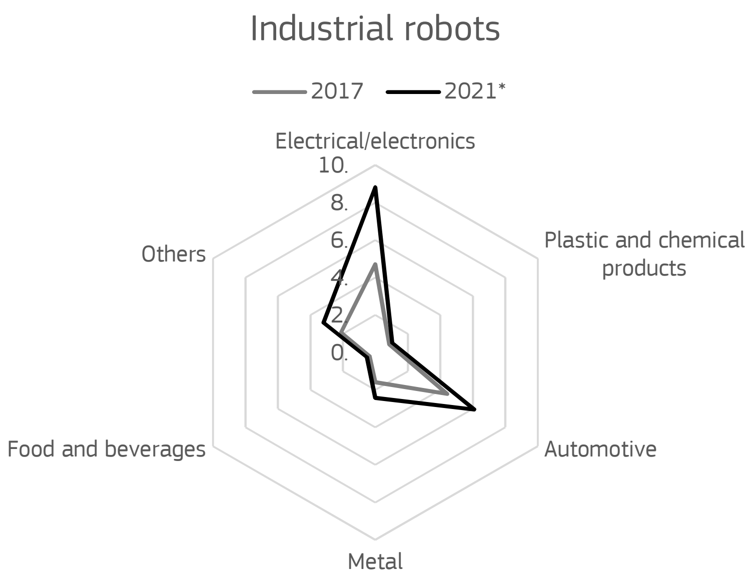
Characteristic	Industrial	Service
Application area	Production	All the rest
Customers	Mostly manufacturing	Manufacturers, hospitals, individuals, and more
Market	Mature	Emerging
Market orientation	B2B	B2B/B2C
Market potential	Low-moderate	High
Margins	Low	Potentially high
Differentiation	Low	High
Installation	Straightforward	Complex
Design	Simple	Multifaceted
Peripherals/complements	Proprietary	Open source
Technology	Specific	Off the shelf
Value chain	Vertically integrated	Ecosystem
Purchase decisions	Based on ROI	Value proposition/Integration
Workspace	Isolated	Alongside humans
Use of Artificial Intelligence	Mostly not	Mostly yes
Execution	Automatic	Semi-automatic
Accuracy	High	Low
Cost/price	High	Low

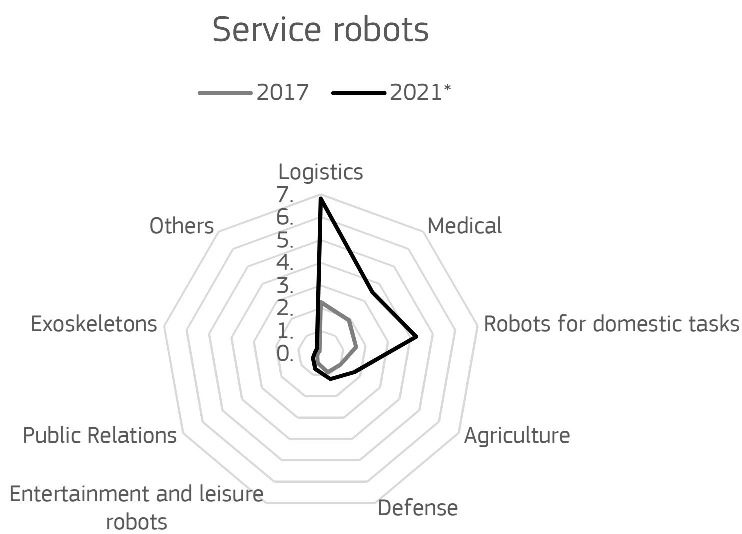
Source: Own compilation from several sources.

The best source of data about the robotics industry is the yearly report on World Robotics produced by the IFR. Since 2010, IFR has split their report into two sections, one for industrial robotics and one for service robotics. It is very clear from the two reports that the type of data available to analyse the different segments varies. Because the industrial robotics industry has consolidated over the years, the data is much more precise than the fragmented service robotics area. Similarly, the data coverage is much broader, enabling a detailed description of the segment. On the other hand, service robotics has different technical and market characteristics. First, it is mostly an emerging activity where only a few players have consolidated strong positions in niche activities, and where entry and exit rates (i.e. instability) are high. Similarly, service robotics solutions require integration of third party technologies, generating an ecosystem-type of organisational solution. This makes it particularly hard to identify all the players involved in the value chain. In addition, different units are used in the quantification of robot stocks and flows. Quantities of robots are either given in market values, and are therefore based on robot price or revenue data or, alternatively, are given as the number of units shipped or installed or as units in weight as metric tons. As a final remark, for both industries, the data available is mostly about the robots themselves and not about the peripherals or integrations around them, which is an important piece of missing information. Thus, with the volume and type of statistical information available today, the task of analysing the robotics industry, and obtaining relevant insights to inform policy makers, becomes quite complex.

Robotics has the potential to influence many areas of private and professional development of individuals by linking the digital and physical worlds, thanks to autonomous devices and digital learning capabilities. Robots are not used only to execute repeatedly the same tasks countless times, but also to perform different tasks in an ever changing environment (Siciliano and Khatib, 2016). Figure 1 shows the main markets in which industrial and service robots are expanding worldwide. Advanced economies like the EU see in automation technologies the chance to reverse the decline in productivity growth that started with the global financial crisis (Agrawal et al., 2018).

Figure 1: Sales value of worldwide robotics market, 2017 (real) and 2021 (forecast), by application area





Note: Values in brackets are billion U.S. dollars. Source: Statista, 2017 (https://www.statista.com/statistics/1018262/industrial-robotics-sales-value-worldwide-by-application-area/ ; https://www.statista.com/statistics/1018311/service-robotics-sales-value-worldwide-by-application-area/).

2.4 An overview of the EU robotics industry

Robotics has been a flagship economic activity for Europe for many years and it is already a key driver of competitiveness and flexibility in several sectors. Without industrial robotics, many successful European manufacturing industries would not be able to compete effectively, neither internally nor in international markets. Robotics is not exclusive of large-scale operations as it is increasingly associated with small manufacturing industries, which are vital to European manufacturing and employability. Enhancing their productivity could greatly increase the EU's overall global competitiveness while re-invigorating the EU's industrial sector.

Similarly, service robots (those that are conceived to provide support and assistance to human beings) can increase the competitiveness of non-manufacturing industries such as agriculture, transportation, healthcare, security, and public utilities, among others. In the coming years, the growth in these areas is forecasted to be even more significant. Despite the currently low installed base, service robots used in non-manufacturing activities, particularly in areas of domestic use such as cleaning and entertainment, are expected to become the largest field of global robot sales.

The current position of the aggregate European robotics industry is strong, representing around one third of the overall world market. While the weight of industrial robotics is similar to the aggregate, European manufacturers account for close to two thirds of the smaller professional (non-military) service robot market. However, the European position in the market for domestic robots is weak, despite the fact that the first ever robotic vacuum cleaner appeared in Europe back in the mid-nineties[14].

2.4.1 Industrial robots

Looking at industrial robots, according to the latest figures provided by the IFR, in 2019 the EU-27 had an operational stock of half a million robots, representing 88% and 20% of the total amount of robots in operation in Europe and the world, respectively. As shown in Figure 2, Germany is home to 44% of the operational industrial robot stock, followed by Italy (15%), France (8%), Spain (7%), and the Czech Republic (4%). Almost 80% of the 70 000 new industrial robot installations in Europe in that same year targeted the manufacturing sector. Within manufacturing, the automotive sector received half of all these robots, which amounts to one third of industrial robots installed in Europe in 2019. Other manufacturing sectors installing a relevant number of industrial robots were activities related to machinery equipment, basic metals and computer and electronic products (18% of total installations), plastics (9%), and food and beverages (6%). Turning to applications, 55% of European robot installations perform handling operations and machine tending, which involves moving things across different places with some precision. Welding and soldering, which enables joining materials by heating them up or filling them with melting metal received 22% of installations. The third category of applications in terms of relevance (5%) relates to sequential assembling and disassembling of standardised parts into a complex product like a car.

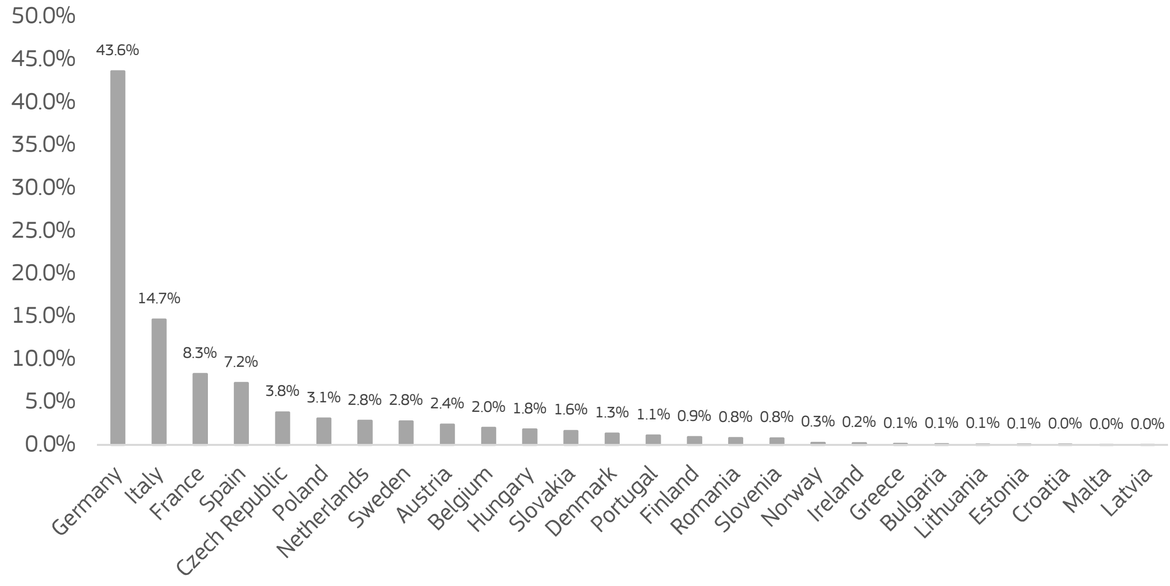
Analysing the relative share of industrial robots by application, the European economy is relatively more specialised in activities such as handling operations and machine tending (such as metal casting, plastic moulding, or handling operations at machine tools) and processing (laser cutting, water jet cutting, mechanical cutting or grinding, for instance). On the other hand, Europe seems to be relatively less specialised in applications such as welding and soldering, dispensing and assembling / disassembling (Figure 3).

2.4.2 Service robots

Due to their very nature, service robotics cover a broad field of applications, most of which having unique designs and different degrees of automation – from full tele-operation to fully autonomous operation. Hence, the service robot segment is more diverse than the industrial robot segment.

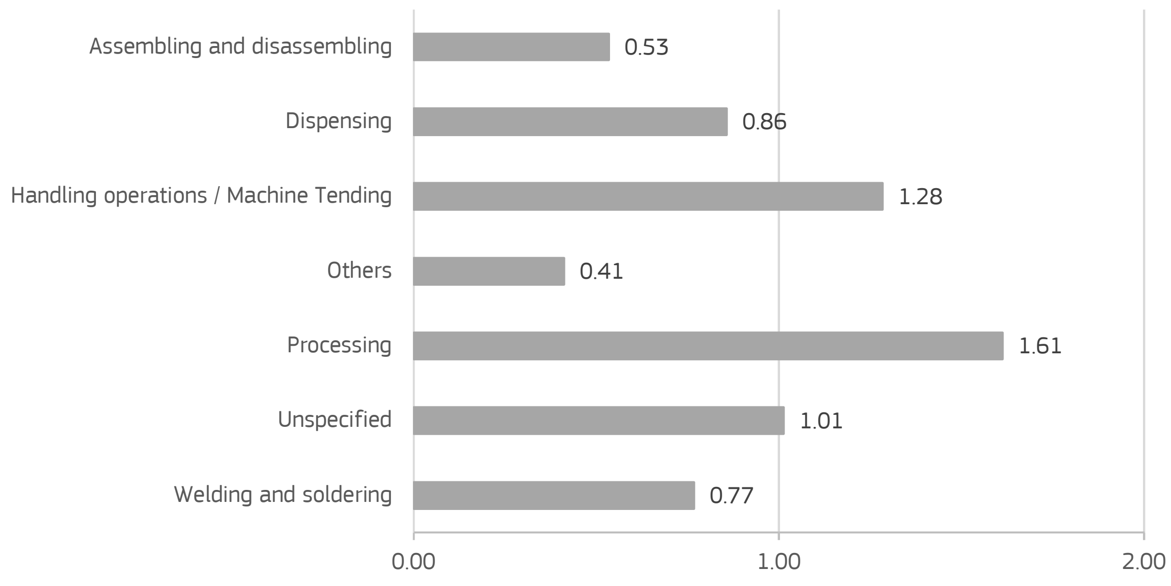
14 https://en.wikipedia.org/wiki/Robotic_vacuum_cleaner

Figure 2: Geographic distribution of the operational stock of industrial robots in EU-27, 2019



Source: IFR, 2020.

Figure 3: Relative specialisation in broad industrial robots applications in EU-27, 2019

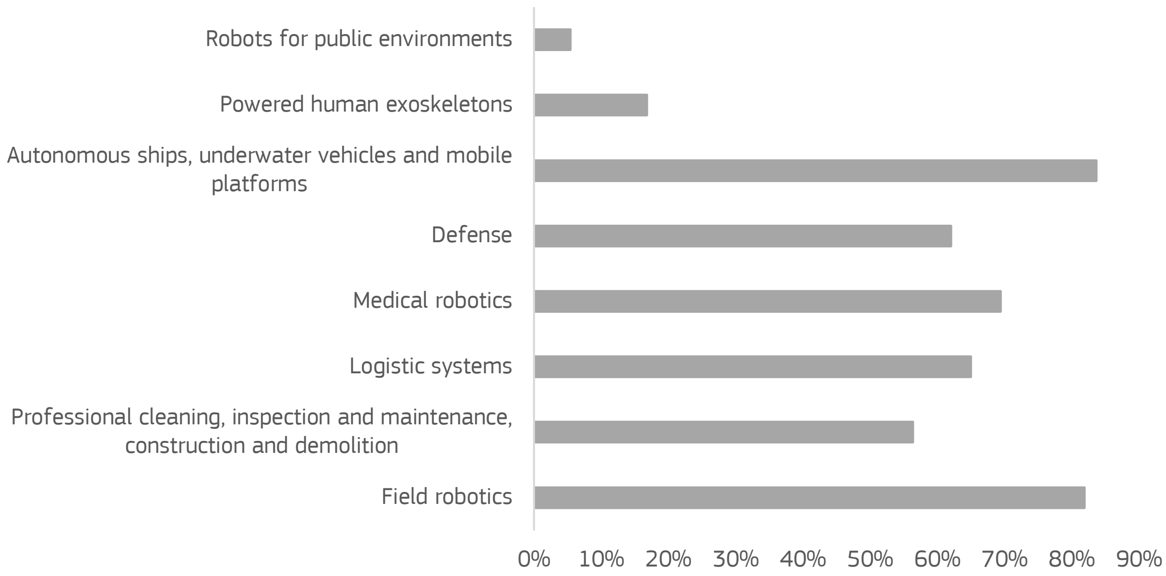


Source: IFR, 2020. Note: a value greater than 1 indicates that Europe is more specialised in the application than the world average, whereas a value below 1 indicates that Europe is less specialised.

According to the IFR, the world market for professional service robots grew strongly in 2019 by 32%, from USD 8.5 billion to USD 11.2 billion, and it is expected to continue growing at rates between 30% and 40% per annum in the coming years. In 2019, Europe represented 55% of the professional robots world market in terms of units sold. Looking at particular applications, the European position is very strong in Autonomous ships, underwater vehicles and mobile platforms, where its share of the world market is close to 85%, and in field robotics, where it is also higher than 80%. Figure 4 shows that the European share in the world's professional robot applications markets is quite substantial, above 50% in all cases Except Robots for public environments and Powered human exoskeletons.

