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Analysis exploring risks and opportunities linked to the use of collaborative industrial robots in Europe

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Analysis exploring risks and opportunities linked to the use of collaborative industrial robots in Europe

Robotics was one of the cornerstones of the third industrial revolution. Today, it is an established technology with an almost continuously growing market. In recent years, 'collaborative robots' or 'cobots', which allow human-robot interaction – even with physical contact – have burst onto the scene. The EU has led the development of this technology as one of the keys to Industry 4.0.

Although the growth of collaborative robotics has been spectacular in recent years, it is still a very small part of robotics. The installation of robotics is closely related to business development, with increases in productivity and accuracy. It is therefore relevant to explore this link further to highlight the potential gains for European companies and society that comes with a positive development in the robotics industry and the use of robots and/or cobots in European companies.

This study analyses the current state of collaborative robotics by exploring the risks and opportunities of this technology and possible options for harnessing the benefits and tackling the risks associated with the increasing deployment of these technologies in EU industry.

AUTHOR

This study has been written by Ernesto Gambao (Universidad Politécnica de Madrid/UPM) at the request of the Panel for the Future of Science and Technology (STOA) and managed by the Scientific Foresight Unit, within the Directorate-General for Parliamentary Research Services (EPRS) of the Secretariat of the European Parliament.

ADMINISTRATOR RESPONSIBLE

Andrés García Higuera, Scientific Foresight Unit (STOA)

To contact the publisher, please e-mail stoa@ep.europa.eu

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Executive summary

Introduction

Robot applications, including 'collaborative robots' (or 'cobots'), designed to collaborate with humans, are in high demand, and their sales and installation figures are constantly on the rise. According to the International Federation of Robotics, the operational stock of industrial robots reached 3.5 million units worldwide in 2021, an increase of 15 % compared to 2020. The global installation of robots increased to a new record level of 517 385 units, growing by 31 % in 2021, with an increase of 31 % in the US and 38 % in Asia, while its growth rate in Europe was 24 %. **Although the collaborative robot market is still a small part (7.5 %) of the total industrial robot market, its growth is higher** (50 % in 2021). **Europe and North America accounted for the largest market share, and most key players in the global cobot market are European companies**. However, they are in danger of being surpassed by the Asia-Pacific region in the coming years. What these figures mean for the overall comparative growth and job creation in Europe is only vaguely explored in the existing literature. The installation of robotics is closely related to development, increases in productivity, and accuracy, with positive gains for businesses. Therefore, it is relevant to explore this link further to highlight the potential gains for European companies and society that comes with a positive development in the robotics industry and the use of robots/cobots in European companies.

Although work has already been done on aspects closely related to this proposal, there is a real need to conduct further research to explore the policy and procedural translation of this work into practical, applicable requirements for the specific question of efficiency and safety of robotic applications. This applies especially to the case of collaborative robots interacting with humans in the workplace.

This study analyses the risks and opportunities of collaborative robotics technology from a scientific and technological perspective. It has been developed based on analysis of existing literature and references, existing legislative work, and information provided by relevant actors through personal interviews and a survey. **It identifies benefits and weaknesses, analyses possible impacts and outcomes, and provides evidence for the development of policy-options to enable the EU to take advantage of benefits and tackle risks associated with the increased deployment of robotic technologies in the EU industry**.

Collaborative robots versus robots

Robotics was one of the main drivers of the third industrial revolution by providing new automation solutions. At present, industrial robotics grows at a practically constant speed and has been strengthened in the manufacturing industry. In traditional robotics, robots work isolated from humans, separated by fences or electronic detection systems. In recent years, a new type of robotics, called collaborative robotics, has broken into the scene, allowing the elimination of human-robot physical separation and even direct collaboration between them. **Therefore, the objective of collaborative robotics is to combine the current capabilities provided by robotics, such as effort and precision capacity, with the inherent human skills to make decisions and solve complex problems in inaccurate tasks**. That is, **the robot does not replace the human but complements and improves his/her abilities while avoiding heavy and repetitive work**. Collaborative robotics is among the main drivers of Industry 4.0 and **Europe is presently a global leader in the supply of Industry 4.0 technology, as well as a leader in its implementation**.
Collaborative robots or cobots have several advantages over traditional industrial robots such as greater flexibility, lower cost, and simplification of the installation, commissioning, and reallocation processes. However, their **capacity to interact with humans implies the need to reduce to the**

maximum or eliminate the possible risks of causing harm to them. For this reason, collaborative robots have less capacity to make efforts or transport loads, lower working range, and lower speed than traditional robots. This limits their use, making them unsuitable when a high volume of production is required or when a high load capacity or a long reach is needed. Although easier to carry out, a risk analysis is still required.

In the literature, different levels of human-robot collaboration have been defined, from the simple co-existence with no shared workspace to the responsive collaboration. **Not all collaboration levels take full advantage of the benefits of collaborative robots, and today most current collaborative applications are at low collaboration levels, where real physical contact between the robot and the human is not envisaged**. Moreover, many current applications using cobots do not allow any real sharing of the workspace at all, and, in this case, collaborative robots are used in the same way as traditional industrial robots. One of the main reasons is that not many applications were originally conceived to be collaborative.

Currently, collaborative robotics is present in many sectors of industrial production, such as the electronic sector of the automotive industry sector. The growth prospects are very positive. In particular, **industrial sectors that need high-mix low-volume productions can take advantage of this technology**. In those robots that are outside industrial automation applications, called service robots, collaborative robots also have great application possibilities in sectors such as healthcare, hospitality, inspection, and construction.

Impacts and policy options

Collaborative robotics implies an important change in the paradigm of human-robot interaction. The possibility of collaborative work between machines and workers implies a series of important impacts in labour, economic, social, and ethical aspects. According to the opinion of most of the experts consulted for this study, **collaborative robotics can have a very positive impact on job creation and retention, especially when used with high levels of human-robot collaboration**. **Collaborative robotics makes it easier for small and medium-sized enterprises to access robotic technology** by simplifying processes and reducing costs. **Collaborative robotics also supposes an improvement of safety in the manufacturing sector and a clear improvement of working conditions**. The experts consulted also agree that collaborative robots are more easily accepted by workers than traditional industrial robots. **This technology can improve the productivity of the manufacturing sector, increase competitiveness, and reduce production costs with a significant positive economic impact**. While the EU maintains a leadership position, this however, is threatened by the growth of other regions such as Asia-Pacific and the need to develop adequate legislation. Ethical impacts are also of great interest when humans can work together with machines. **Collaborative robotics can eliminate barriers to the integration of people with physical or mental disabilities into the labour market. Equally, it can help to eliminate limitations** of physical strength or height for certain tasks.

Based on the above, this study proposes four policy options regarding the implementation of collaborative robotic technology that have been grouped into legislative and standards policies, economic policies, social and environmental policies, and ethical and gender policies.

- **Policy option 1: Human-robot interaction conditions and safety assessments need to be facilitated by developing clearer regulations that do not limit the development of collaborative robots and respect the health and well-being of workers**. Most of the experts consulted for this study agree that existing regulations and standards do not clearly contribute to the development of collaborative robotics technology. It is important to reach a compromise allowing EU companies to compete on a level playing field while ensuring the safety and wellbeing of people through agile and efficient regulation allowing for a quick adaptation to technological developments.

- **Policy option 2: The EU should maintain or even increase the budget for research activities where human-robot interaction or collaborative robotics is relevant**. The leading position of European companies in the implementation of Industry 4.0 and in particular collaborative robotics must be maintained through adequate investment in the most relevant aspects of research in this technology. The EU makes a significant effort in funding research activities that must be maintained or increased to improve the capabilities of collaborative robots and give European companies a competitive advantage. Additionally, collaborative robots can represent an important advance in service robotics in key sectors for a Europe that has an ageing population.

- **Policy option 3: There is a need to encourage the development of policies to support the creation of new real applications using high levels of interaction by promoting the training of all relevant actors in this technology**. The number of applications in which the advantages of collaborative robotics are actually exploited is insufficient. Additionally, knowledge of this technology in industry needs to be improved. Training of workers would also contribute to increase worker's acceptance and minimise the risks of human-robot collaboration.

- **Policy option 4: There is a need for policies that promote ethical assessments to ensure safe human-robot collaboration, acceptance by the worker, and privacy**. Although considerable effort has been made to assess and reduce the potential risks of human-robot collaboration, in most cases, this effort has been limited to the study of possible damage caused by a collision between the operator and the robot. However, a much more comprehensive ethical analysis is needed, including other fundamental aspects such as acceptability, ergonomic aspects, privacy, or possible mental stress that may be caused to the user.

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1. Introduction

Robotics is a mature technology that has acted as a fundamental pillar in the 'third industrial revolution'. The growth of the robot market has been almost constant over the last few years, and during the implementation of Industry 4.0 it has experienced a new impulse. This period has seen the development of collaborative robotics, where robots, instead of performing their tasks in isolation, can share their workspace with humans and even collaborate in carrying out their tasks. The EU has led the development and implementation of Industry 4.0 with collaborative robotics being one of the main drivers of this digitisation technology. Collaborative robotics allows for increased flexibility and efficiency, reducing costs, and considering workers and their working conditions as a critical aspect. Collaborative robotics can improve the capabilities of workers by reducing their physical and mental strain and by leveraging the combined capabilities of human and robot operators. However, although the growth of collaborative robotics is much faster than that of traditional industrial robotics, collaborative robots remain a niche in the global industrial robot market, representing only 7.5 % of the market (IFR, 2022). In addition, as with traditional industrial robotics, Europe's leading position in collaborative robotics is in danger of being overtaken by developments in the Asia-Pacific region.