In 2019, logistic systems represented 50% of European professional robots sales, while professional cleaning, inspection and maintenance, construction and demolition, accounted for an additional 17%. Defence (12%) and field robotics (9%) are other professional robot applications with relevant shares of sales. As can be seen in Figure 5, these four application areas represented 89% of professional robot sales in the EU in 2019, while these same segments represented 77% of world sales. As the figure shows, an important difference is that the world market for powered human exoskeletons and robots for public environments show relevant shares, while in Europe these are marginal activities. The productive structure shown in Figure 5 indicates that the European professional robot market is heavily concentrated, and more specialised than the world market.

Figure 4: European share of the world's professional robots sales in 2019, by application.



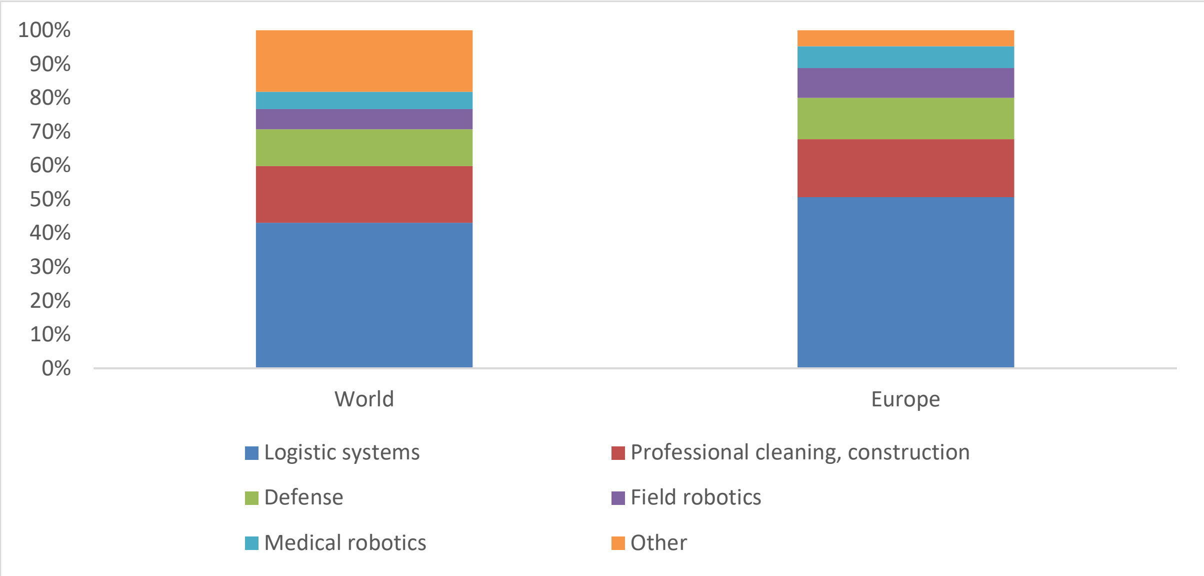
Source: IFR 2020.

Industrial and professional robots are machines used in the production or delivery of final goods and/or services. They have applications in subsequent economic activities, and are mostly demanded by companies in adjacent economic sectors. On the other hand, domestic robots are designed and produced to satisfy individuals' tastes and needs, and are thus mostly sold to end consumers. This is reflected in the sales figures: in 2019, in Europe, some 70 000 industrial robots were installed and around 95 000 professional robots were put in operation, while 2.3 million domestic robots were bought by households and individuals.

The European shares of robots for domestic tasks, Entertainment robots, and Elderly and handicap assistance robots in 2019 were 7%, 23% and 5% respectively, making an aggregate European share of the world domestic robots market of 10%. Looking at the structure of European sales, 53% correspond to robots for domestic tasks while 47% refer to entertainment robots. Out of more than 2 million units, only 643 robots for elderly and handicap assistance were sold in Europe in 2019.

Turning now to the demand side, according to Eurostat, in the EU-27 in 2020 about 5% of firms employ industrial robots and only 2% use service robots. However, notable differences between MS exist: for instance, 9% of Danish and 8% of Belgian firms have adopted industrial robots, while only 1% of companies in Ireland and 2% of companies in Greece and Cyprus use industrial robots. In addition, whereas 5% of Danish companies have adopted service robots, in up to eight MS (Slovenia, Sweden, Hungary, Estonia, Latvia, Romania, Greece and Cyprus) only 1% of firms use service robots. Even if many factors may explain these patterns, there is a positive correlation between the use of robots (either industrial or service) and the MS's labour costs: the higher the hourly labour cost (compensation of employees plus taxes minus subsidies), the higher the proportion of firms that declare to use industrial and service robots.

Figure 5: Structure of the World and European professional robotics market, 2019



Source: IFR, 2020. Other include: Autonomous ships, underwater vehicles and mobile platforms (civil/general use), Powered human exoskeletons, Robots for public environments and other professional service robots

By size, larger companies are more likely to use service robots in every country of the EU. Indeed, 28% of large European firms adopted either industrial or service robots in 2020, contrasting with the figures for medium (13%) and small sized companies (5%). This is a natural consequence of the fact that medium and large enterprises are keener to adopt new technology, since they have easier access to capital for the necessary investment and they can acquire the necessary skills more easily.

3 The economic impact of robots: a literature review

This section provides an overview of the main issues and topics around the economic impact of robotics, discussed mostly in the economics literature and across official institutional documents. The information collected and presented here provides a stocktaking of existing material and a "state of play" perspective on the topic. The first sub-section discusses the main issues related to industrial robots, while the second looks at service robots. The third sub-section reviews the most relevant institutional reports. The main objective of this section is to identify the main data sources used in the (empirical) literature and/or referred to in the rest of the materials surveyed.

3.1 Industrial robots

The existing economics literature on industrial robots is mostly focused on the macroeconomic effects of robot adoption and of automation[15] across different industries and countries. From a macroeconomic perspective the effects of the adoption of industrial robots and automation relate to productivity growth leading to higher GDP, wealth, income distribution and also to the generation of additional tax revenues (Hawksworth et al., 2018). With respect to the impact on employment, theory and evidence is quite mixed as there may be negative effects if machines mostly substitute human labour, while positive effects may prevail if machines complement human workers and increase overall productivity. The latter effect can further increase labour productivity and reduce output prices, which can cause within- and between-sector increases in demand. Increased productivity also yields wage effects which can lead to a reallocation of workers across sectors (Martens and Tolan, 2018). Also economic modelling shows how different assumptions about labour lead to substantially different outcomes (Caselli and Manning, 2019). For example, if labour is the only fixed factor and the relative price of investment goods declines with respect to consumer goods, the average wage should rise. This average wage increase would come from wage increases for some types of labour and wage decreases for other types, creating more inequality. If the supply of labour to different occupations is perfectly elastic, then all types of workers will gain. The threats to wages from new technology may come more from impacts on the competitiveness of markets. Recent JRC reports bring evidence about industrial robots within the European manufacturing sector, showing that robots are actually not reducing the share of workers (not even low-skilled ones) across Europe. On the contrary, they are even associated with an increase in aggregate employment (Anton et al., 2020; Fernández-Macias et al., 2021; Klenert et al., 2020).

From a theoretical perspective, the economics literature foresees that automation technologies, mostly industrial robots, may increase the productivity of capital and labour in some tasks, while radically redefining the content of the remaining tasks. More specifically, automation displaces labour to the degree that it takes over tasks previously performed by workers. However, automation also reinstates labour into a broader range of tasks (Acemoglu and Restrepo, 2019). In so doing, robots are expected to affect particularly low-/middle-skilled jobs even though they stimulate the creation of new tasks (Acemoglu and Restrepo, 2018a) and of new high-paying jobs for skilled workers (Autor, 2015). Acemouglou and Restrepo (2020) quantified for the US that one more robot per thousand workers reduces the employment-to-population ratio by 0.2 percentage points and wages by 0.42%. A recent study on the universe of Dutch firms documents the effects of automation from 2000 to 2016: firms that automate experience higher employment growth and revenue growth than firms that do not automate, while wages continue to rise. Furthermore, these effects arise both among manufacturing and non-manufacturing firms (Bessen et al., 2020). For France, novel evidence about firm-level adoption of robots between 2010 and 2015 shows instead that adoption of robots coincides with declines in labour shares, increases in value added and productivity, and declines in the share of production workers. In contrast to the market-level effects, however, overall employment increases faster in firms adopting robots (Acemoglu et al., 2020).

The adoption of industrial robots pushes the growth of labour productivity at the same time as 'raising total factor productivity and lowering output prices' (Graetz and Michaels, 2018). Another recent study (Autor et al., 2020) presents the "superstar firm" hypothesis for the fall in the labour share of value-added by assuming

[15] Automation describes a wide range of technologies that reduce human intervention in production processes. Human intervention is reduced by predetermining decision criteria, sub-process relationships, and related actions — and embodying those predeterminations in machines. Industrial robotics is a sub-branch in industrial automation that aids in various manufacturing processes. See https://en.wikipedia.org/wiki/Automation#Industrial_robotics

that markets have changed allowing firms with superior quality, lower costs, or greater innovation to reap now much higher rewards than before. Consequently, superstar firms attain higher mark-ups and lower shares of labour on sales and value-added. At aggregate level, the sector-wide labour share falls as superstar firms gain market share across sectors. Finally, in China the rise of industrial robots has accompanied a decline in the growth of the working-age population and an increase in wages, suggesting that the rising cost of labour is an underlying factor of robot usage. Probably, the adoption of robots will also heterogeneously affect the relative prices of factors of production, stimulating substitution effects as it is considered a labour saving technology (Berg et al., 2018).

The consideration of these factors has brought to the fore of the discussions the net effects of automation in terms of employment and wealth redistribution (Korinek and Stiglitz, 2017). Occupation-level approaches significantly overestimate the possibility of automation. When accounting for job-level tasks instead, the risk of automation drops considerably. The analysis at the occupation-level overestimates the share of automatable jobs by neglecting the substantial heterogeneity of tasks within occupations as well as the adaptability of jobs in the digital transformation (Arntz et al., 2017). While automating low-skill tasks may increase wage inequality, automating high-skills tasks actually may reduce it (Acemoglu and Restrepo, 2018b). From a gender perspective it appears that many 'female jobs' are subject to higher risks of disappearing because female workers tend to perform more routinely tasks that are more prone to automation (Brussevich et al., 2019). Yet, some recent evidence suggests that "technology is not causing jobless recoveries in developed countries" necessarily (Graetz and Michaels, 2017). Empirical evidence collected about European regions indicates that "recent technological change has created more jobs than it destroyed" and that "even more jobs would have been created had labour supply adjusted more elastically" (Gregory et al, 2016).

On a practical level, the opening of the first Amazon Go[16], a high-tech store almost completely automated with no cashiers but cameras to do the job, is an example of how specific professional categories are challenged in reality. With forecasts about job replacements that cover a wide spectrum, from very pessimistic[17] to very optimistic (Arntz et al., OECD 2016), the contemporary discussion around AI and robotics presents challenges that relate to displacement of labour but also safety and certification, privacy, taxation, justice and use of force (Calo, 2017).

Implications on skills and wage shifts brought about by robotised industries also prompt the need for suitable educational programs to train current and future cohorts of workers for the new tasks related to, and created by, automation. In this perspective, studies are investigating how to include educational robotics and robotics learning into traditional education. This would improve pupils' technological literacy and would increase the probability of technological innovations right from the school (Eguchi, 2017). Robotic learning also aims to improve innovation literacy and skills, especially for economically disadvantaged students in order to let them fill the 'achievement gap' and improve their future chances of employment (Erdogan et al., 2013). Finally, as technology reallocates low-skill workers to new tasks that are non-susceptible to computerisation, these workers will need to develop creative and social intelligence (Frey and Osborne, 2017).

In Europe, the manufacturing industries have already shown to benefit significantly from robotics, and the greatest expectations are now on the dramatic growth that robotic services (i.e. agriculture, transport, healthcare, security and utilities) are expected to experience in the near future. The transition that currently affects skills and employment also stimulates reflections about the pace at which different industries will automate (Dirican, 2015; Salomons, 2018; Salomons, 2017). The pace of this technological change varies across industries given the considerable differences in the ratios between skilled and unskilled jobs and wages (Blankenau and Cassou, 2011; DeCanio, 2016). Likewise, tasks requiring lower education levels are likely to be robotised quicker than tasks demanding higher education. If this is true, then sectors where the majority of tasks require lower education levels, -for example transportation, logistics, or administration- are relatively more at risk of disruption (Frey and Osborne, 2017).

The transition to a more automated production system is also shaped by firms' new behaviours and needs like interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity

[16] https://foreignpolicy.com/2018/07/11/learning-to-work-with-robots-automation-ai-labor/

[17] https://www.motherjones.com/politics/2017/10/you-will-lose-your-job-to-a-robot-and-sooner-than-you-think/

(Hermann et al., 2016; Mrugalska and Wyrwicka, 2017). In the automated economy[18], concepts like 'computational entrepreneurship' (Vuong, 2019) have emerged to refer to the creation and management of companies with the power of connection, computation, and data analysis tools in order to seize entrepreneurial opportunities and to exploit strategic commercial advantage. Theories about 'ubiquitous manufacturing' propose factories that "design anywhere, make anywhere, sell anywhere, and at any time" (Chen and Tsai, 2017). Horizontal and vertical integration synchronise different manufacturing/business stages and hierarchical levels in order to deliver end-to-end solutions (Liao et al., 2017). At country level, the differences in industrial structure, available skills, and propensity to invest in automation will also turn into heterogeneous effects on countries' development and automation frameworks (Acemoglu and Restrepo, 2020; Arntz et al., 2017; Brynjolfsson and McAfee, 2011; Cheng, 2019). Therefore, the type of industries or services to which each national economy is tied will probably impact on this transition to the extent that large established firms, much more than new companies, are the primary locus of domestic innovation (Lechevalier et al., 2014).

Policies should aim to maximise the type and size of automation benefits by targeting substantial welfare progresses. Some authors have argued that 'a moderate tax on robots, even a temporary tax that merely slows the adoption of disruptive technology, seems a natural component of a policy to address rising inequality' (Shiller, 2017). In this respect, policy can play a key role in moderating this transformation of the economy and the society. Effective policies could ensure that all workers gain by taxing the winners and distribute to the losers without affecting production decisions or taxing robots (Caselli and Manning, 2019). Implementing this redistribution may pose some challenges -especially if the winners and losers belong to different countries. Other studies suggest to make the income-tax system more progressive and to tax robots in order to reduce the income inequalities following from the fall in automation costs (Guerreiro et al., 2017). This solution clearly implies some efficiency losses. Given their central role in the economy, tax policies on automation can become quite critical as tax revenues currently coming from labour income vanish as firms replace employees with robots.

Fiscal systems that consider robots more neutrally vis-à-vis human workers could encompass limitations to corporate tax deductions when automating workers, different categories of 'automation taxes' to mirror unemployment schemes, tax offsets on human workers, taxes for self-employment corporate, and progressive corporate tax rates (Abbott and Bogenschneider, 2018; Zhang, 2019), among others. On the other side, tax schemes that single out robots risk to wrongly address the critical societal and employment issues while engendering unintended consequences like hindering innovations (Mazur, 2018). The final aim of policy actions can alternatively lead towards taxing robots, allowing for owning robots, or help strengthening the comparative advantages of humans (i.e. creative and social intelligence). These aims depend on a range of considerations, such as whether there is a need or desire to compensate individuals negatively (and disproportionally) affected by technological transformation; or whether concerns emerge regarding how groups in society can access the benefits of technological transformation; or due to the fact that robots cannot match human skills for a number of socioeconomic tasks (Csefalvay, Z., 2019). One basic question to frame any redistributive policy action around 'robots' employment' is whether there are cogent reasons for taxing robots any more than, for instance, agricultural tractors, harvesters, engines, vehicles, hydraulic presses, or computers, which –at their introduction- also reshaped the socio-economic dynamics within their domains.

3.2 Service robots

Compared to the large amount of literature devoted to the economic impact of industrial robots, the economic impact of service robots is an under-researched area. This may be explained by the fact that the interest in service robots is more recent, promoted by advances in complementary technologies. Robotics combined with growing forerunner technologies such as artificial intelligence, mobile connectivity, cloud computing, big data and biometrics bring opportunities for the increase of automation in other economic activities, such as agriculture and services. Service robots interact more frequently with humans, and in more mixed and unpredictable ways than industrial robots (Reshef, 2013). There is definitely a lot to learn about the impact of service robots on customers, especially concerning the acceptance and usage of service robots, their characteristics -including anthropomorphism-, and their potential for enhanced and deteriorated service

[18] An economy that relies extensively on automation technologies as a production factor rather than labour. See Ivanov (2021).

experiences. Similarly, little is known today about their net impact on service employees, considering the potential positive effects of less routinely work, enhanced productivity and job satisfaction; and the potential negative impacts related to job insecurity, loss of autonomy, and negative psychological outcomes. Another area that would benefit from more research relates to the new opportunities for human–robot collaboration/interaction and robot-related up-skilling and development requirements for the whole society (Lu et al., 2020). The call for robots to help appears an inevitable choice for organizations operating in challenging -and sometimes unhealthy- working environments. Yet the endorsement of robots should happen in such a way as to improve employment and motivation of employees (Qureshi and Syed, 2014). From home to healthcare, from traffic management to police support, it seems that society does accept the use of robots to perform dull, dangerous, and dirty jobs (Royakkers and van Est, 2015). Public opinion favours robots for jobs that require rote memorization, perceptual abilities, and service-orientation, while it tends to prefer people for occupations requiring artistry, evaluation, judgment, diplomacy, and especially prefers robots doing jobs with people rather than in place of people (Takayama et al., 2008).

At first glance, service robots appear to displace jobs less directly and over relatively longer terms than industrial robots do. In addition, they show more collaborative traits and synergies with humans because of the assistive technologies they offer. A study for the US –potentially applicable to other industrialised economies- showed that services with no close substitutes actually experienced increases in wages and employment as computerization substituted routine tasks and complemented the more creative ones by highly-educated workers (Autor and Dorn, 2013). Particularly, low-skill workers reallocated their labour supply to service occupations that are difficult to automate because 'they rely heavily on dexterity, flexible interpersonal communication, and direct physical proximity' (Autor and Dorn, 2013). In fact, service robots are also positively considered for the convenience they provide to societies and people, such as saving time, better processing administrative procedures, and potential improvements in the precision of doctors' diagnosis and gains in healthcare (Qureshi and Syed, 2014). The adoption of robots, artificial intelligence and service automation depends on factors such as labour and technology costs, customer readiness and willingness to be served by robots, cultural characteristics of both customers and service providers, and the technological characteristics of the automated solutions themselves (Ivanov and Webster, 2017). The deployment of service robots is an additional and differentiating dimension of countries' automation processes. This is so because its pace will differ from industrial economies like Germany to economies more specialised in services such as the Netherlands. Perhaps automating services (such as healthcare or scientific tasks) will take more time than for manufacturing and repetitive tasks.

Service robots can autonomously and dynamically interact, communicate and deliver service to customers either with a physical representation (e.g. Pepper) or just a virtual one (e.g. Alexa). Service occupations involve caring for others' needs like serving food, guarding security, cleaning, aiding at home, and assisting children or the elderly, among others. In any case, intelligent robots although capable of learning and build up knowledge still use human culture as main key of understanding (i.e. including stereotypes, discrimination, prejudices, etc.) and make operational decisions (Dwivedi et al., 2019). As AI-enhanced robots develop along the different types of intelligence (mechanical, analytical, intuitive, and empathetic) required by service sectors, they would take over certain tasks -rather than jobs- and unveil novel opportunities for human-robot interactions (Bock et al., 2020). This process highlights the importance of intuitive and empathetic skills for service employees, which can lead workers to shift their skills and to achieve a productive balance between humans and machines (Huang and Rust, 2018).

As explained in the previous section, service robots are divided in two broad categories, domestic and professional. Professional robots are similar to industrial robots in their applications and also as intermediate inputs in broader production or service delivery processes. In contrast, domestic robots are targeted to end consumers, and as such are designed to satisfy individuals' needs and tastes. However, they are both likely to have important implications also at meso-level (e.g. markets for particular services) and macro-level (as for the societal implications of the micro- and meso-levels) for all key social stakeholders (Wirtz et al., 2018). There is evidence that the adoption of robots, artificial intelligence and service automation enhances competitiveness, service quality, human resource management, service operations processes and standards, among others. Similarly, businesses like hotels, restaurants, event organisers, theme and amusement parks, airports, car rental companies, travel agencies and tourist information centres, museums and art galleries experience improvements in their operating costs and revenues (Ivanov and Webster, 2017; Belanche, 2020). A survey to business leaders reveals that 24% of US companies are already using AI and a 60% expect to use it by 2022[19]. In Europe, a recent survey has shown that 42% of firms with 5 employees or more are currently using at least one AI technology (European Commission, 2020). On the customers' side, the estimated number of people using digital assistants worldwide is projected to reach 1.8 billion by 2021, and 62% of current users of voice-based digital assistants (e.g. Siri, Alexa) plan to buy something through these smart devices within the next month[20].

3.3 Institutional and policy outlooks on industrial and service robotics

A number of institutions around the world have been paying attention to robotics related phenomena. The International Federation of Robotics (IFR)[21], the Robot Report[22], the EC Robotics Public-Private Partnership in Horizon 2020[23] are just examples of organisations or consortia in charge of collecting and exchanging robotics data, and of monitoring their trends. In its 2019 report, the IFR claims that, as for industrial robots around the world, new installations will reach almost 2 million units between 2020 and 2022 and annual sales will reach over 580,000 units in 2022 - with Asia still at the top of both sales and stock followed by Europe and the Americas. In the 2019 service robots report, the IFR points that the assistance of robotics wearables to humans' repetitive tasks is likely to increase productivity, while improving humans' quality of life and protecting them from strenuous repetitive movements. The IFR elaborates on the Covid pandemic and its influence on the current economic situation in its new 2020 report and a dedicated press release[24]. In this context the IFR highlights that robots will play even a bigger role in automating production in the post-Covid economy and that the operational stock of industrial robots is expected to reach about 4 million robots by 2022. The higher deployment of robots, already witnessed during the Covid pandemic, will shape the demand for skilled workers and the offer of educational systems. 'Next Generation Workforce - Upskilling for Robotics' was the topic of the IFR Executive Round Table in December 2020.

The Robot Report provides in a single source of news, product information, analysis, and research related to robot related disciplines such as engineering, technology, and business. The Robot Report focuses on the development, integration, and use of commercial robotics products and services. Furthermore, it also tracks enabling technologies like sensors, imaging systems, motors, and development tools. Additionally, they follow AI and machine learning as they are relevant to robotic cognition, actuation, mobility, navigation, and human-machine interaction. The attention of the Robot Report professionals is also on the analysis of developments in industrial and collaborative robots (co-bots), mobile platforms, drones, autonomous vehicles, and service robots across multiple markets, including manufacturing, supply chain, and healthcare. The yearly Robotics Handbook by the Robot Report reviews all the forefront innovations and occurrences in robotics, like advances in exoskeletons or co-bots around the world.

Initiatives such as the EC Robotics Public-Private Partnership aim to bridge industry with institutions and society. This partnership between the EC, the European industry and academia aims to facilitate the growth and empowerment of the robotics industry and its value chain, from research through production. From 2014 to 2020 the Public-Private Partnership received funds for €700M from the EC and three times as much from European industry, which makes of it 'the largest civilian-funded robotics innovation programme in the world'[25]. Efforts like the EC Robotics Public-Private Partnership are of utmost relevance since robots have quadrupled (from around 95000 to over 430000, IFR data) in EU industry from 1993 to 2016, and 37%-69% of tasks are currently automatable by new technologies, depending on the country (EC, 2018). The EC report on 'Employment and Social Developments in Europe Annual Review' (2018) highlights that, within manufacturing, the automotive sector is the most robotised sector in Europe. The report also reflects the impact on employment, recognising that automation of tasks does not necessarily imply a replacement of people. On the contrary it often creates new professional roles in which individuals can be revalued.

Recently, all the major international institutions and organisations have started policy discussions about social schemes to distribute the gains of automation, on how to reassign older workers to new jobs, and on the relevance of soft skills -like creativity and empathy- that make individuals different from robots (World Bank,

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19 U.S. Employers Expect Growth of Artificial Intelligence in the Workplace But Not Major Job Reductions
20 The Rise of Virtual Digital Assistants Usage – Statistics and Trends
21 https://ifr.org/
22 https://www.therobotreport.com/about-the-robot-report/
23 https://ec.europa.eu/digital-single-market/en/robotics-public-private-partnership-horizon-2020
24 https://ifr.org/ifr-press-releases/news/high-demand-for-robotics-skills-in-post-corona-recovery
25 https://www.eu-robotics.net/sparc/about/index.html

2019). A recent OECD report (Arntz et al., OECD 2016) estimates the job 'automatability' for 21 OECD countries accounting the heterogeneity of workers' tasks within occupations, and shows that, on average, 9% of jobs are automatable. Various heterogeneities exist across OECD countries so that while Korea has only 6% of automatable jobs, Austria holds a share of 12%. The report argues that differences between countries may reflect general differences in workplace organisation, previous investments into automation technologies as well as differences in the education of workers across countries. More recent evidence (OECD, 2019a) shows that occupations for middle-skills have strong and negative correlations with robots. Therefore, this reassures against the hypothesis of labour market polarisation (i.e. an increase in both high-skill and low-skill employment) for all OECD countries but the US.

The World Bank 2019 report highlights instead how technology have changed the demand for skills and firms' structure. In particular, this report shows that, since 2001, the share of occupations requiring non-routine, cognitive and socio-behavioural skills increased from 19% to 23% in emerging economies and from 33% to 41% percent in advanced economies. Labour changes its nature, and so does firms' organisational design as robotics create the possibility of business integrations that allow to create value from ideas and in places that sometimes are difficult to detect beforehand. . In any case, the major global institutions are quite unanimous about the robotics megatrends which have not led to structural unemployment as many feared, but to increases of high-skilled jobs, higher welfare and trade levels (Artuc et al., World Bank 2018). Around 25% more jobs for high-skilled tasks emerged only in OECD countries during the last decades (OECD, 2019b) along with greater productivity, employment and wages (IMF, 2018). In Europe, firm-level evidence indicates that the use of industrial robots does not directly affect –neither negatively nor positively– firms' employment (EC, 2015 and 2016). Besides, industrial robots systems appear as a key enabler for exploiting the competitiveness and growth potentials of the European manufacturing industry.

The Trade and Development Report (UNCTAD, 2017) argues that many studies focus exclusively on the technical feasibility of job displacement that lead to overestimate the potential adverse effects of automation on jobs. According to UNCTAD (2017) jobs automation and displacement is more profitable in skill-intensive and well-paying manufacturing activities (like the automotive and electronics sectors) than in labour-intensive and low-paying sectors (like apparel). From the United Nations the concern is also raised about inclusiveness of growth to the extent that robots may reduce the known benefits of industrialization as a development strategy (ITU, 2019). On the one hand, robots seem not yet suitable for many labour-intensive industries leaving the chance for developing countries to step into industrialization through traditional ways. On the other hand, developing countries would also benefit from the digital revolution and opportunities.

At the global level, key facts about leading countries in the adoption of industrial robots come from the Information Technology and Innovation Foundation (Atkinson, 2018). According to this report Korea was the world's largest adopter of industrial robots in 2017, with 710 robots per 10,000 workers, Singapore was second (658 robots per 10,000 workers), Germany was the third (322 robots), Japan was the fourth (308), Sweden was the fifth (240), the United States were the seventh (200). On the laggards' side, Russia and India were the last with 4 and 3 robots per 10,000 workers, respectively.

In Europe, several government plans appeared in support of the fourth industrial revolution going with the name of Industry 4.0 (Bartodziej, 2017). The German action plan 'High-Tech Strategy 2020', endorsed in 2012, sets billions of euros every year for the development of cutting-edge technologies (Kagermann et al., 2013). In France, in 2013 the government initiated the strategic review 'La Nouvelle France Industrielle' which identifies 34 sector-based initiatives defined as France's industrial policy priorities (Conseil National de l'Industrie, 2013). In 2008 the European Commission lunched the Public-Private Partnership[26] on 'Factories of the Future'[27] to support emerging industries like robotics until 2020. Several other national plans to support Industry 4.0 followed since 2014[28]. In March 2020, the European Commission presented a new industrial strategy[29] that would support the twin green and digital transitions, make EU industry more competitive globally, and enhance Europe's open strategic autonomy. The next day, the World Health Organisation declared the COVID-19 outbreak a pandemic. The European Commission updated its industrial strategy in May

[26] https://ec.europa.eu/digital-single-market/en/public-private-partnerships; https://ec.europa.eu/digital-single-market/en/robotics-public-private-partnership-horizon-2020.

[27] www.effra.eu.

[28] https://ec.europa.eu/growth/tools-databases/dem/monitor/tags/industry-40

[29] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1593086905382&uri=CELEX:52020DC0102

2021[30] to ensure the industrial ambition takes account of the new circumstances following the COVID-19 crisis, while ensuring European industry can lead the way in transitioning to a green, digital and resilient economy. The strategy is meant to support the development of key enabling technologies that are strategically important for Europe's industrial future, including robotics.

The European Parliament's Report on Civil Law Rules on Robotics (Delvaux, 2015) has proposed to regulate robots. Moreover, in the specific European legal context, the same institution (Delvaux, 2015; European Parliament, 2017; Nevejans, EU 2016) has stated the need to create common European standards before Member States develop separate bodies of law about robotics, which might prevent the possibility of integration and substantial exchanges among countries at European level. This situation would heavily jeopardise the position of the EU vis-à-vis global players, with the risk of keeping national robotic achievements separate from one another and to miss synergies among national robotic contributions. There are especially strong interest for European industrial policy at stake, considering that 'around a quarter of all industrial robots and half of all professional service robots in the world are produced by European companies' (European Parliament, 2018). The various reports by the European Parliament also reflect on the principles to establish a legal status for certain robots. In this way, robots with the legal status of electronic persons would be responsible for damages they may cause. This legal status would be particularly applicable to robots that make autonomous decisions or independently interact with third parties. Finally, these reports account for a number of vulnerabilities, such as the danger that some people might be moved towards ungrounded affection to expressive robots, the need to investigate what professional categories of jobs or tasks would be more exposed, as well as to care for excluded individuals, pushed to the margins by automation and the digital divide.

Finally, it is quite important that policy look at societal perceptions and public acceptance of robots. To this purpose a dedicated survey 'Special Eurobarometer 382: Public Attitudes towards Robots'[31] was administered in 2015 and 2019 to better understand public opinion about robotics. Particularly, the objective of this survey was to investigate familiarity, personal experiences and attitudes towards robots, while also examining application areas for robots. More recently, the 'Special Eurobarometer 460: Attitudes towards the impact of digitisation and automation on daily life'[32] revealed that individuals' attitudes to robots and artificial intelligence are generally positive. Respondents were especially enthusiastic about the possibility that robots can take over hard and dangerous jobs, and that they can be of help both in society and in people's private lives. Nonetheless, concerns about employment and awareness that these technologies need careful management are also present in respondents. Specific experiences are also arising across the EU countries, like the Finnish project ROSE[33] whose focus is on how to enhance societal welfare and healthcare by exploiting the potential of service robots. This project seeks to observe how to organise robotics-related services and their impact on society. The objective is to create and remodel products and services towards a renewal of the welfare system which is also ethically viable and shared across a wide group of stakeholders. Likewise, the Statement on Artificial Intelligence, Robotics and 'Autonomous' Systems (DG RTD, 2018) highlights the new ethical, societal and legal challenges of 'autonomous technologies' and on the need to find effective ways to employ these technologies to maximise the common good.

3.4 The role of robotics data on the reviewed literature

From the literature review covering the economic impact of industrial and service robotics, as well as the institutional reports, we detect that 90% of the references using robot data rely on the information provided by the IFR. A summary is presented in table A1, in the Annex. Few studies combine IFR data with information from Eurostat or firm-level databases, but in most of these papers the analyses focus on a single country and year. The next section will provide more information on the different data sources available to analyse the robotics industry.