This study, developed from a scientific and technological perspective, analyses the risks and opportunities of robotics technology and, in particular, collaborative robotics, providing evidence for the development of policy options to enable the EU to achieve the best economic and social development outcomes. Particular emphasis is placed on the safety and working conditions aspects of implementing a technology that enables collaboration between workers and robots. The study identifies benefits and weaknesses, assesses risks, and recommends solutions based on an analysis of the key impacts of this technology. The study has taken into account the position of the most relevant stakeholders through personal interviews and a survey.

1.1. Objectives of the study

The overall objective of the study is to provide evidence for policy-making on the risks and opportunities linked to the use of industrial robots and, in particular, collaborative robots (cobots) in Europe, whose relevance to the work of the European Parliament is evident in the current international context. The study focuses on the definition of industrial robot according to ISO 8373:2012.[1] The standard explicitly states that 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'. Classification as an industrial or service robot is done according to its intended application. Industrial robots are robots 'for use in industrial automation applications', while a service robot 'performs useful tasks for humans or equipment excluding industrial automation applications'. Therefore, the study focuses on robots and specifically collaborative robots that are used in industrial applications such as painting, assembling, welding, handling, grinding, or packaging, and also considering the development of applications in service robotics. In 2021, the European operational stock of industrial robots was computed at 678 706 units.[2] Europe accounts for nearly 19.3 % of the total global sales of industrial robots and is the leading continent for the number of robots per 10 000 employees. However, in recent years, Asia has seen the strongest growth in the robot market, with China leading the way (IFR, 2022).

The study has been developed from a scientific and technological perspective, including all aspects of economic and social development, and paying special attention to workplace safety and working

[1] https://www.iso.org/standard/55890.html

[2] https://ifr.org

conditions. The aim of the study has been to identify benefits and weaknesses, assess risks, and recommend coordinated solutions and alternatives to possible disadvantages. The key impacts considered are:

- Economic, social, and environmental impacts
- Impacts on safety and working conditions
- Impacts on job creation
- Ethical impacts
- Knowledge management

The analysis has been accomplished based on the literature related to different aspects of the increasing deployment and current state of play of robots and specifically collaborative robots in industry, and the existing related legislative files and standards. The STEEPED[3] approach has been used to help ensure that this technology-related topic is investigated over the most extensive ('360-degree') range of perspectives. However, the study avoids previous discussions and focuses on the efficiency and safety aspects of industrial collaborative robots, identifying weaknesses and paying special attention to the situations where possible contacts between humans and the robot are possible.

Risks associated with the deployment and use of robots and cobots in industry that have been evidenced in accidents and working conditions for European workers have been explored. On the other hand, the analysis reviews the current potential of robotic and cobotics systems, identifying and quantifying the opportunities related to economic growth, job creation and retention, and other socio-economic and environmental benefits related to the use of robots and cobots in European industry. The study has taken all possible stakeholders into account, including a list of key relevant actors: scientists, industry, end users, policy makers, non-governmental organisations (NGOs) and any other groups and associations interested or affected.

As a result of the previous findings, the study provides a list of possible courses of policy actions. These actions are assessed for their possible impacts, including their impact on society and a wide range of possible intended and unintended impacts, as previously listed. The policy actions are grouped into the following topics:

- Legislative and standards policies.
- Economic policies.
- Social and environmental policies.
- Ethical and gender policies.

The policy options have not been developed as recommendations, but by implementing an analysis-scenario of their possible applications, assessing and describing their relative potential advantages and disadvantages. That is, the main goal of the policy options list is to provide Members of the European Parliament with a balanced and easily understandable summary of the potential impacts and outcomes of alternative policy options regarding ways to ensure the preparedness of the EU to face disruption and to maintain its industrial competitiveness and living standards in the topic of robots and cobots deployment.

[3] Evidence for policy-making

1.2. Legislative, standards and technological assessment background

On 21 April 2021, the Commission put forward a proposal for a New Regulation on Machinery Products[4], as part of a wider 'AI Package'[5]. These discussions on the Machinery Directive[6] and the AI Act[7], are already very advanced. Robots and cobots are included as part of the Machine Directive. The proposal on machinery products addresses a number of problems identified in the current EU framework: insufficient coverage of new risks stemming from new digital technologies (such as AI, IoT, and robotics); legal uncertainty concerning the scope and definitions and potential safety gaps in 'traditional' technologies; insufficient coverage for 'high-risk machines'; costs due to the required paper-based documentation; inconsistencies with other pieces of product-safety legislation; and divergences in interpretation across Member States due to transposition (hence the choice of a Regulation instead of a Directive).

STOA has performed in recent years a series of related analyses, in particular its study on the Ethical Aspects of Cyber-Physical Systems[8] (CPS) providing insights into the potential ethical concerns and related unintended impacts of the possible evolution of CPS technology by 2050. The outcome of the study was reflected in a policy briefing for Members of the European Parliament[9] describing legal instruments to anticipate the impacts of future developments in the area of cyber-physical systems, such as intelligent robotics systems, linked with the Internet of Things.

The International Organization for Standardization (ISO), a worldwide federation of national standards bodies, provides a number of standards and technical specifications on robots and collaborative robots. The normative on robots was prepared by the SO Technical Committee 299 (ISO/TC 299) under the title 'Robotics'.[10] Since 2016, there is a specific standard for collaborative robots, ISO/TS 15066:2016[11], that specifies safety requirements for collaborative industrial robot systems and the work environment supplementing the requirements and guidance on collaborative industrial robot operation given in ISO 10218-1 and ISO 10218-2.

The most important documents in relation to safety are the following:

- ISO 10218-1:2011 Robots and robotic devices -- Safety requirements for industrial robots -- Part 1: Robots.
- ISO 10218-2:2011 Robots and robotic devices -- Safety requirements for industrial robots -- Part 2: Robot systems and integration.
- ISO/TS 15066:2016 Robots and robotic devices -- Collaborative robots.
- ISO/DTR 20218-1 Robots and robotic devices -- Safety requirements for industrial robots -- Part 1: Industrial robot system end of arm tooling.
- ISO/PRF TR 20218-2 Robots and robotic devices -- Safety requirements for industrial robots -- Part 2: Industrial robot system manual load stations.
- ISO 12100 Safety of machinery – General principles for design – Risk assessment and risk reduction.
- ISO 13850 Safety of machinery – Emergency stop function – Principles for design

[4] New Regulation on Machinery Products

[5] Artificial Intelligence Package

[6] Machine Directive

[7] AI Act

[8] Ethical aspects of Cyber-Physical Systems (STOA)

[9] Legal and ethical reflections concerning robotics (STOA Policy Briefing)

[10] https://www.iso.org/committee/5915511/x/catalogue/

[11] https://www.iso.org/standard/62996.html

- ISO 13855 Safety of machinery – Positioning of safeguards with respect to the approach speeds of parts of the human body.
- IEC 60204-1 Safety of machinery – Electrical equipment of machines – Part 1: General requirements.

Although previous work has already been done on aspects closely related to the topic, the objective of the study intends to cover the real need to conduct further research to explore the policy and procedural translation of this work into practical, applicable requirements for the specific question of efficiency and safety of robotic and cobotics applications. This applies especially to the case of collaborative robots that interact with humans in the workplace. Therefore, the study analyses this specific question and avoids the repetition of previous discussions.

2. Methodology and resources used

2.1. General methodology and resources

The methodology used for the development of the study has been based on the use of the following tools:

- Analysis of the existing literature, references, and accessible data
- Analysis of existing legislative files in the EU and existing standards
- Analysis of documented case studies
- Analysis of the information provided by relevant actors in robotics and, in particular, collaborative robotics through the use of personal interviews and a survey[12]

Based on the study of the existing literature, references, relevant use cases and accessible data, the analysis assesses the most relevant characteristics of robotics technology and, in particular, collaborative robotics technology to provide evidence for policy-making in this subject. The study will be relevant to ongoing legislative work on the Machinery Directive and the AI Act, specifically to legislative work related to future regulation of robots and cobots. The study will also be relevant in a broader debate about automation and robotics in Europe. The analysis concerns the digital domain with a focus on robots and cobots, and legislative work in the following Parliamentary Committees: 'European Parliament's Internal Market and Consumers' (IMCO) and 'Industry, Research and Energy' (ITRE). Relevant existing standards and technical specifications on robots and collaborative robots provided by the International Organization for Standardization (ISO) have been studied.

The efficiency of the application of this technology to industrial automation has been explored on the basis of case studies and information provided by relevant stakeholders. The analysis assesses the existing accident risks in the use of robots and cobots in industrial workplaces and how the deployment of this technology affects the safety and working conditions of European workers. The study also identifies and quantifies opportunities related to effects on economic growth, job creation, job maintenance, and other potential socioeconomic benefits. Other important outcomes and impacts, such as environmental, ethical, gender, or safety, have also been explored.

The current state of the market for cobots for different applications has been studied in relation to the market for industrial robots in the EU. This allows to assess the current position of the EU in the use of this technology, where Europe accounted for the largest market share (Bogue, 2016, IFR 2022), but is in danger of being surpassed by the Asia-Pacific region in the following years.

The study reviews the current potential of robotic and cobotic systems, assessing weaknesses, benefits, and disadvantages associated with the use of robotic technologies in the industrial production sector, especially where these systems are expected to work in collaboration with humans. Other key factors such as the role of Artificial Intelligence in collaborative robotics, ethics in the application of this technology, gender issues or intellectual property rights protection, and open robotics have been addressed. As a conclusion of the state of play study, future trends in collaborative robotics are presented.

The STEEPED approach has been used in the preparation of the study to help ensure that this technology-related topic is investigated over the most extensive ('360-degree') range of perspectives.

[12] The survey has been distributed to relevant people in academia and science, robot manufacturers and end users.

Finally, the study explores the challenges, possible evolution of the market, and options to harness the benefits associated with the increased deployment of robotic and cobotic technologies, listing possible courses for policy actions and their impacts, and describing possible benefits and disadvantages. The policy options have been grouped into legislative and standard policies, economic policies, social and environmental policies, and ethical and gender policies.

2.2. Questionnaire on collaborative robots in Europe

In order to support the study's decisions, a survey was sent to the most relevant stakeholders in collaborative robotic technology including academics, researchers, cobot manufacturers, and end users. The questions included a selection of answers and a free text box for possible comments. Participants were asked if they wanted to be included in a list of contributors that will be included in an appendix to the final version of the study.

The survey contained the following questions:

Collaborative robots (cobots) versus traditional industrial robots

Comparing the features of cobots with traditional industrial robots, indicate your agreement or disagreement with the following statements (1 totally disagree/5 totally agree):

- Collaborative robots allow for easier risk analysis
- Collaborative robots are easier to program than traditional industrial robots
- Collaborative robots are more easily accepted by workers than traditional industrial robots
- The cost of acquisition, installation and use of collaborative robots is lower than that of traditional industrial robots
- Collaborative robots are more efficient than traditional industrial robots
- Collaborative robots are easier to reallocate and are more adaptable to frequent task changes than traditional industrial robots
- Collaborative robots can help automate applications that cannot be automated with traditional industrial robots
- When the human operator cannot be replaced by a traditional robot, collaborative robots can improve ergonomics and working conditions
- Collaborative robots are only useful for a limited number of applications where high speed, high precision, or high force are not required and where the working range is small.
- Collaborative robots are less reliable than traditional industrial robots

Risks

Human-robot collaboration is a source of potential risk due to possible accidents. Rate the usefulness of the following measures used in collaborative robots to prevent accidents (1 not at all useful/5 very useful):

- Reduction of the maximum robot speed
- Reduction of the maximum force exerted by the robot
- Design of the robot to avoid or minimize damage in the event of contact with a human
- Configurable stopping time & stopping distance
- Proximity detection system (using machine vision, the system detected the presence of a person and acted, e.g., by slowing down movement or by stopping altogether).
- Collision detection system (mechanical detection of collision, through force or torque sensing in the robot joints, and subsequent reaction to that collision)

- Projection-based space monitoring system (safety system by means of which a safety zone around the immediate area of influence of the robot is monitored and any external intrusions in that area will cause the movement to slow down or stop)
- Variable stiffness in actuators (through the mechanical design, the stiffness of the actuators in each join could be adjusted according to programmed rules, transitioning from a mechanically rigid robot to a low stiffness one that would give in when, e.g., colliding with a person)

Regarding human-robot collaboration using collaborative robots, indicate your agreement or disagreement with the following statements (1 totally disagree/5 totally agree):

- Collaborative robots are completely safe for human-robot interaction even when contacts are possible
- Collaborative robots still need more advanced sensor capabilities to allow a completely safe human-robot interaction
- Tasks where contact between the human and the robot is possible exposed human operators to additional stress

Market trends for industrial and collaborative robots

There are still important barriers that prevent the adoption of collaborative robots. Indicate the importance of the following possible barriers in order to prevent the use of cobots (1 not very important/5 very important).

- Safety is not guaranteed
- Legislation and standards are still not completely developed
- Costs are still very high
- There is a lack of knowledge about collaborative robots in the industry
- Worker's acceptance is still very low

Regarding the market evolution for robots in the following five years, please indicate your agreement or disagreement with the following statements (1 totally disagree/5 totally agree):

- During the last 5 years the installations of industrial robots worldwide have maintained a growth rate of around 11%. Industrial robot installations around the world will maintain a growth rate of more than 10% per year
- In 2021, 74% of all newly deployed robots were installed in Asia (2020: 70%) and only 16% in Europe. The growth of the industrial robot market will continue to be higher in Asia than in Europe
- Due to measures such as relocation, the differences in growth of the industrial robot market in Europe compared to Asia will become smaller and smaller
- In 2021, collaborative robots accounted for 7.5% of the total robotics market, but their growth was 50%. The growth of the collaborative robotics market will continue to be higher than that of the industrial robot market
- Europe and North America accounted for the largest collaborative robots market share; however, they will be surpassed by the Asia-Pacific region in the upcoming years

Impacts:

Rate the impact of collaborative robotic technology in the EU in the following aspects (1 very negative impact/5 very positive impact)

- Job creation
- Job retention
- Productivity of the manufacturing sector
- Productivity of Small and Medium-sized Enterprises

- Competitiveness of the manufacturing sector
- Reduction of the production cost of the manufacturing sector
- Improvement of safety of the manufacturing sector
- Improvement of working conditions in the manufacturing sector
- Elimination of barriers for the incorporation of less physically gifted workers to the manufacturing sector
- Reduction of the carbon footprint of the manufacturing sector

Finally, the survey included free space for possible additional comment.

3. Synthesis of the research work and findings

3.1. Collaborative robots versus robots

The main objective of Industry 4.0 is the digitalization of industrial procedures, increasing flexibility and efficiency, reducing costs, and considering working conditions and especially ergonomics of workers as a critical aspect (Ustundan et al., 2018). Collaborative robotics is one of the main drivers of Industry 4.0 along with additive manufacturing, cyber physical systems, augmented reality, cloud computing, and big data (Villani et al., 2018; Kadir et al., 2018). Europe is presently a global leader in the supply of Industry 4.0 technology, as well as a leader in its implementation (Davies, 2015). The Vision Report of the Industry 2030 High-Level Industrial Roundtable also positions the European industry as a global leader that will responsibly deliver value to society, the environment, and the economy (European Commission, 2019). Intelligent machines based on human-machine dynamism provide an opportunity to enhance human labour with new robots and AI tools instead of substituting human labour with robots (Vanderborght, 2020). Collaborative robotic technology is considered one of the 12 potentially economically disruptive technologies that will transform life, business, and the global economy.

3.1.1. Benefits of collaborative robots

The objective of collaborative robots is to combine the repetitive performance of industrial robots with the individual skills and ability inherent to humans. Although robots exhibit precision, endurance, and power; humans have an excellent ability to solve complex problems and make decisions, especially in imprecise exercises. Therefore, collaborative robots assist the human operator: **The machine does not replace the human, but complements her/his capabilities and relieves him of arduous tasks**.

To achieve safety, robotic applications traditionally exclude operator access to the operation area while the robot is active, by installing fences, light curtains, or other sensors that prevent the presence of a human. Therefore, tasks that require worker intervention often cannot be automated using robots. Collaborative robots open the possibility of optimal human-robot collaboration, without separation and without barriers, and in this way it is possible to automate new applications. However, **in tasks where a robot and a human share the same workspace, the integrity of the safety-related control system is of major importance**, particularly when process parameters such as speed and force are being controlled. Therefore, a comprehensive risk assessment is required to assess not only the robot system itself, but also the environment in which it is placed and especially the potential operator in it (Adriaensen et al., 2021; Pauliková et al., 2021). When implementing applications in which humans and robots collaborate, **ergonomic benefits are also critical**.

The **main advantages of this concept of human-robot collaboration** implemented in cobots are the following.

- Maximum flexibility in production
- Avoids ergonomically poor positioning of tasks
- Reduced risks for operators implementing:
  - Sensors that allow them to stop in case of obstruction
  - Lightweight robots
  - Adequate design
- Improved process quality
- Ease of installation and programming
- Increased productivity

Figure 1 shows a comparison of the applicability of traditional industrial robots versus collaborative robots. Consequently, collaborative robots have helped to lower important barriers that have prevented the use of traditional industrial robots in many applications, and, in particular, the use of this technology in small and medium-sized enterprises (SMEs). Robots that are easy to install, program, and use and that are intrinsically safe for workers **favour the introduction of this technology in small and medium enterprises** that typically do not have qualified personnel for these tasks and, on many occasions, perform batch production that requires constant changes in the programs and even in the configuration of the machines. The introduction of collaborative robotic technology in SMEs can therefore **improve the quality of industrial production, increase the throughput of smaller batches, and improve working conditions**. SMEs are a very significant part of the European production sector. Among the 82.239 enterprises registered in the machinery sector, only 1.703 (2%) are large companies, while 81.024 (98%) are SMEs [13]. Although the sector has important large players, SMEs are its main driving force. On the other hand, the assertion of **complementing the human operator rather than replacing him or her can also have a significant influence on maintaining employment, giving this technology a friendly image in the eyes of society**.

Collaborative robots are also good drivers for the introduction of **new business models** called '*robots-as-a-service*', where the buyer is paying for the use of the physical device through a subscription-based contract, and '*pay-as-you-use*', a payment model in cloud computing that charges based on resource usage.

Figure 1: Traditional industrial robots versus collaborative robots

If you need...	...consider a traditional industrial robot	...consider a collaborative robot ("cobot")
High-volume, high-speed production	☑	☐
Similar throughput as a human worker	☐	☑
High payload or very long reach, especially at high speed	☑	☐
Ability to program and set robot up in-house	☐	☑
Ability to easily redeploy robot to different processes/tasks	☐	☑
Extremely high accuracy, including at high speed	☑	☐
Minimal changes to existing production layout	☐	☑
Human workers to enter the robot cell to complete their tasks	☐	☑
Integration options with other machines and robots	☑	☑
Low initial cost and payback in under a year	☐	☑
Ability to run processes with few or no employees	☑	☑
Automation of processes or products that won't change over time	☑	☑

Source: Universal Robots.