30 https://ec.europa.eu/info/files/communication-updating-2020-new-industrial-strategy-building-stronger-single-market-europes-recovery_en

31 http://data.europa.eu/euodp/en/data/dataset/S1044_77_1_EBS382

32 https://data.europa.eu/euodp/en/data/dataset/S2160_87_1_460_ENG

33 http://roseproject.aalto.fi/en/about

4 Statistical data sources on robotics

Timely and relevant data is crucial for the successful completion of the task to analyse the evolution of the European robotics market share over the past ten years. From the analysis of the robotics industry, and from the literature review, we have identified some important sources of statistical information. From desk research, we have identified some other sources. Several institutions collect information related to the robotics industry. The main sources of statistical information are described below.

4.1 World Robotics, by the International Federation of Robotics (IFR)

Following the definition of robots (see section 2), the IFR provides a comprehensive longitudinal database of both stocks and installations of industrial robots across 50+ countries over the period 1993-2018. The IFR offers breakdowns by application and industry of robots stocks and installations. Respectively, these breakdowns account for 40+ applications and 45+ industries. From 2004 onwards, the applications were revised in agreement with robot suppliers and earlier data was transformed to the revised classification. As for industries, from 2010 the data are broken down by industrial branches in accordance with the ISIC Classification rev. 4. This is the most comprehensive and precise database on sectoral industrial robot installations, and it also contains collaborations across countries' private companies and robotic associations. It is worth noticing that applications and industries are separate classifications that do not allow references from one to the other.

The IFR also offers yearly sales information about 700+ companies that produce service robots. Service robots are classified by application areas of personal/domestic and professional robots, respectively. Data on service robots cover companies' country of origin, size, area of engagement, plus their production (i.e. units sold) of service robots both by continent of origin and type of robot. Yet, some of this information relies on estimates produced with methods that are revised every year, this poses challenges about the precision of certain values for the construction of a consistent time-series. Similarly, the group of robotics companies providing information changes every year due to the volatility of this emerging segment. This poses additional challenges to get consistent values of service robotics sales and value that can be comparable over time.

4.2 Comtrade, by the United Nations (UN)

Comtrade contains trade data of industrial robots in monetary values (i.e., values in USD) and quantities (i.e. kilograms and numbers)[34]. Specifically, trade account for exports, imports, re-exports and re-imports of robots declared by 180+ 'reporting countries' from/to 200+ 'partner countries' during the period 1996-2018. Robots are classified by the UN definition of 'Industrial robots, not elsewhere specified or included' (i.e. code '847950') which is different from the IFR definition. The heterogeneity of the definitions may constitute an issue at the moment of combining the IFR data with Comtrade information. However, Comtrade is definitely a valuable source of information to infer the average export/import prices by country in order to assess the competitiveness of the European industrial robotics industry with respect to the rest of the world.

4.3 Dealroom.co[35]

Dealroom provides start-ups' information related to their growth and tech ecosystems both in Europe and worldwide. Specifically this website provides the total funding and its sources, location, number of employees, short description and other information like social media performance for the identified start-ups and scale-ups. The number of companies included in this source and employed for this study is 3685, located all over the world.

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34 See section 2.3 for an explanation of these different units of measurement.

35 https://dealroom.co/

4.4 The Robot Report[36]

This source contains information about 6463 robotic companies worldwide and it is one of the most comprehensive database of this type. The variables of this dataset relate to companies' address, website, type and subtype. The limitation of this source is that although it has a thorough categorization, sometimes it is difficult to distinguish among robot producers and auxiliary businesses. It includes both industrial and service robots for private and commercial use.

Table 3 summarizes the characteristics of the main data sources presented above.

Table 3: Overview of the main characteristics of the data sources identified

Source	Period	Level	Type of data	Type of robots	Classification of robots	Country coverage
IFR	1993-2018	countries	installations	industrial	by application; by industry	worldwide (50+ countries)
IFR	2010-2019	companies	sales	service (domestic & professional)	by application	worldwide
Comtrade	1996-2018	countries	trade data	industrial	-	worldwide (180+ 'reporting countries'; 200+ partner countries)
Dealroom	2019	companies	company characteristics	industrial	-	worldwide (3685 companies)
Robot Report	2019	companies	company characteristics	industrial; service	-	worldwide (6463 companies)

Note: dashes (i.e. '-') indicate that the information is not applicable to a certain data source or not available.

4.5 Firm-level datasets

The sources listed so far offer relevant data but aggregated at the country level. Even if Dealroom and the Robot Report provide information about the number of robotics companies (supply of robots and robotics solutions), it is not possible to extract from these sources relevant variables about the performance of companies that have adopted robots for their production process (demand side).

From the literature review, and desk research, we have identified some firm-level datasets that provide information about the characteristics of firms (size, sector, profitability, exports, adoption of robots, among others) that would allow for a more in-depth analysis of the conditions under which some firms adopt robotics solutions, as well as the effects on firm performance from that investment decision. Unfortunately, all these databases are country-specific, and even sometimes country-sector specific. This makes it difficult to use them for the purposes of this task. The different datasets are listed below:

- Encuesta Sobre Estrategias Empresariales (ESEE), supplied by the SEPI foundation (Spain), covering the period 1990-2016 and including an unbalanced sample of 5500 firms.
- Dutch firm-level automation data set (no observation of specific automation technology), for the period 2000-2016, including 36,490 firms.

[36] https://www.therobotreport.com

- French firm-level data in manufacturing, for the period 2010-2015, including 55,390 firms
- Robot adoption firm survey conducted by Statistics Denmark, including 6-digit product code Foreign Trade Statistics Register (UHDI) for the period 1995-2016
- China Employer-Employee Survey (CEES). In 2016, 1,115 firms were surveyed, with information on 8,848 workers.
- The Canadian institute of statistics, identified 3,085 individual business numbers associated with robot purchases for the period 1996-2017.

Table A2 in the Annex summarises this information and provides the links to these different firm-level datasets, or the references citing them.

4.6 Other sources of statistical data

In addition, other sources provide interesting but indirectly related data:

I. **Eurostat:** It provides descriptive statistics on the use of robots[37] that may complement the information available from the supply side. This source covers only the European Member States, and in some cases also other countries of the European Economic Area for the years 2018 and 2020. Eurostat also provides information on the production, export, import value and quantity of industrial robots for multiple purposes (Product Code NACE Rev2: '28993935'). The main difficulty with this source is the very high presence of missing data.

II. **AngelList**[38]**:** This is one of the most comprehensive sources of start-ups. The IFR uses it as its main source for compiling their service robots database. The data have been mined for the categories of robotics, machine learning (ML) and AI in order to identify potential robotic companies using ML or AI. Some 1,300 companies could be obtained from this database along with information about their website, location (city level) and amount raised as a start-up. Eventually the information by AngelList seems to overlap significantly with the one provided by Dealroom.co.

III. **Venture Source:** Retrieving robotic companies from this source requires a text mining exercise to identify a list of robotic keywords to search in the companies' descriptions. However this source contains information similar to other sources that have been included as primary databases.

IV. **SimilarWeb:** This web-analytics database that provides information about the popularity of robotic companies in different geographic locations of the world.

V. **ORBIS:** Finally, this source provides an array of financial and employment variables that could potentially be used within broader analysis, for example on the employment of the robotics industry in different countries. An issue posed by ORBIS relates to potential difficulties in robustly matching its information with the information by other sources.

[37] http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=isoc_eb_p3d&lang=en

[38] https://angel.co/

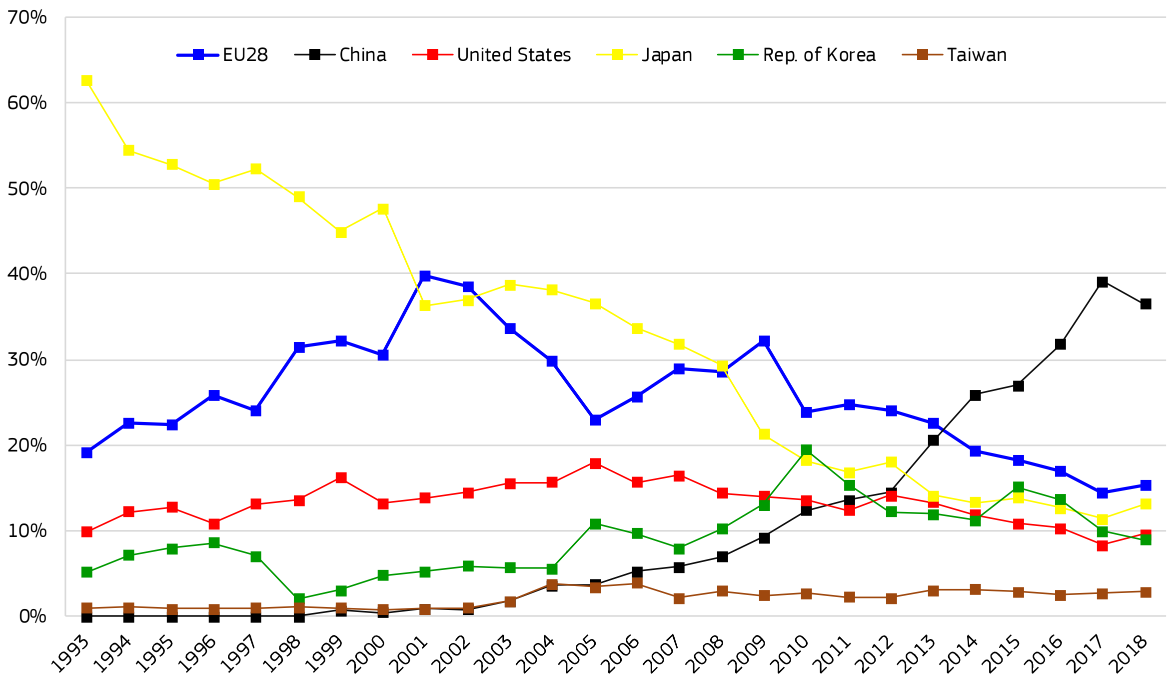
5 The EU share of robotics across different data sources

This section explores the main data sources described in the previous section, in order to identify the most relevant data for the calculation of the EU robotic market shares. Each dedicated sub-section below illustrates more in-depth the specific content of each database.

5.1 The International Federation of Robotics data

The main IFR database provides data on the new industrial robotics installations by industry, country and year. Figure 6 offers a first snapshot of the world shares of new industrial robotics installations by the EU-28 and selected countries as reported by the IFR. Specifically the figure shows the evolution of the EU28 world-shares of new robotics' installations in all industries vis-à-vis other global players such as China, United States, Japan, Republic of Korea, and Taiwan, from 1993 to 2018, (therefore pre-Brexit), according to the IFR data. In 1993 the EU28 held almost 20% of the world new installations of robotics. Around 2000, the EU-28 share of the world new installations of robotics reached up to 40%. Since 2010, right after the financial crises, the EU28 shares of world new installations of robotics started to decline until reaching the value of 15% in 2018. At the same time other players increased their shares of world new installations in robotics, this has been the case for China, the Republic of Korea and, to a lower extent, for Taiwan too. The shares of the United States kept instead rather steady between 10 and 20%, while the Japanese shares of new robotics' installations hugely dropped from 63 to 13% from 1993 to 2018.

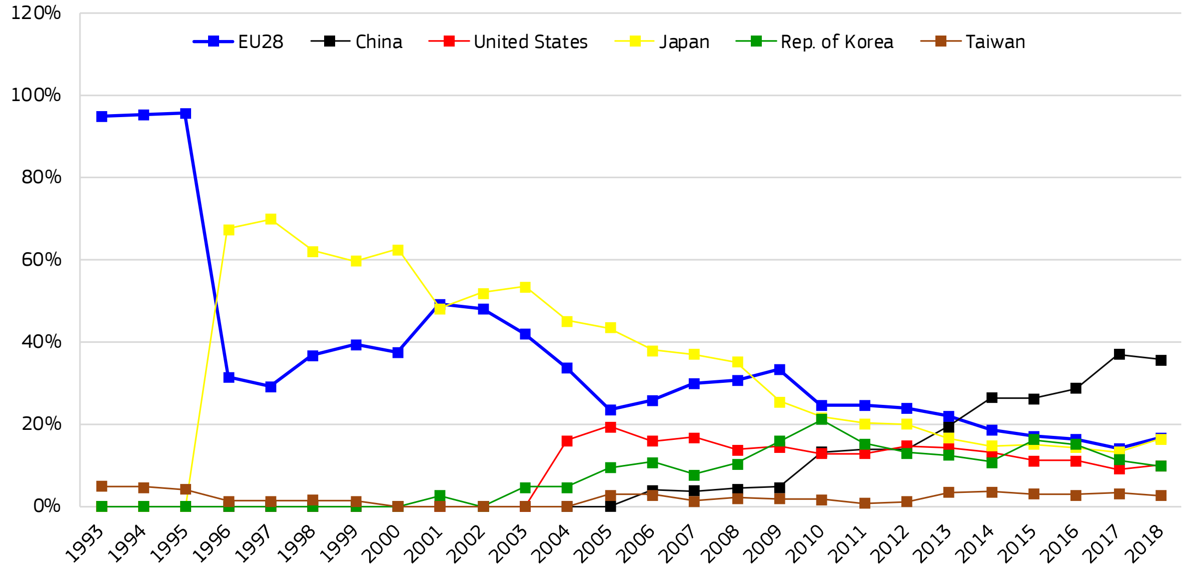
Figure 6: Evolution of the EU28 world-shares of new industrial robotics installations in all industries vis-à-vis other global players from 1993 to 2018



Source: IFR, 2019.

As explained in section 2, at industry level the IFR provides aggregate information for the following sectors: 1. Agriculture, forestry, fishing; 2. Mining and quarrying; 3. Manufacturing; 4. Electricity, gas, water supply; 5. Construction; and 6. Education/research/development. Overall, every year from 1993 to 2018 almost 100% of global robots installations by IFR feed into the manufacturing sector. Figure 7 presents the evolution of the EU-28 world-shares of robotics' new installations in manufacturing vis-à-vis other global players from 1993 to 2018. In this case, the declining trend of the EU-28 is even more apparent as it went from being around 95% in the early nineties to 16% in 2018. The EU-28 trend in Figure 7 tracks very closely the trend of the automotive sector, one of the key European sectors. Yet the EU-28 portion of new installations in the automotive sectors are overall slightly higher, in 2018 the EU-28 held around 22% of the new global robots installations in the automotive sector.

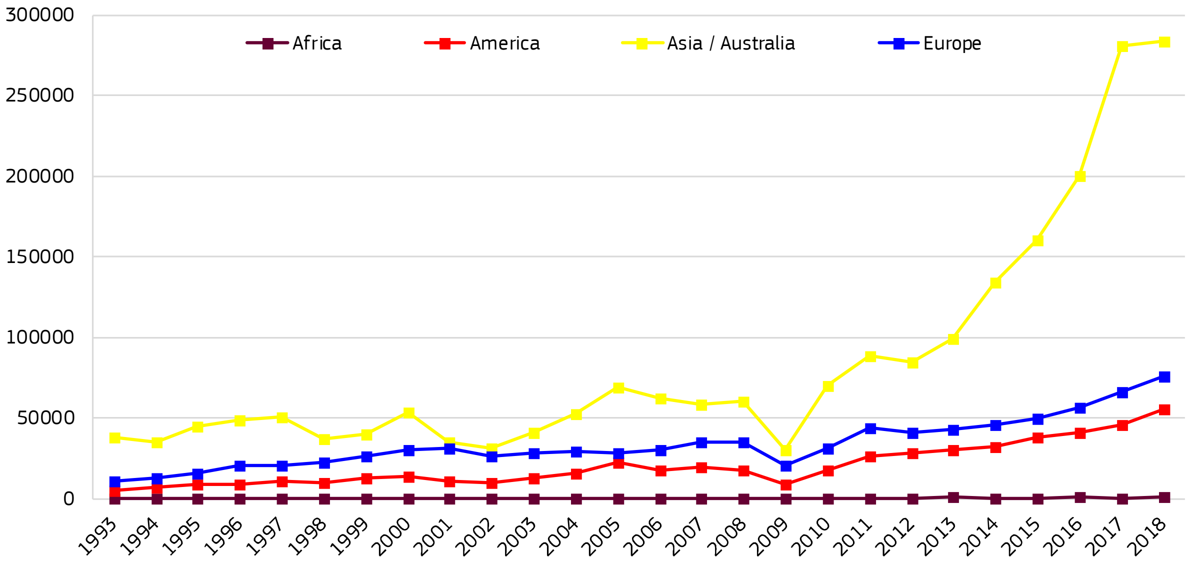
Figure 7: Evolution of the EU28 world-shares of new industrial robotics installations in manufacturing vis-à-vis other global players from 1993 to 2018



Source: IFR, 2019.