[13] https://ec.europa.eu/docsroom/documents/45508/attachments/4/translations/en/renditions/native

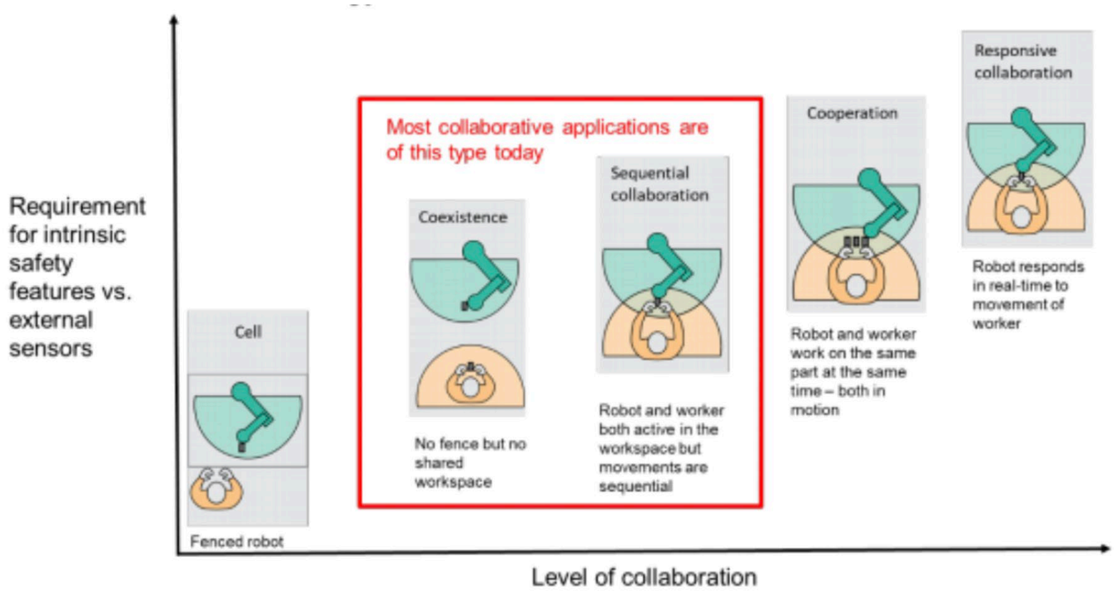
3.1.2. Human-robot collaboration

There are different types of human-robot collaboration, as shown in Figure 2. Of course, not all possibilities take full advantage of the benefits of collaborative robots and do not have the same safety and risk assessment requirements. **Today, most current collaborative applications are of the type 'co-existence' or 'sequential collaboration', where a real contact between the robot and the human is not foreseen**. Moreover, many current applications using cobots do not allow any real sharing of the workspace at all, and, in this case, collaborative robots are used in the same way as traditional industrial robots but taking advantage of other benefits such as low cost, light weight, easy commissioning and programming, etc. Therefore, **the claim of complementing the human operator rather than replacing it is not completely applicable to all existing cobots in operation**.

Figure 3 shows the increase in productivity and speed with different types of workspace sharing between humans and robots when using collaborative robots. Situations where contact between a human and the robot is possible while the robot is moving are still very rare.

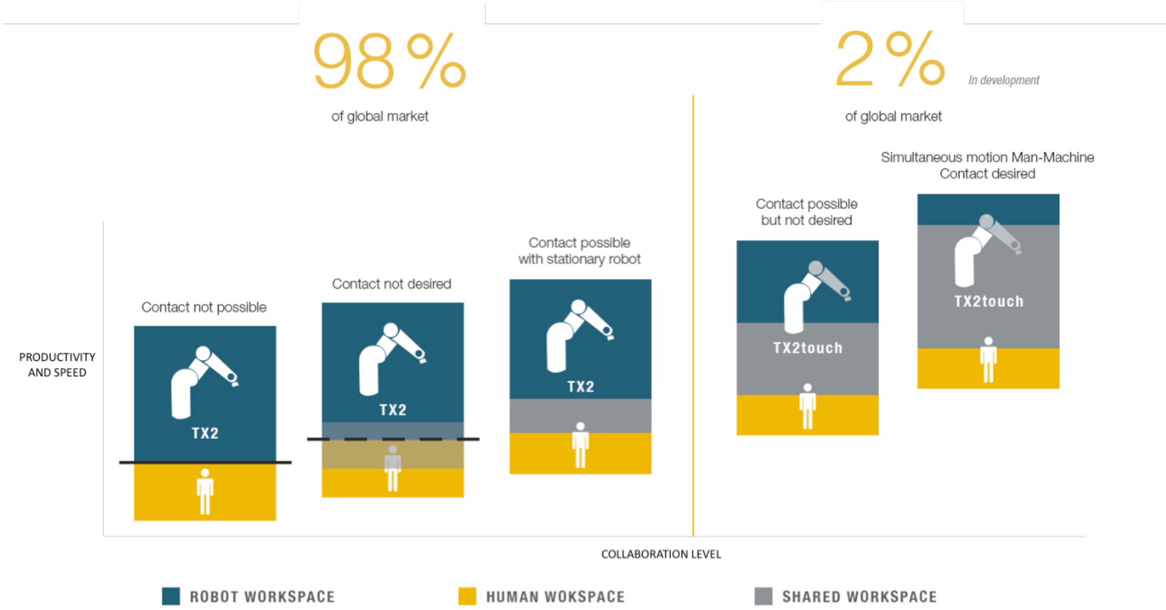
Wearable robotics or exoskeletons are a more extreme form of collaborative robots in which the robot is worn on the body. Several new companies have been created in Europe during the last years for applications in manufacturing such as Exhauss, Marsi Bionics, RB3D, Ottobock, Laevo, Noonee, Skelex, and German Bionic. There are also European robotics manufacturers, such as Comau, that produce this kind of devices. This market is still very new.

Figure 2: Types of collaboration with industrial robots



Source: IFR, based on Bauer et al (2016).

Figure 3: Collaboration level when using collaborative robots



Source: Stäubli

3.1.3. The growth of collaborative robots. Situation in Europe

Market for industrial robots

According to statistics from the International Federation of Robotics (IFR), global robot installations reached a new record of 517,385 units in 2021 (see Figure 4). This represented a growth rate of 31% over 2020 and exceeded the previous record level of 423,321 units achieved in 2018 by 22% (IFR, 2022). In 2021, the operational stock of industrial robots was computed at 3,477,127 units (+15%). Since 2016, the operational stock of industrial robots has been increasing by 14% on average each year. The European operational stock of robots was computed at 678,706 units. **Europe is the second largest market after Asia**. Robot installations in Europe were up 24% to 84,302 units, and the annual average growth rate from 2016 to 2021 was +8%. Installation counts in Germany, the largest European market and the only European one in the global top five, gained 6% to 23,777 units. In contrast, installations in the second largest European market, Italy, skyrocketed by 65% to 14,083 units. The third largest European market, France, gained 11%, installing 5,945 units. In Spain, the fourth largest robot market in Europe, installations remained steady at 3,423 units (+1%) in 2021.

Market for collaborative robots

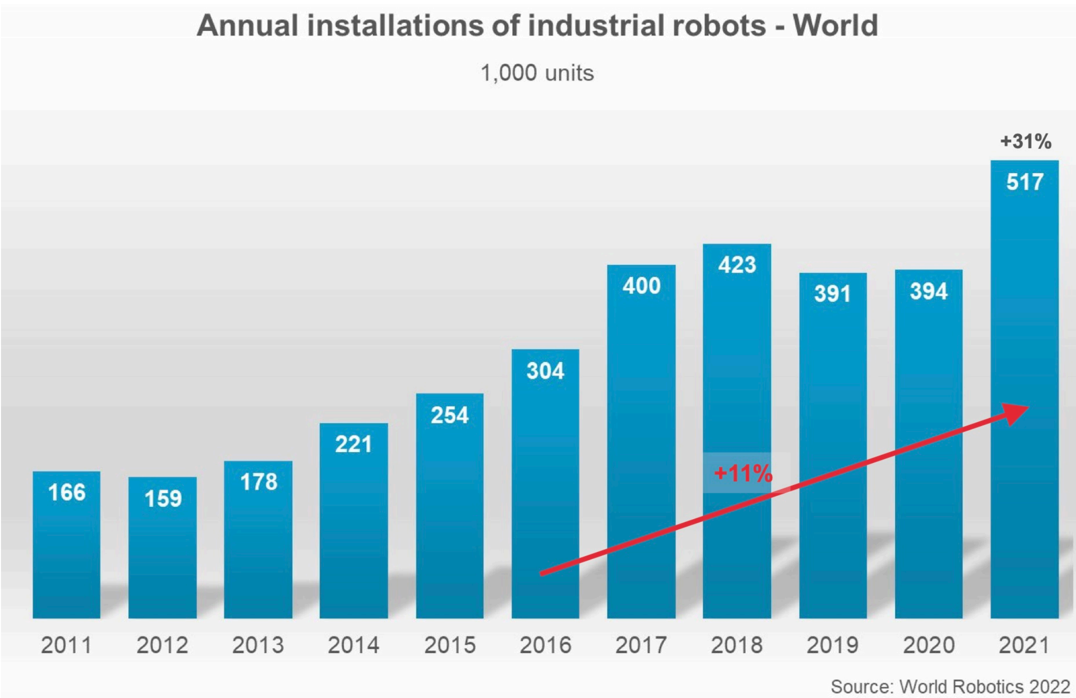
Collaborative robots have experienced significant growth in recent years and have become one of the fastest growing sectors of the robotics market (Goldberg, 2019). The evolution of cobots has been remarkable in the last ten years (Fast- Berglund et al., 2016; Hentout et al., 2019; Knudsen et al., 2020). Figure 5 shows a comparison between the market for traditional industrial robots and collaborative robots in the last 5 years. The growth in 2021 was up to 50%. Several recent studies forecast cobot market growth of up to 20% and even as much as 30% annually[14]. However, currently **the cobot market represents only 7.5% of the total robotic market** (IFR, 2022).