Figure 8 shows the details of the European new robotics' installations in manufacturing vis-à-vis other continents from 1993 to 2018. Consistently with previous figures, the advancements of Asia are apparent while Europe stands behind with similar trends vis-à-vis America.

Figure 8: Evolution of the European new industrial robotics installations in manufacturing vis-à-vis other continents from 1993 to 2018



Source: IFR, 2019.

The IFR database is also the main source of information regarding the production of service robots. The IFR reports on service robots provide data on the production of service robots by continent of origin for different types of robots. Table 4 shows the market shares of Europe, Asia/Australia and the Americas for different types of professional and domestic robots. According to this IFR classification, field robots cover robots that are used in agriculture, livestock, farming, forestry, mining and space. Logistic robots refer to robots used for the management of the flow of goods in the areas of transportation, handling and packaging. Medical robots are used mainly in diagnosis/therapy as well as in medical surgeries. Human exoskeletons are devices that resemble a human form and are worn by their operator. They are used in the areas of defence, manufacturing (reducing loads) and in rehabilitation. The final professional type of robots are public-relation robots where one can find robots that perform types of tasks like transferring suitcases to hotel rooms or serve foods and drinks in restaurants. With regards to personal robots, robots for domestic tasks include vacuum cleaners, and humanoid robots that imitate human mobility and behaviour. The last type is Entertainment robots that include toy and hobby robots for entertainment or education (IFR, 2019)

Table 4: Market shares of Europe, Asia/Australia and the Americas for different types of professional and domestic robots

Types of robots		Europe				Americas				Asia/Australia			
		2015	2016	2017	2018	2015	2016	2017	2018	2015	2016	2017	2018
Professional service robots	Field robotics	92%	93%	52%	49%	3%	2%	6%	7%	5%	5%	42%	44%
	Logistic systems	8%	9%	5%	4%	81%	78%	87%	91%	11%	13%	8%	5%
	Medical robotics	48%	55%	63%	67%	51%	43%	36%	32%	1%	1%	1%	1%
	Powered Human Exoskeletons	4%	5%	11%	12%	82%	85%	78%	77%	14%	9%	11%	11%
	Public relation robots and joy rides	1%	3%	3%	7%	0%	31%	36%	52%	99%	66%	61%	41%
Personal/ Domestic Robots	Robots for domestic tasks	3%	2%	7%	4%	64%	65%	58%	73%	33%	33%	35%	22%
	Entertainment	42%	38%	23%	24%	0%	0%	37%	31%	58%	62%	39%	45%

Source: IFR, 2016-2019; authors' calculations.

Figure 9 and 10 show the evolution of the units of professional and domestic service robots, respectively, produced and sold in Europe, Asia/Australia and North America. These figures provide an insight about the distribution of service robots by the region of origin. Specifically, the information displayed in these figures comes from a survey of service robots that the IFR has administered on a sample of service robots producers for the last 10 years. This survey is not exhaustive of all service robot suppliers.

The data provided by the IFR confirms that, in 2019, 55% of the sampled professional service robots were produced in Europe, 34% were from North America and 11% came from Asia. For the same year, 66% of the sampled personal/domestic service robots were from North America, 24% originated in Asia, and 10% in Europe.

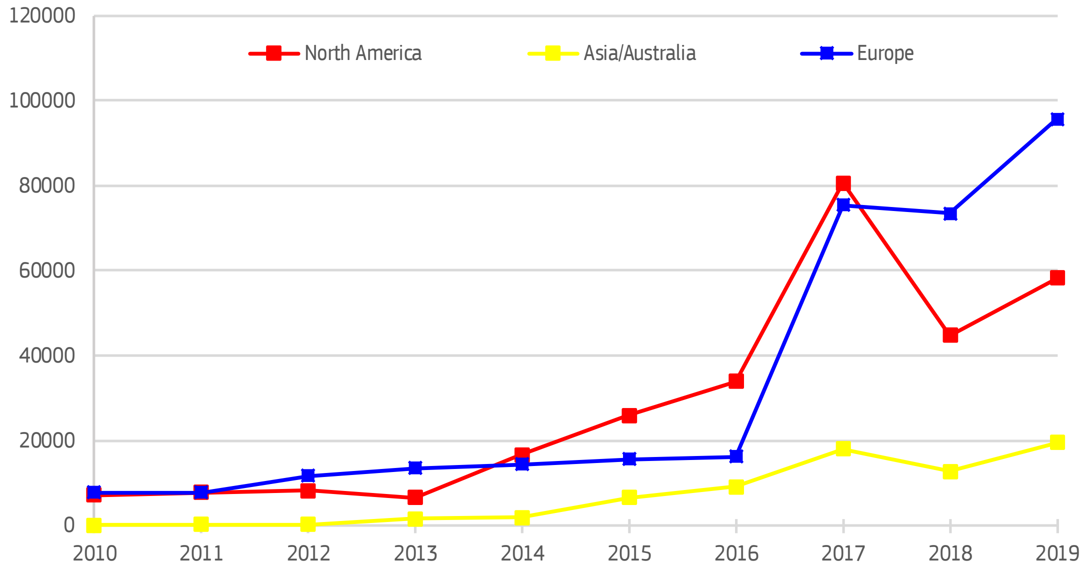
5.2 The United Nations Comtrade data

As mentioned above, Comtrade provides bilateral trade data on industrial robots over the period 1996-2018. Table 5 illustrates a snapshot of aggregate bilateral trade (in thousands of 2017 US dollars) of industrial robots based on exports from the reporting continents (rows) to their partner continents of destination (columns) in 2017[39]. The table shows that the European reporting countries exported industrial robots for a value of USD 613.3 million to trade partner countries in America. Intra-Europe trade, on the other hand, implied exports for a value close to USD 1.5 billion back in 2017. Continents are constructed according to the UN geographical classification[40].

39 In the Annex 2, table A3 includes bilateral trade data between the EU-28 Countries and six other major robot exporters for 2017 in 2017 US dollars.

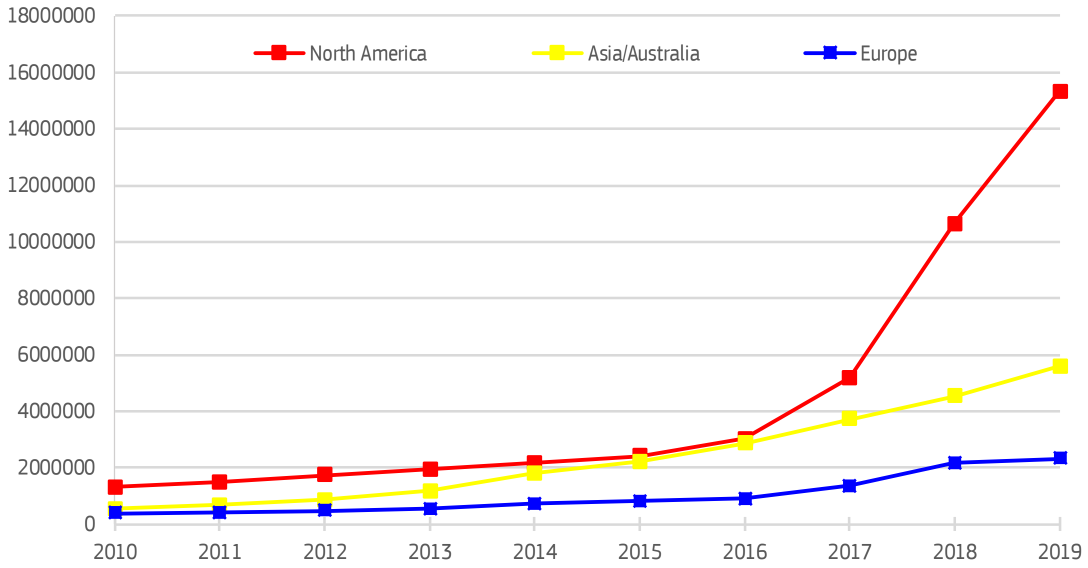
40 https://unstats.un.org/unsd/methodology/m49/overview/

Figure 9: Evolution of the number of professional service robots sold in 2010 to 2019, by continent



Source: IFR, 2010-2020.

Figure 10: Evolution of the number of personal/domestic service robots sold in 2010 to 2019, by continent



Source: IFR, 2010-2020.

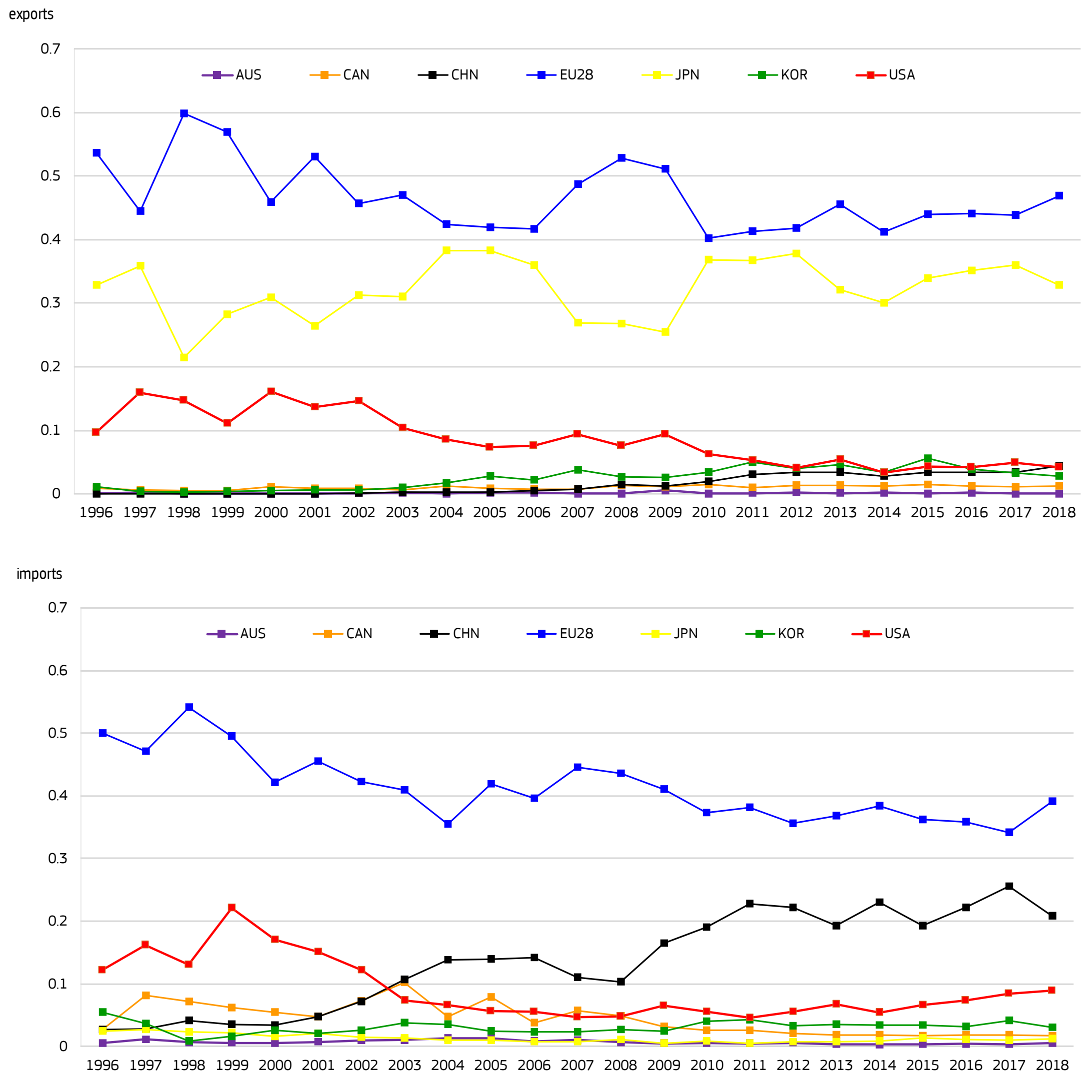
Table 5: Bilateral trade in industrial robots in 2017, by continent (Billion of 2017 US dollars)

	Africa	Americas	Asia	Europe	Oceania
Africa	0.24	0.86	0.16	2.53	0.00
Americas	2.17	208.99	77.33	91.47	4.75
Asia	6.17	695.49	1,502.55	502.98	13.27
Europe	38.21	613.31	571.39	1,493.47	13.53
Oceania	0.01	2.35	2.52	0.69	1.57

Source: Comtrade, authors' calculations.

Figure 11 shows the evolution of the export/import market shares of the EU-28 and the 6 biggest exporters of industrial robots: Australia, Canada, China, Japan, Korea, and the United States. The EU-28 and Japan are the biggest exporters. At the same time, while Japan's domestic demand of industrial robots seems almost fully satisfied by the domestic production, the EU-28 is also the largest importer of these robots. In addition to this, from a visual inspection it seems that Japan and the EU-28 are direct competitors in export markets as their export shares move in opposite directions. A more rigorous statistical analysis would better explain the movements of the export market shares in the period under analysis.

Figure 11: Evolution of exports and imports market shares for the EU-28 and the 6 biggest exporters, 1996-2018

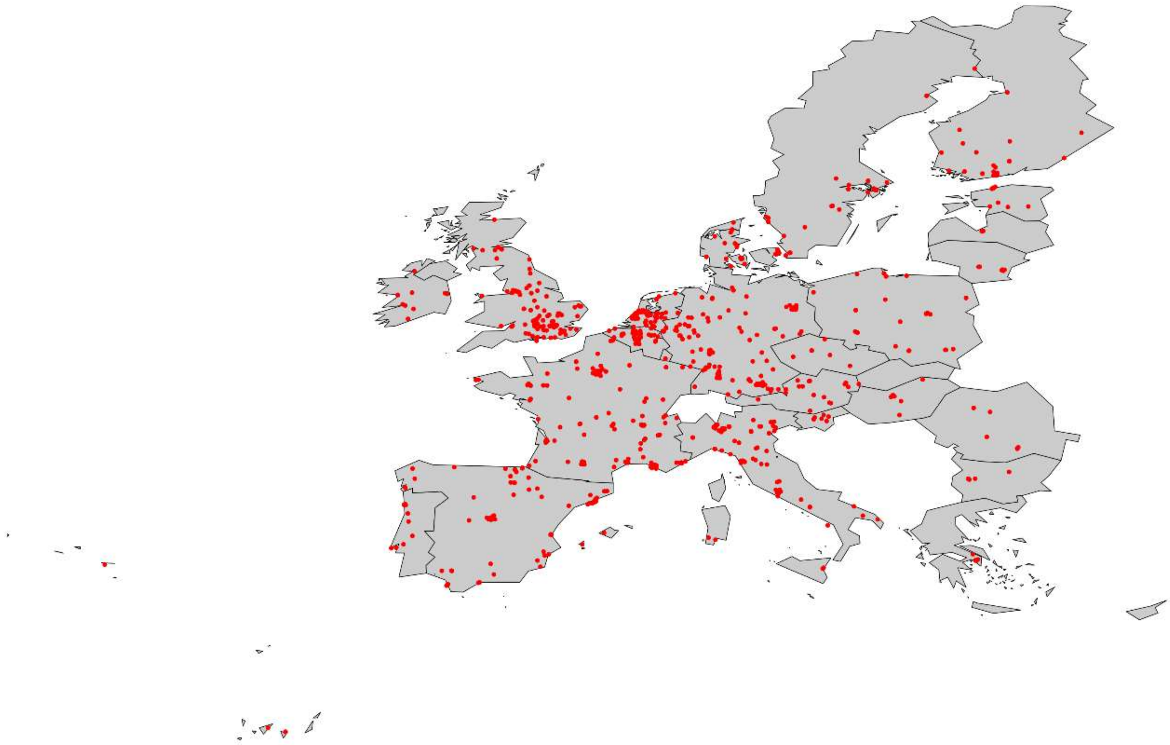


Source: Comtrade; authors' calculations.