[14] https://www.interactanalysis.com/cobot-market-set-for-annual-growth-rates-of-20-30/

Several companies have emerged in the EU in recent years, including Universal Robots, FerRobotics, Franka Emika, BioRob-Arm, F&P Robotics, and MRK Systeme. Many of these new European players specialise in cobots. The EU cobots market was worth EUR 343 million in 2019 and was expected to grow at a rate of 41% annually between 2020 and 2026 (Newsmantraa, 2022). Since the emergence of collaborative robots on the market, most European robot manufacturers have incorporated cobots in their product portfolio, including key players such as ABB, Comau, Stäubli, Festo, or Bosch. In fact, **most of the key players in the global cobots market are European companies**.

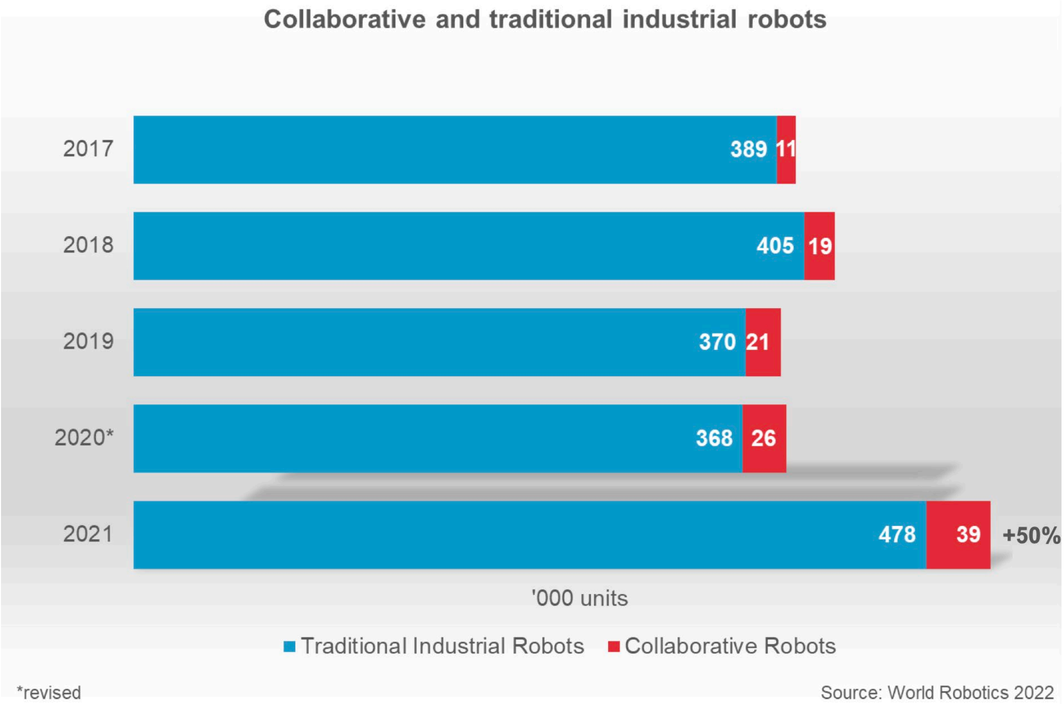
The largest player in the global market is the Danish company Universal Robots (UR), which sold the world's first commercial collaborative robot in December 2008. Currently, UR has a market share of more than 50% of the global market. This is particularly remarkable considering that 50% of global robot sales go to China (52% of total installations in 2021), where there is a clear tendency to purchase domestic products. The business volume in 2020 was US$219 million. Universal Robots was purchased by the US company Teradyne for US$285 million in 2015, but the firm remains on the initial denomination maintaining its base in Denmark.

Figure 4: Evolution of the world robot market



Source: IFR (World Robotics 2022)

Figure 5: Evolution of the world robot versus cobot market



Source: IFR (World Robotics 2022)

3.2. State of play regarding the deployment of robotic technologies for different applications in the industry of the EU

3.2.1. Industrial Automation Applications of Robotics and Cobotics

Industrial robots

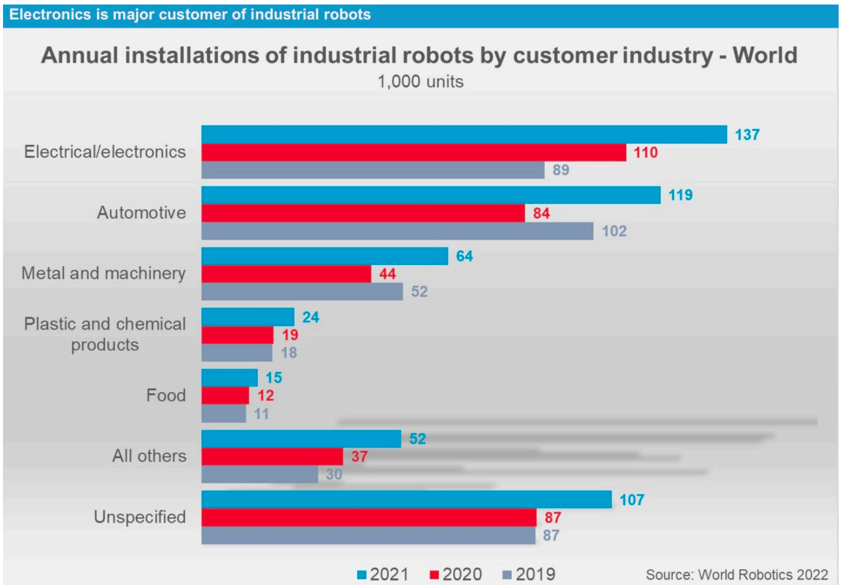
According to the IFR World Robotics 2022, the electronics industry surpassed the automotive industry in terms of annual robot installations in 2020 and maintained this position in 2021, installing 26% of all robots installed that year. Robots were installed in the production of household appliances, electrical machinery, semiconductors, solar panels, computers, telecommunication devices, and video and electronic entertainment goods (IFR, 2022). Consumer electronics demand has continuously grown over the last few years, showing that there is a limitation in production capacity that needs to be addressed.

Second is the EU's critically important automotive industry with 23% of installations, driven mainly by the parts supplier segment. The global production of cars and commercial vehicles dropped by 16% in 2020 and recovered by just 3% in 2021 (OICA, 2022). The automotive industry is involved in the transition from combustion engines to electrical engines. However, various problems, such as disruptions in supply chains due to the pandemic and legislation, have limited the expansion capacity.

The metal and machinery industry ranks third (12% of installations) just ahead of the plastic and chemical products industry (5%) and the food and beverage industry (3%).

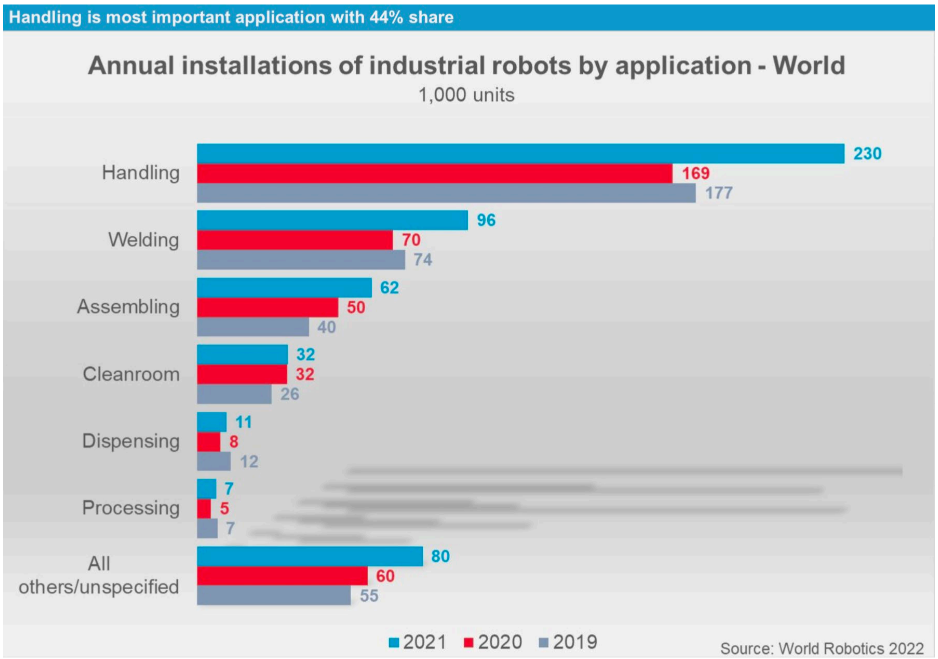
Figures 6 and 7 show the annual installations of industrial robots by customer industry and by application, respectively, in the period 2019-2021.

Figure 6: Industrial robots by customer industry



Source : IFR (World Robotics 2022)

Figure 7: Industrial robots by application



Source: IFR (World Robotics 2022)

In 2021, the average robot density in the manufacturing industry was 141 robots per 10,000 employees. **The European robot density has been growing by just 8% Compound Annual Growth Rate (CAGR)[15] since 2016 and was 129 units per 10,000 employees in 2021**. The growth in the same period was 18% CAGR in Asia (156 units per 10,000 employees in 2021) and 8% CAGR (117 units per 10,000 employees in 2021) in the Americas (IFR, 2022).

With respect to service robots, the top 5 applications in professional use are transportation and logistics, professional cleaning, medical robotics, hospitality, and agriculture. **Europe leads in the number of companies that supply service robots for professional applications**.

Collaborative robots

As we have seen, the use of collaborative robots has experimented a remarkable growth during the last years. The reasons for using collaborative robots in industrial automation are saving floor space by giving up physical separation; allocating tasks to collaborative robots that are either ergonomically or psychologically inconvenient for humans; or for increasing accuracy, speed, and repeatability beyond human capability (Adriansen et al., 2022). According to many studies (Kildal et al., 2018; Bogue, 2016; Knudsen, 2020), most collaborative robotics are used for automation applications at low level of collaboration (see Figures 2 and 3). The cobots use their ability to work with humans but not at higher levels of collaboration that included real cooperation or responsive collaboration with humans. Therefore, many cobots are used for automation purposes in ways similar to traditional industrial robots, replacing humans rather than engaging in real collaboration with them.

The reasons to use cobots at a low level of collaboration are:

- In many cases, collaborative robots are used for simple tasks
- Collaborative robots can work in many applications as a "uncaged" traditional industrial robot with lower acquisitions, installation, and commissioning costs
- Not many applications were initially conceived to be collaborative

To increase the number of applications where there is a genuine human-robot interaction, further advanced perception, human awareness or decision-making capabilities will be required (El Zaatari et al., 2019). These new applications should be conceived as collaborative from the outset and designed accordingly to use cobotics technology.

In electronics, cobots are mainly used in quality inspection of microprocessors, chips, and PCBs, increasing accuracy and efficiency and reducing potential human errors.

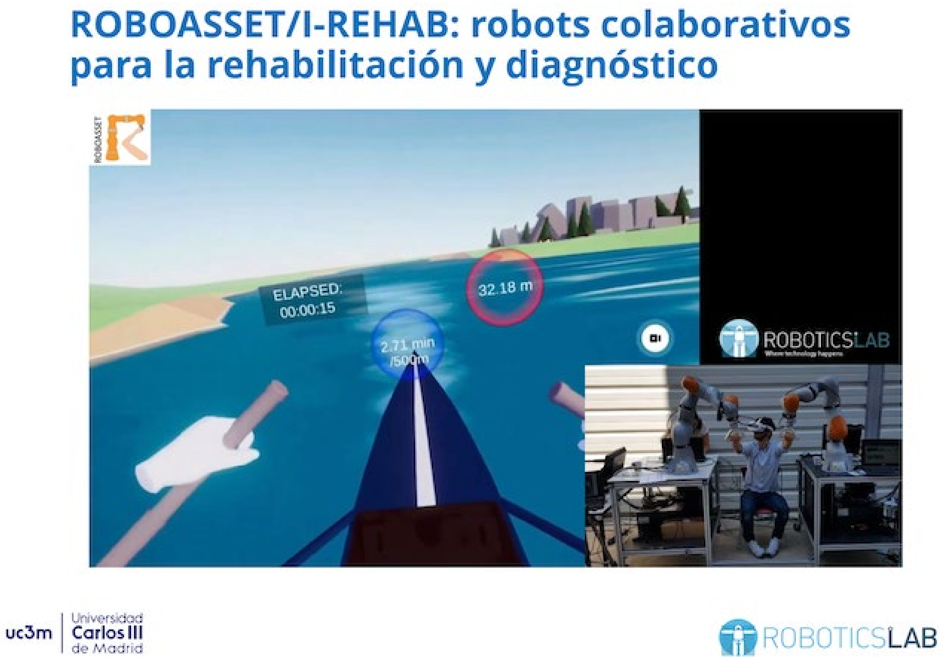
In the automotive industry, cobots are currently mainly used in car assembly and surface polishing. Several large car manufacturers, such as Mercedes, Audi, or Volkswagen, have proposed '*intelligent factories*' that introduce collaborative robots and human-robot interaction as a key driver to increase the flexibility of their production and to implement the best possible working conditions.

There are other industrial sectors that are moving to high-mix low-volume production where collaborative robotics is very useful to increase flexibility and reduce changeover times.

[15] Compound Annual Growth Rate

With respect to collaborative service robots, there are promising sectors, such as healthcare, hospitality, or construction, where cobots can help workers. Figure 8 shows an example of the use of collaborative robots in healthcare. Two KUKA LBR iiwa robots are used in rehabilitation.

Figure 8: RoboAsset rehabilitation with cobots



Source: RoboticsLab (Universidad Carlos III de Madrid)

3.2.2. Efficiency, safety and working conditions in human-robot collaboration

Risk assessment in collaborative robotics

When using robotic technologies, traditional safety-related measures are focused on keeping workers safe, separating active machinery and robots from operators. Safety is considered a major challenge in much of the literature regarding cobot systems (Chemweno et al., 2020; Lasota et al., 2017; Vicentini, 2020; Zacharaki et al., 2020). Recent updates to robot safety standards address new scenarios where humans and robots can share working space (Villani et al., 2018). The international ISO standard identifies **four collaborative modes**:

- Safety-rated monitoring stop (SMS)
- Hand guiding (HG)
- Speed and separation monitoring (SSM)
- Power and force limiting (PFL)

Progress must be made on safety issues within each of these four collaborative modes. Safety solutions must also take into account the needs of vulnerable users and recognise different skills and capabilities (Villani et al., 2018). **All human factors must be considered in the definition and design of collaborative robots, from ergonomics to worker acceptance**. In the original formulation of the cobot concept, ergonomics was considered a major point of interest. In Europe, more than 30% of workers in the manufacturing sector are affected by lower back pain (Maurice et al., 2017). **Collaborative robotics reduce physical effort at work and, therefore, can help reduce work-related musculoskeletal disorders, stress, and fatigue of operators** (Knudsen et al., 2020). **Cobots can also yield more inclusive labour markets in which ageing workers may be able to stay on for longer periods before retirement than now** (Calzavara et al., 2020).

Risk assessment in the use of collaborative robots remains a complex task. Various regulations must be consulted, and not all aspects are fully covered. For example, as highlighted by several contributors to this study, **the use of robotic tools, such as grippers or cutting tools, or the transport of potentially dangerous objects is not easy to assess**.

Robot programming and accidents

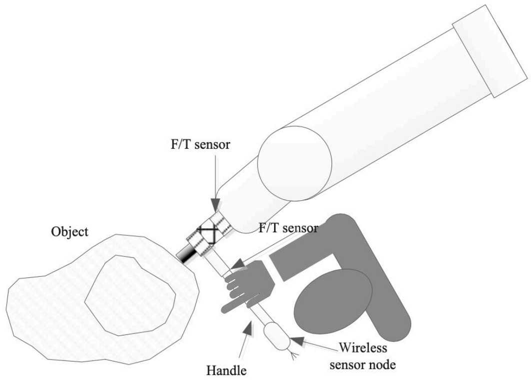
Although there is no official record of accidents caused by robots, collaborative robots report very few accidents involving humans. **No reports of serious accidents caused by collaborative robots are available**. Most accidents in traditional industrial robots occur during the programming, commissioning, or maintenance phase. However, modern programming methods have significantly reduced accidents in this phase (Brunete et al., 2016). Traditionally, industrial robots are programmed by means of guidance, moving the robot manually or by means of a teach pendant or programming palette (see Figure 9), or textually, by writing the programs on a terminal or on the teach pendant itself. Normally, both methods are combined, so guidance is used to select the spatial points through which the robot must pass, and these points are used to construct the complete program. The use of the teach pendant to guide the robot normally requires the programmer to be within the robot's field of action, and, although the speed of the movements is normally limited, there is a risk of accident at this stage or when testing the programmes carried out.

Figure 9: Teach Pendant

Source: Comau

Recently, a guided programming system known as programming by demonstration has been introduced. In this case, the robot is equipped with sensors that measure forces and/or torques, F/T sensor (see Figure 10), so that the operator can move the robot by pushing it directly or gripping it by means of an additional system. Most collaborative robots allow this type of guidance.

Figure 10: Robot programming by demonstration



Source: author and VTT Technical Research Center Finland

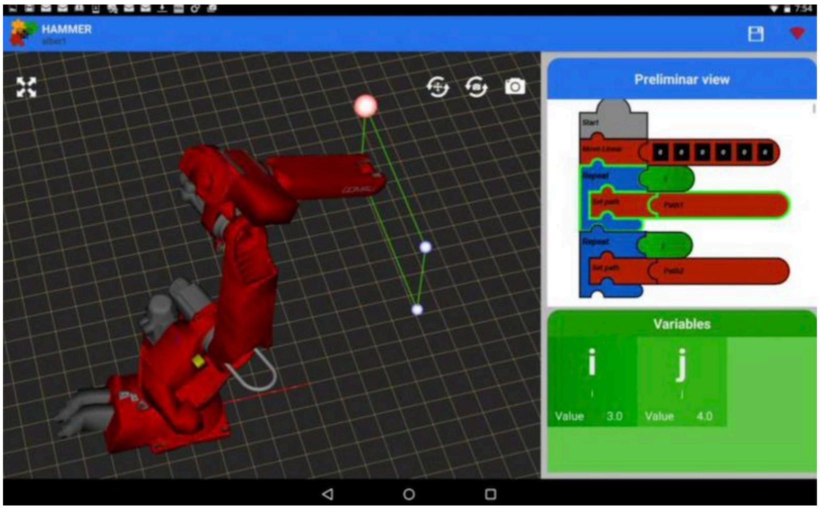
With the development of software applications, simulators, that allow the implementation of virtual programming environments, it is possible to program a robot completely off-line. The advantages of these environments are many, as the robot is not physically needed, and, therefore, the possibility of any accident is eliminated. However, it is always necessary to adapt the programmes to the real environment. Examples of software for off-line programming are RoboDK[16] or ABB RobotStudio[17].