5.3 Dealroom

The main source of information on robotic start-up companies comes from Dealroom. Figure 12 maps Dealroom robotic startups and scaleups retrieved in Dearloom in 2019 for the EU28[41].

Figure 12: Map of robotic companies by Dealroom



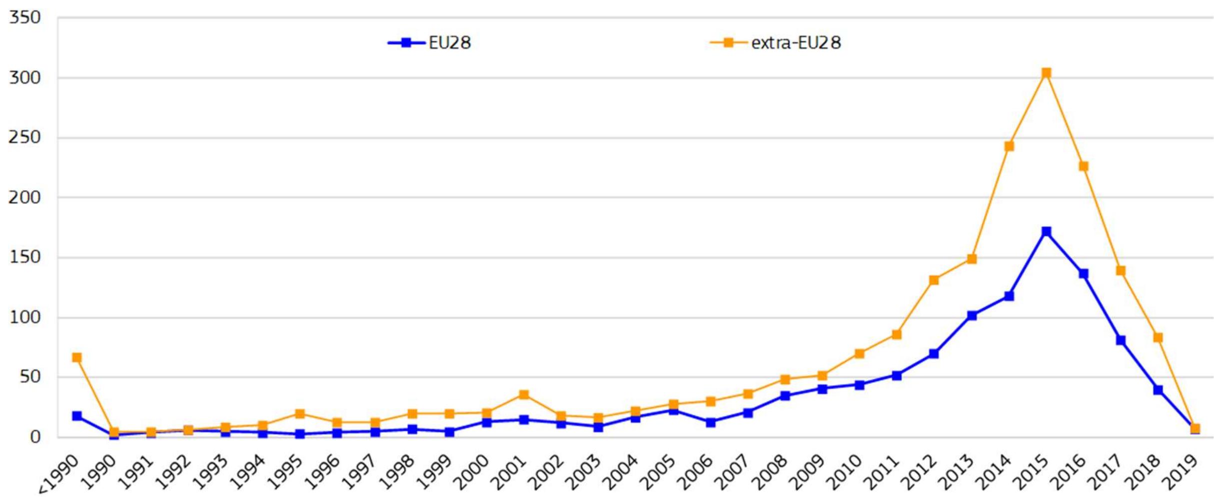
Source: Dealroom (1281 companies from the EU28, 2019).

Figure 13 plots the number of robotics companies by their launch date (i.e. from 1990 to 2019) in the EU28 vs. extra-EU countries according to Dealroom data in 2019. The creation of new robotics companies reached a peak in 2015. The total number of EU-28 and extra-EU28 companies whose launch date is available in Dealroom is indicated in brackets underneath the figure.

Figure 14 displays the distribution of employees working in the robotic start-up and scale-up companies in Dealroom. The figure indicates that the majority of companies employ between 2 and 10 workers. The number of companies whose class of employees is available is in brackets underneath the figure. Furthermore, by observing the information (when available) about companies' additional sectors of activities further to robotics, we noticed a majority of companies combining robotics with transportation, internet-of-things, and software enterprise as sectors of their activities.

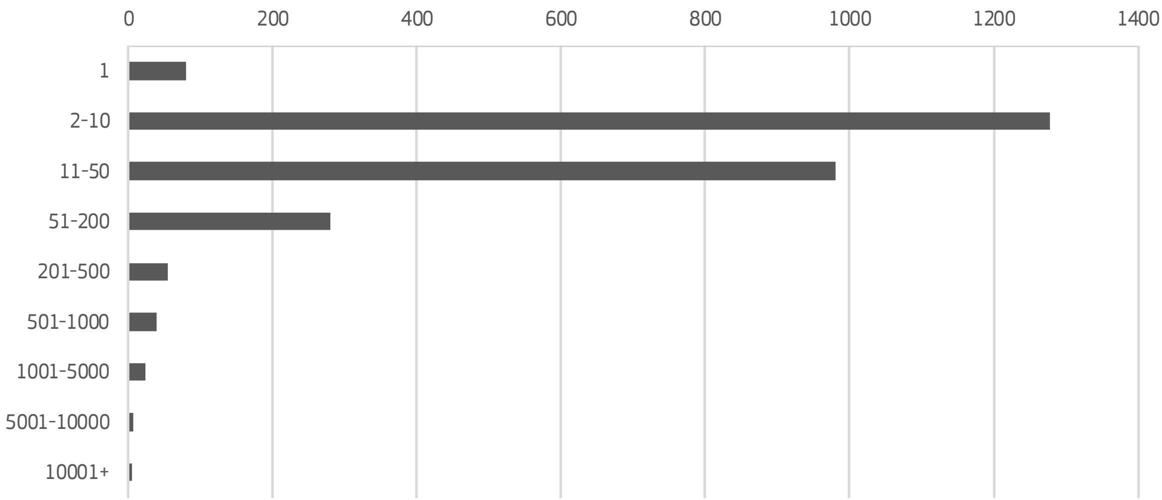
[41] Data are available worldwide.

Figure 13: Number of companies by launch date, 1990-2019



Source: Dealroom (1085 companies from the EU28; 1942 companies extra-EU28, 2019).

Figure 14. Number of companies by classes of employees.



Source: Dealroom (2743 companies, 2019).

5.4 The Robot Report

The Robot Report[42] is a robotics and intelligent systems company database created and maintained by business-to-business publisher WTWH Media. The database covers the full range of innovations in robotics and intelligent systems, including the latest research and breakthroughs coming from universities and research institutions. The database of robotics companies, organisations and related stakeholders, offers the following classification, and definitions:

42 https://www.therobotreport.com/

Educational and Research Facilities and Organizations: Universities and other educational institutions, research facilities, labs, and selected public-private research initiatives with a specific focus on robotics.

Industrial robots: An automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications. The main customer for industrial robots – the automotive industry – is changing and diminishing. There is a worldwide trend towards automation in the 'non-automotive industry'. Robot suppliers are offering increasingly tailored solutions to these customers. The metal industry, the electronics industry, the food and beverage industry, the glass industry, the pharmaceutical and medical devices industries, and the photovoltaic industries to name a few.

Integrators: Integrators are generally engineering firms which design, build and install turnkey robot systems but do not manufacture robots for resale or distribution by other companies. Some of these firms often partner with robot manufacturers and act as distributors; others consult and offer design solutions after comparing robot manufacturers and selecting the one(s) that make the most sense for the required solution.

Service Robots for Governmental and Corporate Use: A service robot is a robot which operates semi or fully autonomously to perform services useful to the well-being of humans and equipment, excluding industrial automation applications. They are capable of making decisions and acting autonomously in real and unpredictable environments to accomplish determined commercial tasks and are usually operated by a trained operator. Defence, rescue and security applications account for the majority of applications thus far. Unmanned aerial, mobile and underwater vehicles are included in this category. Field robots (mainly milking robots), cleaning robots, construction and demolition robots, laboratory, medical, rehabilitation, and surgical robots, and mobile robot platforms for general and small business use. Also logistic systems, inspection systems and educational and public relations r the required solution.

Service Robots for Personal and Private Use: A service robot is a robot which operates semi- or fully autonomously to perform services useful to the well-being of humans and equipment, they exclude manufacturing operations, and they are capable of making decisions and acting autonomously in real and unpredictable environments to accomplish determined tasks. Personal service robots, which include vacuum cleaning and lawn-mowing robots, tele- and remote-presence, elder care and medical companions, and entertainment and leisure robots, including toy robots, hobby systems and kits, and home education and training robots are examples of personal service robots which are usually operated by a lay person.

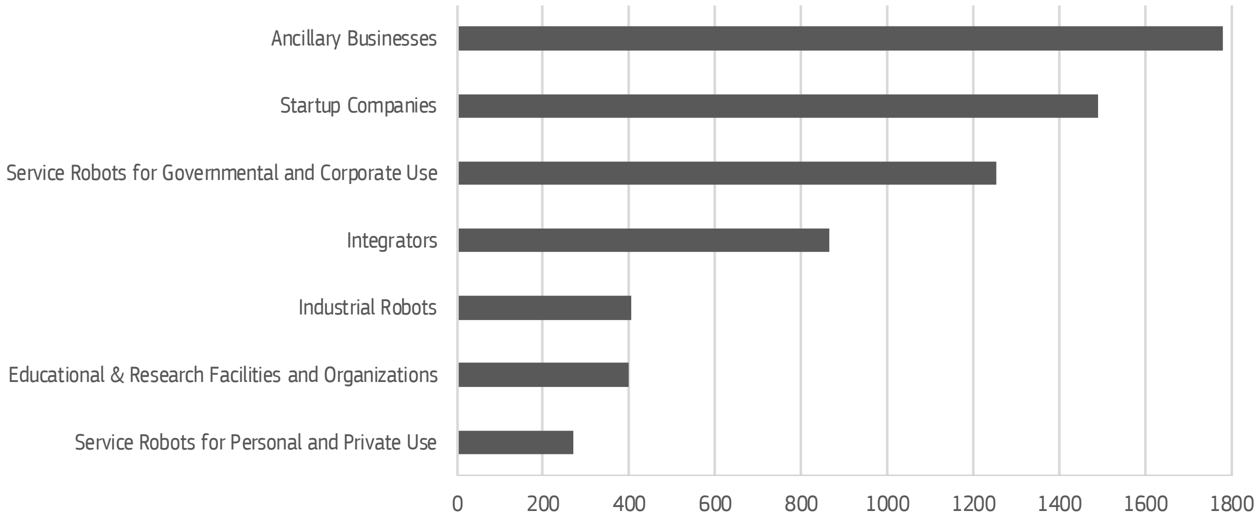
Start-up Companies: Privately held robotic companies established to develop a concept or product or robotic-related service for sale but doesn't yet have it all together. They have established a business and are in motion toward their goals but haven't made any sales or aren't fully funded, haven't finished developing the product, or all of the above.

Ancillary Businesses: These companies are mainly providing products such as software to robot manufacturers. These companies include software and vision systems developers and providers, magazines, research organizations, engineering and consulting firms, component manufacturers, resellers and distributors.

Figure 15 shows how the 6463 companies and different institutions (research institutes, universities, professional associations) from the Robot Report are distributed across the above described classification.

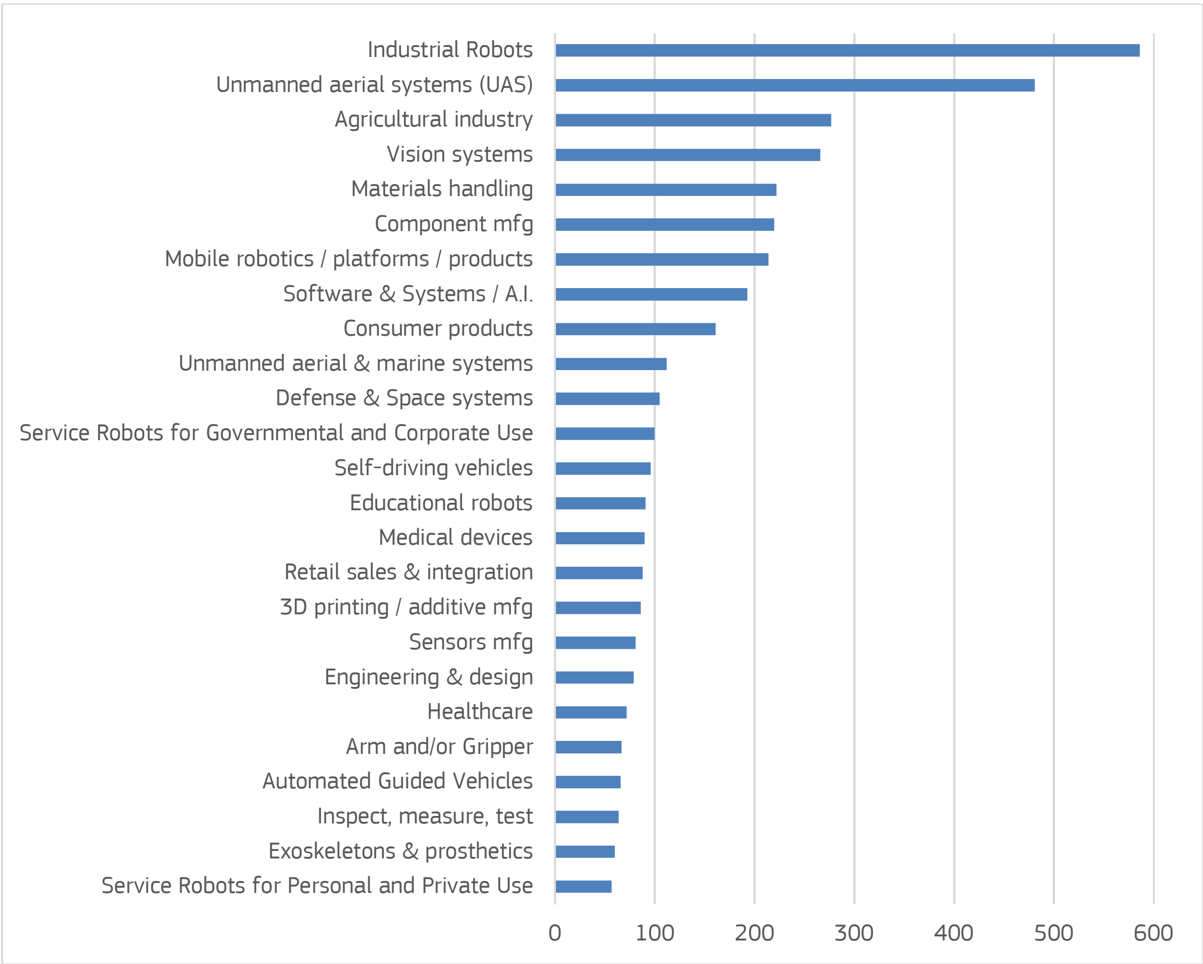
The Robot Report further divides organizations according to their focus of interest. Figure 16 shows that the number of companies dealing with AI (i.e. Software and system/AI) is particularly high. These companies are also mostly included in the ancillary business, start-ups or integrators categories. Another relevant sub-category revealed by the figure is unmanned aerial systems (UAS), which use advanced simultaneous localization and mapping (SLAM), a technology that can be classified as AI. The total number of companies whose sub-type is available is in brackets underneath the figure.

Figure 15. Number of worldwide companies by type (the Robot Report classification)



Source: The Robot Report (6463 companies, 2019).

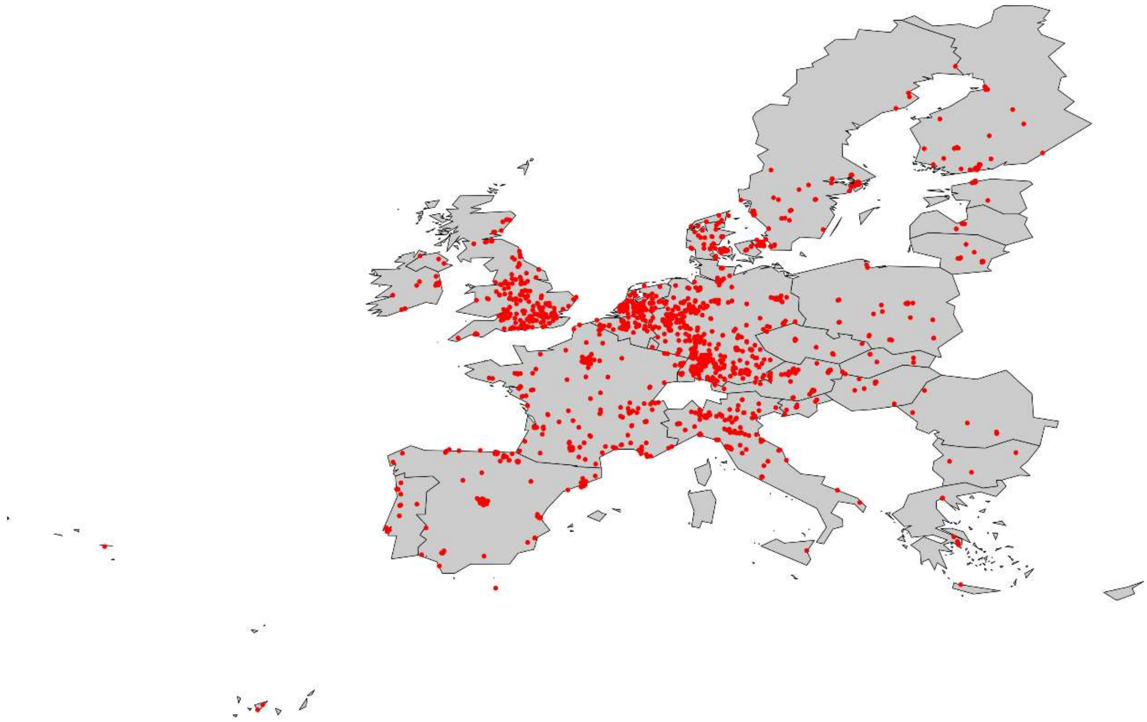
Figure 16: Top 25 sub-types in the Robot Report classification by number of companies worldwide



Source: The Robot Report (4767 companies, 2019).