In recent years, programming systems are being developed that include new technologies such as model-based development, scratch programming (see Figure 11), or the use of augmented reality (see Figure 12) and virtual reality (see Figure 13). These systems make it possible to implement much safer human-robot interfaces, reducing the possibility of accidents to a minimum.

[16] https://robodk.com

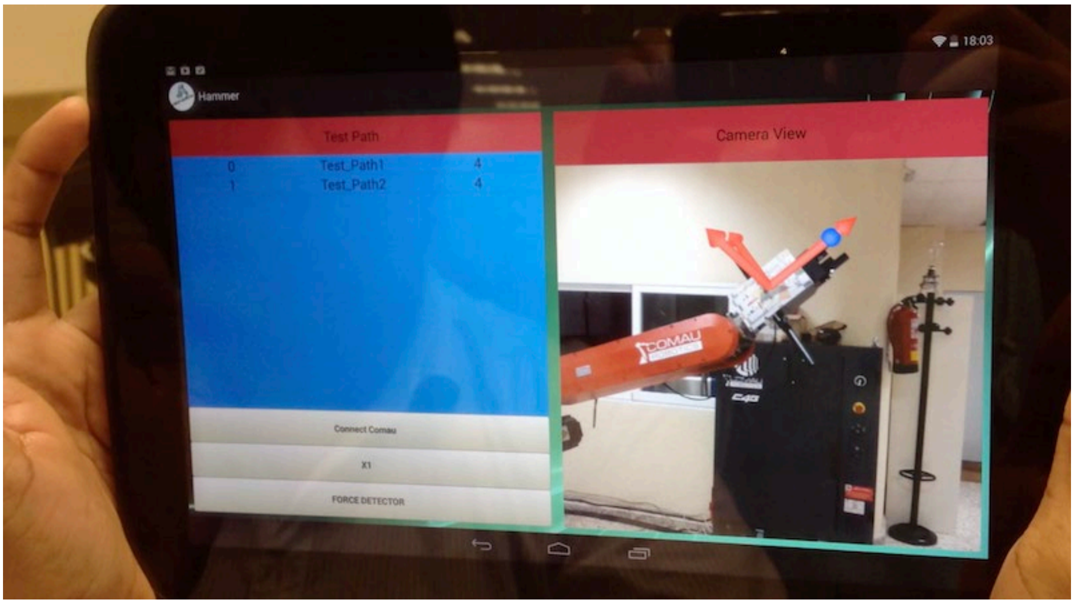
[17] https://new.abb.com/products/robotics/en/robotstudio

Figure 11: Scratch programming with a virtual environment



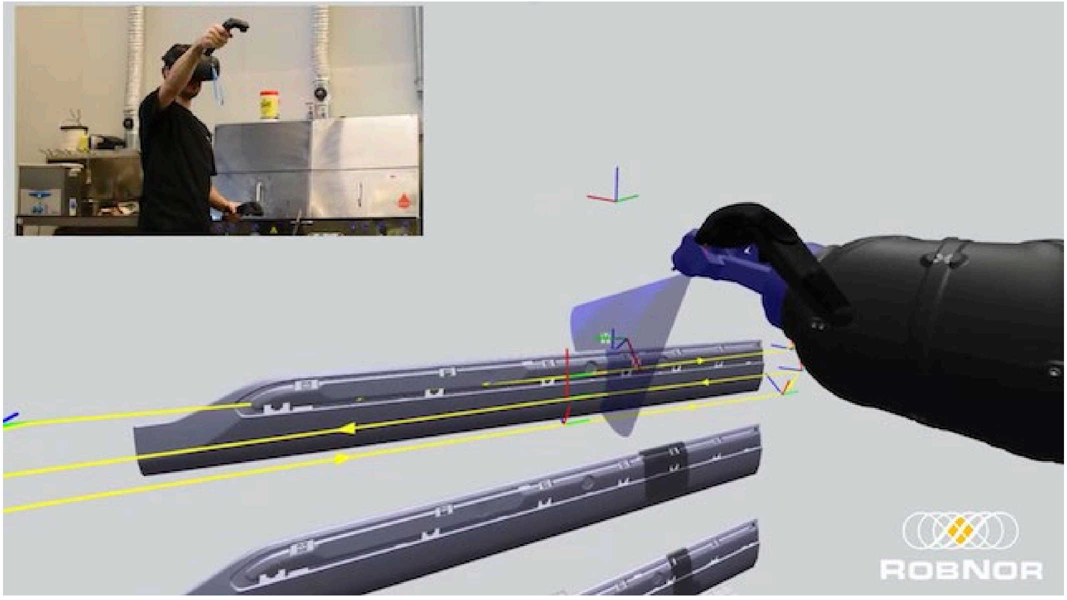
Source: author

Figure 12: Augmented reality robot programming environment



Source: author

Figure 13: Virtual reality robot programming



Source: Robnor

3.2.3. Examples of human-robot collaboration in industrial automation

Currently, most existing collaborative robots have been applied to the manufacturing sector. As with robots in general, there are virtually no limits to the applications of cobots. Over the next few years, cobots are likely to be used in healthcare, hospitality, construction, inspection, and other areas of service robotics.

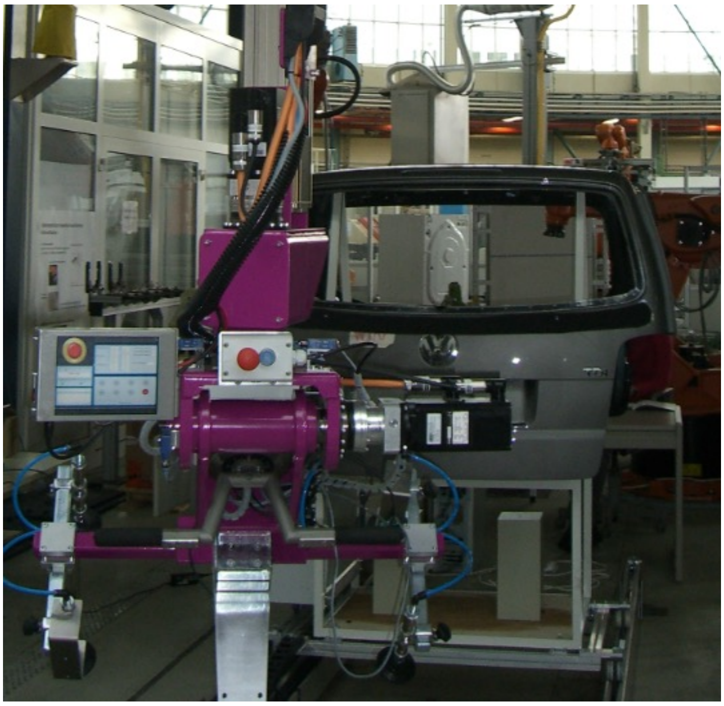
Cobots are already present in the automotive industry, during many years the largest market sector for industrial robots, in applications with at least some collaboration level. **The automotive industry can increase dramatically the application of cobots in Europe** by expanding from their principal applications, traditionally in the body-in-white areas of the factories, into the assembly areas where few robots are presently used, mainly because of the proximity of human workers (Gambao et al., 2012). In 2011 a collaborative robot prototype was tested performing the assembly of wind- screens for the Volkswagen car assembly line in Wolfsburg (Germany) (Figure 14). In 2015 Audi announced that it had installed a number of units at its main Ingolstadt (Germany) production facility on the A4, A5 and Q5 production lines (Bogue, R., 2016). KUKA partner MRK-Systeme GmbH produces the KR 5 SI robots, which have been installed at the Audi plant in Ingolstad (Germany) to improve cycle time and operator ergonomics and reduce the likelihood of injury when handling coolant expansion tanks. The cobots pick up the components and pass them to the assembly workers. These robots have also been installed for adhesive application in the body shop in direct contact with humans [18]. In 2022 a Comau Aura collaborative robot was installed in a Ford factory in the production of the fully electric F-150 Lightning pick-up truck. The robot is used to calibrate the vehicle's on-board scale by applying a predefined payload while allowing aggressive cycle times [19]. As another clear example of improved ergonomics, KUKA, in cooperation with Dürr, installed a

[18] https://www.mrk-systeme.de/produkt/anwendungsbeispiele-safeinteraction-kr-5-si

[19] https://twitter.com/comaugroup/status/1483733088786161666

collaborative robotic application to adjust fog lamps at the Ford plant in Saarlouis (Germany). The operator and a robot KUKA LBR iiwa work collaboratively in the same work area.

Figure 14: PISA cobot work-cell



Source: author (PISA 6th FP Project)

Danish Trelleborg Sealing Solutions deployed 42 Universal Robots which carry out machine tending on CNC machines. Due to space restrictions, operation without safety guards was critical, and the ease of programming enabled the agile manufacturing required to accommodate orders ranging from a single unit to series of several million. Furthermore, they allow one operator to keep a cell with eight CNC machines running, where previously the maximum was three. As a result, Trelleborg saved 1.5 employees/cell/shift (Bogue, R., 2016).

At a Greek Johnson & Johnson plant, a Universal Robots UR5 robot has significantly improved the packaging of shampoos and skincare products. The robot arm picks up three bottles simultaneously from the production line every 2.5 seconds, orientates them, and places them in the packing machine. While human operators can handle 45 bottles per minute, the robot handles 70 and frees the workforce from repetitive and tedious tasks. As any employee can quickly re-programme the robot for new tasks, the cost of hiring external programmers has been eliminated (Bogue, R., 2016).