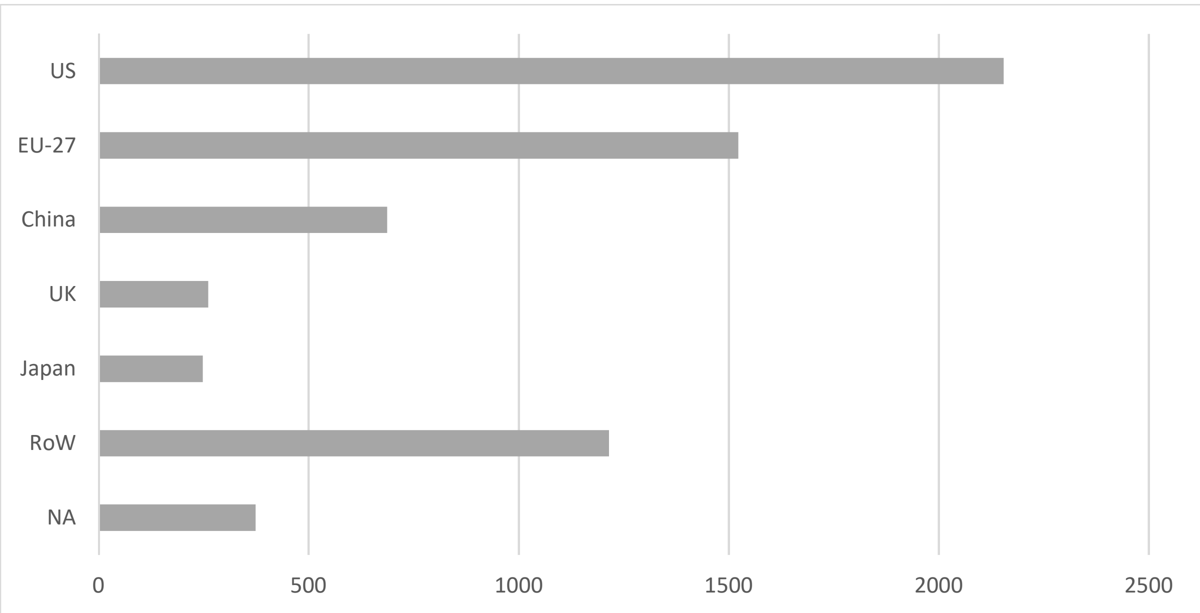
The Robot Report provides information on the addresses of companies, which allows to place them on a map. Focusing on those companies that are located in the EU, FFigure 17 shows the results of geocoding the companies' addresses (i.e. the most fine-grained information is at city level) using the ArcGIS API. This information can be used to identify clusters of industrial and/or services robots, as well as clusters of ancillary businesses, research and educational hubs or agglomerations of integrators dedicated to robotics. Similarly, this information is useful to know the proportion of EU-27 companies in this database, as provided by Figure 18. As the figure shows, the EU-27 is the second largest area hosting robotics companies, just behind the US.

Figure 17: Map of robotic companies by the Robot Report



Source: The Robot Report (1780 companies from the EU28, 2019).

Figure 18: Number of robotic companies in the Robot Report, by region or country



NA: Not available. Source: Robot Report (6463 companies, 2020)

6 Methodological challenges

One of the objectives of the AI WATCH is to calculate the EU robotics market shares over the past ten years. An important precondition to study market shares is the availability of appropriate data. However, as is evident throughout the report, the volume and type of statistical information available today is not sufficient to completely fulfil the objectives of this task and the needs of European policy-makers. Hence, there is a clear need to develop an appropriate methodology and assemble a database describing the world robotics industry, particularly distinguishing industrial and service robots, with which it will be possible to calculate the EU market share in robotics and analyse its evolution over the past 10 years.

Based on the analysis of the industry, the literature review and the data sources presented in previous sections, several methodological challenges can be identified to assess EU market shares.

Differences in robots' types

Previous sections of the report indicate that robots can vary in design, functionality and degree of autonomy, which makes it difficult to class them in a common typology. Moreover, robots are used in a great variety of economic sectors, with different degrees of penetration/adoption, depending on the characteristics of the activities. The most relevant distinction is between industrial and service robots, and there are important differences between them. While industrial robots are highly used in manufacturing industries and factories for carrying out dangerous tasks, service robots are mostly used in offices and homes for carrying out human tasks.

With the volume and type of statistical information available today, the task of analysing the robotics industry, and obtaining relevant insights to inform policy makers, becomes quite complex.

Both industrial and professional service robots are used in the production of final goods and the provision of services. On the other hand, domestic service robots are designed and produced to satisfy individuals' tastes and needs, and are thus mostly sold to end consumers.

Differences of data availability across robots' types

Industrial robotics is a consolidated sectors, and the available data are much more abundant than for the emerging service robotics industry. Service robotics solutions require the integration of third party technologies, generating an ecosystem-type of organisational solution. This makes it particularly hard to identify all the players involved in the value chain. As a final remark, for both industries, the data available are mostly about the robots themselves and not about the peripherals or integrations around them, which is an important piece of missing information.

The main challenge lies in an appropriate description of the service robots segment. In addition, going back ten years in this case will be also extremely complicated.

Limited data sources of robotics information

The key source of robotics information is the IFR data. Its main advantage consists of being the only robotics data source that covers both industrial robots and service robots. Furthermore, this database offers yearly data and a fine geographical granularity for industrial robots. On the other hand, its main disadvantage lies in the heterogeneity of the information provided vis-à-vis industrial and service robots. Specifically, the IFR data on industrial robots entails the stocks (i.e. the number of robots currently deployed) and the number of installations –therefore, both measures only relate to quantities- across the IFR classifications of both applications and industries. Instead, the IFR data on service robots entails numbers of units sold and market data (i.e. companies' sales) for about ten years, about half of the years covered by the IFR data on industrial robots.

It is worth noticing that the geographical granularity of the IFR data for industrial robots reaches the level of countries, while it only covers continents for service robots. This feature limits the possibility to use the IFR data for an in-depth analysis of service robots at country level, and hampers a country-by-country comparison with the IFR industrial robots.

The second valuable source of robotics information considered in this report is Comtrade that encompasses bilateral trade data about industrial robots over more than ten years. This database offers country-level information about import and export quantities and values of industrial robots. In addition, this database also provides information about geographical aggregates -like continents and the world- that are useful to calculate countries' market shares and revealed comparative advantages. Consequently, the geographical granularity and aggregates by macro-areas constitute the main advantage of Comtrade data. Another feature of Comtrade, especially in comparison with the IFR data of industrial robots, is the availability of information about monetary values, not only quantities.

The limitation of Comtrade data is that it only focuses on industrial robots and lacks information about service robots. Similarly, it is abundant for the quantities, and scarce for the values.

Other explored sources of information are company-level, most notably Dealroom.co and the Robot Report. These sources provide information to better understand the entrepreneurial robotics ecosystems shaped by new technologies across years and geographical spots. This information could be beneficial for correlation analysis once the key information from the IFR and Comtrade has led to an estimation of robotics demand and supply. On the other hand, the main drawback of these sources is the limited possibilities of integrating them with the IFR and Comtrade data, given their specific characteristics and focus.

Complexity of data aggregation

The aggregation of industry and firm-level sources may be complicated, given the different characteristics of the data.

Moreover, many statistical series exhibit the issue of missing values. For example, for a given year, data might be available only for a limited number of countries or geographical areas, or only for certain variables. From a time series perspective, even if all the data points are available for one year, they might not be available for all the years for the period under study. This adds an additional level of complexity on whether data could be extrapolated or imputed. Thus, statistical imputation methods will be used to address these missing values.

7 Methodological goals

The exercise carried out in this report of analysing in depth the main characteristics of the robotics industry, the literature looking at the economic impact of robots and the most relevant data sources is, in our opinion, a necessary step for the final goal of calculating the EU market shares in robotics. In order to be able to fulfil the objective, and given the methodological challenges outlined in previous section, the proposed methodology should aim specifically at the calculation of a matrix of countries of origin and destination of robots (Figure 19) for each year and by type of robots (i.e. industrial vs service robots). A similar exploration will be conducted to assess the possibility of creating specific matrices for industries and application areas. However, this last objective will be seriously threatened by the lack of availability of highly disaggregated data. In addition, these matrices would also account for robot quantities and values where this information is available.

Despite the existence of several data sources, the review and appraisal of available data sources revealed a wider availability of information on robot quantities than robot values (e.g., revenues from robotics industries and applications are scarce). The construction of these matrices should allow the inference of robotics supply and demand, and consequently to estimate the EU market shares in the global robotics market during the last decade. Specifically, the supply of robots can be inferred from the information available on countries that produce and export robots, while the demand of robots can be inferred from the information available on countries that import, install and use robots. The data sources that appear, for now, to be the best candidates for this endeavour are the IFR data set for robot stocks and installations (i.e. robot usage/demand) across different years and countries, and the UN Comtrade data set for international robot imports and exports (i.e. robot production/supply). However, these sources present some limitations. For example, the IFR data is, at least in some years, of poor quality and riddled with problems, particularly when moving from NACE level 1 sectors to NACE level 2 or 3. These problems would need to be addressed before using the IFR data as an input, as suggested by Fernandez-Macias et al. (2021) and Graetz and Michaels (2018).

Figure 19: Matrix of countries of origin and of destination of robots, by year

Type of robots {Industrial; Service}
Classification {Industry; Application}
Measurement {Quantity; Value}

$year_1$	DESTINATION$_d$; *(d from 1 to n)*			Total *(origin)*
ORIGIN$_o$; *(o from 1 to m)*	*$country_{1,1}$*	...	*$country_{1,n}$*	*$country_1$*
	$country_{2,1}$	...	*$country_{2,n}$*	*$country_2$*
	...	...	...	...
	$country_{m,1}$	...	*$country_{m,n}$*	*$country_m$*
Total *(destination)*	*$country_1$*	...	*$country_n$*	

... →

Type of robots {Industrial; Service}
Classification {Industry; Application}
Measurement {Quantity; Value}

$year_{10}$	DESTINATION$_d$; *(d from 1 to n)*			Total *(origin)*
ORIGIN$_o$; *(o from 1 to m)*	*$country_{1,1}$*	...	*$country_{1,n}$*	*$country_1$*
	$country_{2,1}$	...	*$country_{2,n}$*	*$country_2$*
	...	...	...	...
	$country_{m,1}$	...	*$country_{m,n}$*	*$country_m$*
Total *(destination)*	*$country_1$*	...	*$country_n$*	

Source: own elaboration.

Since the data on production and installations, and on export and import of industrial and service robots is sometimes incomplete, missing data will be one of the challenges to the calculation of EU market shares in robotics as highlighted in previous section. To overcome this limitation, the next step will be finding suitable statistical imputation methods for the data. The purpose of this step is to reconstruct missing data wherever needed. The selection and implementation of imputation methods thus constitutes the second relevant challenge to the estimation of EU market shares in robotics during the last ten years. Box 1 provides an overview of existing imputation techniques that will serve as basis for reflection on the possibilities and alternatives for the next stage.

For the construction of the different matrices, we need to carefully evaluate the informational gains provided by the different sources of data. Some datasets are collected over time and hence can provide relevant information about the evolution of the robotics industry (e.g., the IFR and Comtrade datasets), while others provide information on a particular point in time (e.g., the Robot Report). We will extract all the relevant information included in these different sources to produce the most accurate, comprehensive and up-to-date matrices. Once the construction of the different matrices, as shown in Figure 19, is completed, we will evaluate, and apply, suitable imputation methods in order to fill in the missing cells to provide a complete perspective of the robotics industry. The combination of different data sources, by year and type of robot, along with the imputation method, should allow us to fulfil the task of computing the EU market share of robotics over the last 10 years.

Box 1: Brief review of the most common imputation methods

Missing values can render calculations less reliable for the units of analysis (e.g. countries, or firms) for which information is limited. Statistical imputation methods[43] aim to replace the missing values with an approximation or an estimate. These techniques allow to proceed with analysing the full data set as if the imputed values were actual observed values.

In general, methods that deal with missing data belong to three main groups: (i) case deletion, (ii) single imputation or (iii) multiple imputation. In case deletion, the imputation omits the missing records from the analysis, which only produces unbiased estimates if deleted records are random. The other two approaches consider the missing data as part of the analysis by reconstructing values either by single imputation (e.g. mean/median/mode substitution, regression imputation, hot- and cold-deck imputation, expectation-maximisation imputation) or multiple imputation (e.g. Markov Chain Monte Carlo algorithm).

The following are the most common single imputation methods:

• **Mean/median/mode substitution**: substituting missing information with the mean/median/mode of the available data. This method is easy to perform, but it tends to distort the statistical nature of the data by underestimating the standard errors and altering the relationship among variables;

• **Linear interpolation**: this technique assumes a linear relationship between data points and employs adjacent values to compute a missing data point;

• **The nearest neighbour**: substituting missing information with its most similar available information;

• **Model-based imputation** estimate the missing values through regressions performed on available variables. As missing values of one variable are predicted based on other variables, these methods preserve relationships among variables involved in the imputation model, but not the variability of the predicted values.

Finally, **multiple imputation** is based on the use of the average output of sequential regressions. This method reconstructs missing information by an interactive estimation process. Regression analysis produces a first estimate of missing values, then these predictions are employed to update the model parameters and the process is repeated until the parameters converge to maximum-likelihood estimates.

[43] Joint Research Centre-European Commission, 2008. Handbook on constructing composite indicators: methodology and user guide. OECD publishing. https://ec.europa.eu/jrc/en/coin/10-step-guide/step-4 ; https://www.oecd.org/sdd/42495745.pdf

8 Conclusion

This report has provided an overview of the robotics industry –including its main definitions-, reviewed the literature referring to the economic impact of robotics, and has presented the key features of the statistical sources of information that could potentially be employed for a coherent estimation of EU market shares in robotics. The description of the industry, including the definitions, typologies, and main differences between industrial and service robots, as well as the analysis of the most recent economics literature served to build-up a stronger and updated knowledge of research questions, approaches and data that scholars and policy makers have used in order to study robotics around the world, and more specifically in Europe. The data sources identified in this report have also served to provide information about the state of play of the robotics industry worldwide, and in Europe in particular. The statistical analysis contributes to placing Europe in the global landscape of robotics usage and production, and it can inform policy on gaps and strengths of the European robotics industry.

The report has highlighted the upcoming challenges of estimating the EU market shares –to which a following report will be dedicated- and the possible suitability issues related to the available data for this task. In line with this, the report also identifies the next actions that are required in order to merge heterogeneous data into a meaningful and consistent dataset to estimate the EU shares of robotics demand and supply, for both industrial and service robots. Concerning the available information on robotics, the most complete and useful database is from the IFR, as it provides the most relevant facts and figures about robotics. Nonetheless, complementing these data with other sources will enhance the value and the significance of the overall estimation exercise of the EU robotics market shares. However, the other sources presented in this report will likely require data imputation work before becoming fully suitable for the purpose. These additional sources will also require cleaning and specific checks for duplicates, especially when carrying out a deeper analysis at firm level. Finally, the coherent combination of different sources will provide a comprehensive overview of the production and adoption for both industrial and service robots.

Further to the above technical challenges at the level of data, from a conceptual viewpoint a key challenge for properly delineating the emerging robotics activities lies in the effective identification of AI-enhanced robots, namely robots that have some degree of AI capability, notably that can make autonomous decisions or independent learning. As mentioned in the introduction, in this report we have only looked at AI from a distance, when required for the description and analysis of the data sources or for the description of the emerging service robots segment. A separate AI Watch report (forthcoming) will look at the landscape of AI-enhanced robotics in more detail.

In conclusion, this report has aimed to provide useful information in order to build a dedicated database to study the evolution of the European market share of robotics over the past ten years. At this stage the report provides:

- A description of the robotics industry, including definitions, typologies, areas of application and main differences between industrial and service robots
- A literature review off the economic impact of industrial and service robots, including institutional and policy reports and projects related to robotics
- An inventory of the main sources of robotics data and information worldwide;
- A description of these data sources to initiate a reflection about the EU market shares
- A discussion of methodological challenges related to the usage of these different sources of information for the future in-depth analysis of the evolution of the EU market share of robotics.

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Zhang, P., 2019. Automation, wage inequality and implications of a robot tax. *International Review of Economics & Finance*, 59, pp.500-509.

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Annexes

Annex 1 Identified data sources on robotics

Table A1: Overview of the empirical literature on robotics and their main data sources

Citation	Robot Data	Other Primary Data	Comment
Anton, J.I., Klenert, D., Fernández-Macias, E., Brancati, M.C.U. and Alaveras, G., 2020. The labour market impact of robotisation in Europe (No. 2020-06). Joint Research Centre (Seville site).	IFR (2018)	EU-LFS EU-KLEMS WITS (2019)	Robots <-> Labor Market
Fernández-Macías E, Klenert D and Antón JI (2021) Not so disruptive yet? Characteristics, distribution and determinants of robots in Europe. Structural Change and Economic Dynamics 58: 76–89.	IFR (2019)	European Job Monitor EU-LFS	Robots <-> Labor Market
Klenert, D., Fernández-Macias, E. and Anton, J.I., 2020. Do robots really destroy jobs? Evidence from Europe (No. 2020-01). Joint Research Centre (Seville site).	IFR (2017)	EU-LFS	Robots <-> Labor Market
Acemoglu, D. and Restrepo, P., 2020. Robots and jobs: Evidence from US labor markets. Journal of Political Economy, 128(6), pp.2188-2244.	IFR (2014)	EU-KLEMS	
Csefalvay, Z., 2019. What are the policy options? A systematic review of policy responses to the impacts of robotisation and automation on the labour market (No. 02/2019). JRC Working Papers on Corporate R&D and Innovation.	IFR (2017), EUROSTAT		
Lechevalier, S., Nishimura, J. and Storz, C., 2014. Diversity in patterns of industry evolution: How an intrapreneurial regime contributed to the emergence of the service robot industry. *Research Policy*, 43(10), pp.1716-1729.	IFR (2013)	Japan Patent Office (JPO)	
Graetz, G. and Michaels, G., 2018. Robots at work. *Review of Economics and Statistics*, 100(5), pp.753-768.	IFR (2006)	EU-KLEMS	
Cheng, H., Jia, R., Li, D. and Li, H., 2019. The rise of robots in china. *Journal of Economic Perspectives*, 33(2), pp.71-88.	IFR (2017), China Employer-Employee Survey (CEES)	-	
European Commission, 2015. DG Communications Networks, Content & Technology; Fraunhofer ISI; Karlsruhe University of Applied Sciences - Jäger, A., Moll, C., Som, O., Zanker, C., Kinkel, S. and Lichtner, R., 2015. Analysis of the impact of robotic systems on employment in the European Union.	IFR (2013)	European Manufacturing Survey (EMS)	
European Commission, 2016. DG Communications Networks, Content & Technology; Fraunhofer ISI - Jäger, A., Moll, C., and Lerch, C., 2015. Analysis of the impact of robotic systems on employment in the European Union - Update.	IFR (2013)	European Manufacturing Survey (EMS)	
UNCTAD, 2017. Trade and Development Report 2017–Beyond austerity: Towards a global New Deal.	IFR (2016)		
Atkinson, R.D., 2018. Which Nations Really Lead in Industrial Robot Adoption? *Information Technology & Innovation Foundation*.	IFR (2018)	-	
Qureshi, M.O. and Syed, R.S., 2014. The impact of robotics on employment and motivation of employees in the service sector, with special reference to health care. *Safety and health at work*, 5(4), pp.198-202.	IFR (2013)		
Artuc, E., Bastos, P. and Rijkers, B., 2018. *Robots, Tasks and Trade*. https://openknowledge.worldbank.org/bitstream/handle/10986/31076/WPS8674.pdf?sequence=5	IFR (2012)		

IMF, 2018. *Land of the Rising Robots*. Finance & Development, June 2018, Vol. 55, No. 2. https://www.imf.org/external/pubs/ft/fandd/2018/06/japan-labor-force-artificial-intelligence-and-robots/schneider.htm	IFR (2017)		
Bessen, J., Goos, M., Salomons, A. and van den Berge, W., 2020, May. Firm-Level Automation: Evidence from the Netherlands. In AEA Papers and Proceedings (Vol. 110, pp. 389-93).	Dutch firm-level automation data set (no observation of specific automation technology), 2000-2016, 36,490 firms	-	
Acemoglu, D., Lelarge, C. and Restrepo, P., 2020. Competing with Robots: Firm-Level Evidence from France. In AEA Papers and Proceedings (Vol. 110, pp. 383-88).	French firm-level data in manufacturing, 2010-2015, 55,390 firms Identify 598 firms that purchased industrial robots		
Autor, D., Dorn, D., Katz, L.F., Patterson, C. and Van Reenen, J., 2020. The fall of the labor share and the rise of superstar firms. The Quarterly Journal of Economics, 135(2), pp.645-709.	-	US Economic Census	
Hawksworth, J., Berriman, R. and Goel, S., 2018. Will robots really steal our jobs? An international analysis of the potential long term impact of automation. *PricewaterhouseCoopers*, https://www.pwc.co.uk/economic-services/assets/international-impact-of-automation-feb-2018.pdf	-	OECD PIAAC	Assesses potential for automation, no use of robot data.
Brussevich, M., Dabla-Norris, M.E. and Khalid, S., 2019. Is Technology Widening the Gender Gap? Automation and the Future of Female Employment. *International Monetary Fund*.	-	PIAAC	
Graetz, G. and Michaels, G., 2017. Is modern technology responsible for jobless recoveries?. *American Economic Review*, 107(5), pp.168-73.	-	EU-KLEMS WIOD	
Gregory, T., Salomons, A. and Zierahn, U., 2016. Racing with or against the machine? Evidence from Europe. *ZEW-Centre for European Economic Research Discussion Paper, (16-053).*	-	EU-LFS	
Arntz, M., Gregory, T. and Zierahn, U., 2016. The Risk of Automation for Jobs in OECD Countries: A Comparative Analysis. *OECD Social, Employment and Migration Working Papers, No. 189, OECD Publishing, Paris*, https://doi.org/10.1787/5jlz9h56dvq7-en.	-	PIAAC	
Erdogan, N., Corlu, M.S. and Capraro, R.M., 2013. Defining innovation literacy: Do robotics programs help students develop innovation literacy skills?. International Online Journal of Educational Sciences, 5(1), pp.1-9.	-	Self-collected	Experimental
Frey, C.B. and Osborne, M.A., 2017. The future of employment: How susceptible are jobs to computerisation?. *Technological forecasting and social change*, 114, pp.254-280.	-	Bureau of Labor Stastics	
Salomons, A., 2018. Is automation labor-displacing? Productivity growth, employment, and the labor share	-	EU KLEMS	
Salomons, A., 2017. Robocalypse Now: Does Productivity Growth Threaten Employment?. In Economics of Artificial Intelligence. University of Chicago Press.	-	EU KLEMS	
Blankenau, W.F. and Cassou, S.P., 2011. Industry estimates of the elasticity of substitution and the rate of biased technological change between skilled and unskilled labour. *Applied Economics*, 43(23), pp.3129-3142.	-	ICPSR	
DeCanio, S.J., 2016. Robots and humans–complements or substitutes?. *Journal of Macroeconomics*, 49, pp.280-291.	-	US BLS	

Hermann, M., Pentek, T. and Otto, B., 2016. Design principles for industrie 4.0 scenarios. In 2016 *49th Hawaii international conference on system sciences (HICSS)* (pp. 3928-3937). IEEE.	-	Scopus, EBSCOhost Business Source Complete, ECONIS, ScienceDirect, OAlster	
Guerreiro, J., Rebelo, S. and Teles, P., 2017. Should robots be taxed? (No. w23806). *National Bureau of Economic Research.*	-	Current Population Survey (CPS), Annual Social and Economic Supplement (ASEC)	
Acemoglu, D. and Restrepo, P., 2019. Automation and new tasks: how technology displaces and reinstates labor. *Journal of Economic Perspectives*, 33(2), pp.3-30.	-	Bureau of Economic Analyses	Only use proxies for automation
Autor D., 2015. Why are there still so many jobs? The history and future of workplace automation. *Journal of economic perspectives*, 29(3), pp.3-30.	-	IPUMS	Essay
Reshef, A., 2013. Is technological change biased towards the unskilled in services? An empirical investigation. *Review of Economic Dynamics*, 16(2), pp.312-331.	-	CPS, BEA	
Takayama, L., Ju, W. and Nass, C., 2008, March. Beyond dirty, dangerous and dull: what everyday people think robots should do. In 2008 3rd ACM/IEEE International Conference on Human-Robot Interaction (HRI) (pp. 25-32). IEEE.	-	Survey data (self-collected)	
Autor D., and Dorn, D., 2013. The growth of low-skill service jobs and the polarization of the US labor market. American Economic Review, 103(5), pp.1553-97.	-	Census Integrated Public Use Micro Samples, American Community Survey	
OECD, 2019b. OECD Employment Outlook 2019: The Future of Work, OECD Publishing, Paris. https://doi.org/10.1787/9ee00155-en	-	OECD data	Report focusing on emplyoment
European Commission, 2020. European enterprise survey on the use of technologies based on artificial intelligence. Luxembourg, Publications Office of the European Union. ISBN 978-92-76-20108-3 doi:10.2759/759368	-	Survey	Report
Arntz, M., Gregory, T. and Zierahn, U., 2017. Revisiting the risk of automation. *Economics Letters*, 159, pp.157-160.	-	-	Simulation

Table A2: Firm-level datasets identified

Data set	Country	Time Range	Size
Encuesta Sobre Estrategias Empresariales (ESEE), by the SEPI foundation	Spain	1990-2016	Unbalanced sample of 5500 firms. One third use robots
https://www.fundacionsepi.es/investigacion/esee/en/spresentacion.asp			
China Employer-Employee Survey (CEES)	China	2016	1115 firms surveyed, 8.6% are robot adopters
https://pubs.aeaweb.org/doi/pdfplus/10.1257/jep.33.2.71			
Dutch firm-level automation data set (no observation of specific automation technology)	Netherlands	2000-2016	36,490 firms
https://www.aeaweb.org/articles?id=10.1257/pandp.20201004			
French firm-level data in manufacturing, assembled from several sources	France	2010-2015	55,390 firms; 598 robot adopters
https://www.openicpsr.org/openicpsr/project/117522/version/V1/view			
How to Build a Robots! Database	Canada	1996-2017	3,085 individual business
https://epe.lac-bac.gc.ca/100/201/301/weekly_acquisitions_list-ef/2020/20-45/publications.gc.ca/collections/collection_2020/statcan/11-633-x/11-633-x2020004-eng.pdf			
Robot adoption firm survey conducted by Statistics Denmark in 2018, 6-digit product code Foreign Trade Statistics Register (UHDI)	Denmark	1995-2016	Universe of Danish firms; 454 robot adopters
https://static1.squarespace.com/static/5d35e72fcff15f0001b48fc2/t/5dcf78576d59eb44eac86f63/1573877848584/humlumJMP.pdf			

Annex 2 Bilateral trade in industrial robots, 2017

Table A3: Bilateral trade in industrial robots in 2017, EU-28 MS and six main trade partners (Million of 2017 US Dollars)

	AUT	BEL	BGR	CYP	CZE	DEU	DNK	ESP	EST	FIN	FRA	GBR	GRC	HRV	HUN	IRL	ITA	LTU	LUX	LVA	MLT	NLD	POL	PRT	ROU	SVK	SVN	SWE	JPN	USA	CAN	KOR	CHN	AUS
AUT		1648	728		16560	47221	865	7010	40	586	2876	3260	685	176	5428	140	4948	649	23	25	465	1169	10371	2180	5293	2034	738	1631	226	20381	1097	3633	10175	52
BEL	138		579		552	10915	180	393	41	61	4874	1342	35		826	59	828	7	6954			12704	106	5	171	5		974	79	311	6	1	602	4
BGR																	332					22					471		61	3404		31	930	
CYP																																		
CZE			70			5925		52				23			495								216			1686		7	29	1664		43	221	69
DEU	65837	16899	3127		41080		4509	33028	181	1603	24685	26866	283	490	51450	6822	51984	2090	2565	537	3521	9813	20513	5327	6738	8229	2466	7741	4056	149278	6066	11686	154929	3976
DNK	1621	60	161		2874	26894		6627	110	1082	9992	3368	84	25	2806	632	5124	283		164		3680	2641	948	913	331	799	8077	8028	43406	3387	4163	17991	1661
ESP	225	144	52		4862	8274	65		1	79	5834	1738	193	2	1929	64	1568	66	18	13		2328	4814	2994	1871	0	696	44	41	3732	2478	98	4907	875
EST										129										29								139		182				
FIN		242				3044	2368		96		1926	92					390					22			226			401	849	16380	1243		7881	8
FRA	4111	4772	42	8	7165	78211	425	19620	138	609		8094	3	0	1141	161	15303		365			2643	6178	2953	6771	5578	1510	818	1332	45683	3532	2593	44993	650
GBR	210	677	133		141	8545	1044	715	83	136	935		62	2	459	2927	685	46	26	40		1841	170	79	747	143	83	905	2108	32664	898	233	2676	399
GRC			18								169					249																		
HRV	189					10308									158		8									3	11							
HUN	12104		14		18	759		222			44					24	103	23	4			53	12		1419	102			19	112			144	
IRL												102													128				141	538	2		209	157
ITA	8436	40061	643		6816	25479	697	7710	240	486	23868	3915	2511	487	1788	225		423	2350	54	522	13330	21945	2557	6846	659	585	1403	84	84096	5761	690	43981	1859
LTU	34										160									690														
LUX	1282	8274	33		964	21344	33	4075		349	24961	1947	1		16630		9210	15				2366	788	93	781	138	173	420	510			5		
LVA									54														35											
MLT																																	1251	
NLD	3111	20463	496	55	2898	30889	2328	1927	48	1033	7118	7499	806	24	590	3536	11911	73	789	207	147		3996	309	2633	131	104	1495	243	7285	687	177	3805	808
POL		114			301	743		49			85	45			49	154	242					4			0	134	720	226		44	49	22	107	45
PRT	946	491			1173	1065		6493			176				406		370				291		346		19			192	53	237			232	
ROU		0	22		903	2273		76		5	1621	1			320		22											0		262			2674	
SVK					1580	161					1	160			3								507							38		20		
SVN	59				167	224	81					178		1303					19						553				16	24				
SWE	231	1549	106		965	7962	2528	2914	124	2540	7082	2682			394	29	6179	228				5127	1107	1972	677	56	267		6017	20287	4062	1581	33487	1017
JPN	2698	72			1384	77183	9	188	38	12	700	9627			1833	753	1920		###		15	12337	3090		540	401		19571		545266	38966	205316	674839	2294
USA	807	6673	119		827	32603	859	1482	35	21	5351	6932			3217	1234	1022	83				831	337		1995	7751	334	471	13881		62867	11085	27565	2307
CAN		118			82	1700	27	270	13	23	2589	831	22	51		51	279	115				276		158		35	232	106	1102	48843		280	4608	2007
KOR	23	3			4119	483	1006	45			221	176					1755	2	3			0	694	54		3476			2016	17842	66		99021	47
CHN	205	516	106	2	488	9140	270	1914	62	519	1869	1216	3	4	270	74	8330			44	5	1376	528	118	42		39	1234	5894	16064	3182	49044		3947
AUS	6					371	100				84											30						74	511	1160	36		164	

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