During recent years, new forms of human-robot collaboration have emerged through the combination of mobile bases with collaborative manipulation robots (Hentout et al., 2019; Unger et al., 2018) have emerged. These technologies increase the versatility of collaboration, but at the same time create new paradigms and research topics.

3.2.4. European initiatives in collaborative robotics research

The European Commission has promoted numerous research activities related to collaborative robotics. Some of the most important projects on this topic are: PISA, SHERLOCK, COROMA, COLLABORATE, SAPHARI, PHRIENDS, ROSETTA, ROBO-PARTNER, ROBO-MATE, SPEXOR, ROSSINI, SYMBIO-TIC, FourByThree, SHOP4CF, THOMAS, SHAREWORK, RESPECT, MERGING, AI PRISM, FELICE, RaRe2, FEROX, SHOPIA, CONCERT and SESTOSENSO. Collaborative robotics technology has been one of the key topics in the H2020 Robotics Multi-Annual Roadmap prepared by SPARC, the Partnership for Robotics in Europe, and it will also be in the agenda of the new partnership in artificial intelligence, big data, and robotics ADRA.

3.3. Review of the current potential of robotic and cobotic systems

3.3.1. Benefits and disadvantages of collaborative robotics technology

As established in chapter 3.1.1, collaborative robotics technology presents several clear benefits over traditional industrial robotics. Cobots are inherently safe for human-robot collaboration, which simplifies and reduces commissioning costs, as they do not require fencing or other technologies to isolate the robot from humans, are easier to programme, and can be easily relocated and reinstalled. Cobots introduce a new paradigm of automation in which the operator is not replaced by a machine (robot), but the machine is introduced to assist the operator by improving and complementing his/her capabilities (accuracy, endurance, power) and making their work more productive while reducing risks. Collaborative robots are key in agile production and can contribute to deploy new business models. These advantages facilitate the introduction of robotics technology in new applications and lower barriers to its use in small and medium-sized enterprises that often work in small to medium batch production and do not have skilled robotics workers.

The main advantages of collaborative robotics are:

- Reduced commissioning costs
- Simplified installation, relocation, and programming
- Do not replace the operator when using in collaborative tasks
- Maximum flexibility in production
- Avoids ergonomically poor positioning of tasks
- Reduced risks for operators
- Improved process quality
- Increased productivity
- Facilitate new applications and business models

On the other hand, cobots do not have the high speed, high payload, long reach, high precision, and high productivity that traditional industrial robots can have. This limits their use, making them unsuitable when a high volume of production is required or when a high load capacity or a long reach is needed. Although their safety is inherent in human-robot collaboration, cobots still need a safety assessment and must be accepted by workers who need to adapt to new ways of working.

As it was established in chapter 3.2.1, despite the advantages of collaborative robots, many of them are being used as traditional industrial robots for simple applications where the operator is replaced by a machine without a high level of collaboration between the two. The main objective here is to reduce costs.

The main disadvantages of collaborative Robotics are:

- Low speed, low payload capacity, short reach, low precision
- Low productivity
- Limited use to low-volume production
- Still need a safety assessment
- Need acceptance by workers
- Currently cobots are mainly used for low levels of human-robot interaction

3.3.2. Artificial Intelligence in collaborative robotics

The rise of AI and international developments in it are high priorities for European policymakers (Vanderborght, 2019). However, AI is an inevitable shift for the European Union, however, the United States and China are world leaders in the field (Bughin et al., 2018). In 2021 the robotics public–private partnership (PPP) SPARC merged with the Artificial Intelligence and Big Data PPPs to create a new PPP ADRA – AI, Data and Robotics Association asbl[20]. The term Artificial Intelligence (AI) is used as an umbrella term for neural networks, deep learning, machine learning, computer vision, natural language processing, artificial agents, and robotics. One of the main objectives of ADRA is to develop a common strategic research and innovation agenda for AI. Traditional robot control algorithms do not necessarily use AI methodologies, although the introduction of AI in robotics research is clearly increasing in many aspects such as navigation, behaviour control, task planning, or perception. In particular, collaborative robotics research is incorporating many AI based algorithms to increase safety or versatility. Many EU projects in collaborative robotics technology are using AI algorithms.

3.3.3. Intellectual property rights and open robotics

Over the last few years, the robotics community has seen a remarkable increase in the development of open-source software that is being used both by researchers in the field and by the business sector. The Robot Operating System (ROS)[21], a set of software libraries and tools that help to build robot applications, is probably the most famous example. Open-source software for dynamic simulation in robotics has also been developed, such as Webots[22] or Gazebo[23], and there are widely available libraries such as OpenCV[24], for computer vision, and OpenSLAM[25], for simultaneous localisation and mapping. In this way, the robotics community has benefited by avoiding duplication of development and continuously cooperatively improving the availability of open-source software. Commercial robots are now available that make use of open-source software and hardware. The European Commission has promoted these developments that allow access to these open resources to any interested user.

Currently, intellectual property rights face many challenges in artificial intelligence and robotics. The current robotics innovation ecosystem is a combination of open and competitive (proprietary) approaches to intellectual property management (Vanderborght, 2019). Since the Horizon2020 Programme, the European Commission encourages the use of open-access journal for the publication of the research results obtained in European projects. In the current Horizon Europe Programme, open-access publication is mandatory.

With respect to intellectual property, the use of open-source software and proprietary code must be combined in a way that protects the added value of developments that actually represent the potential commercial benefit to companies.

[20] https://adr-association.eu

[21] https://www.ros.org

[22] https://cyberbotics.com

[23] https://gazebosim.org/home

[24] https://opencv.org

[25] https://openslam-org.github.io

3.3.4. Ethics and social aspects in collaborative robotics

Collaborative robotics and robotics, in general, can contribute to improved resource efficiency and work as important enablers of remanufacturing and circular economy (Huang et al., 2019; Sarc et al., 2019).

All technological developments require an ethical analysis. EU directives and rules must be followed in the development of new research and technological development. Ethics should be considered an important differentiator of the EU from the United States and China, embracing change on the basis of the values of the Union and developing a sustainable approach to technologies (Vanderborght, 2019).

Ethical considerations apply to robotics in general, but especially to collaborative robotics involving the inclusion of humans working together with machines. The acceptance of these systems by workers is of vital importance. As noted above, **collaborative robots present a more favourable image than traditional industrial robots** in that they avoid replacing the human with a machine and are designed to enhance the operator's capabilities by reducing operator effort and avoiding possible damage to the operator. If cobots are used in a way that involves a high-level interaction between the operator and the robot, taking ergonomic aspects into account, the social benefit is clearly justified. In any case, **it is necessary to take into account not only the physical safety aspects but also the possible mental stress that may be caused to workers**. It is also important to ensure the privacy of operators, as cobotic systems can acquire information about them or learn from them. **Collaborative robotics can also mean the elimination of physical barriers (strength, height, physical condition, dexterity, mental disorders, etc.) that prevent certain people from accessing the world of work** (Mandischer, 2023), (Kalatzis, 2022).

The EU is committed to implementing the UN Sustainable Development Goals (Agenda 2030) in both its internal and external policies. Robotics, and in particular collaborative robotics, can bring benefits in achieving the proposed goals.

3.3.5. Future trends in human-robot collaboration

Human-robot collaboration is a promising technology that has experienced remarkable growth in recent years. According to relevant stakeholders and IFR forecasts, this growth will continue in the coming years. However, many problems still need to be solved. In typical collaborative robots, the robot system controls hazards by limiting the power or force the robot can exert before stopping. This methodology has had a significant impact on collaborative manufacturing, but it has important limitations. Stopping is only triggered in response to a collision detected by the sensors of the robot. This approach only works for smaller, slower, and lighter robots that will not harm a person in contact, limiting the size, velocity, and payload capacity of the robots. As pointed out by some experts consulted, **the end effectors and objects carried by the robots also need to be taken into account in the risk assessment.** Even a small and lightweight robot carrying a sharp object or cutting tool would still be dangerous. Although there are collaborative robots with medium-high payload capacity and large size like the Comau Aura (170 kg payload and 2.8 m reach)[26], the majority of the collaborative robots are small, lightweight, and slow compared with traditional industrial robots.

Although traditional industrial robot technology is well established in large manufacturing companies, there are significant barriers that have prevented the use of robots in small and medium-sized enterprises (SMEs). In typical batch production, robots must be reprogrammed frequently, which increases costs and requires skilled workers in SMEs. **Collaborative robots have introduced**

[26] https://www.comau.com/en/competencies/robotics-automation/collaborative-robotics/aura-collaborative-robot/

many of the same benefits to SMEs that traditional robotics and automation offered to large organisations. Collaborative robots offer a safer, more compact, and intuitive solution that can be deployed and programmed more quickly and cost-effectively. In this way, SMEs in the manufacturing sector can gain a significant technological advance in the next future. As we have seen, collaborative robots are also good drivers for the introduction of new business models called 'robots-as-a-service' and 'pay-as-you-use', these new models could also have a significant impact on the use of robotic technology by SMEs.

Collaborative robots are also key to support agile production methodologies, i.e., the ability to respond quickly to rapidly changing customer or market needs. This is particularly important in the electrical and consumer electronics industry, which is characterised by ever shorter product lifetimes (Bogue, R., 2016). Collaborative robots are usually easier to program and allow fast reconfiguration and movement of the robot. Therefore, cobotic technology can help reduce changeover times and interruptions and improve productivity in the production of low-volume and customised products.

Of course, there are still many problems to be solved and research to be done to improve the capabilities of collaborative robotic technology. **There is still a need to develop improved safety systems that minimise risks and facilitate the usability of cobots**. **There is also a need to improve associated standards and regulations** to enable safe and easy installation of cobots. The European Commission has supported and is supporting numerous projects that aim to develop and promote the use of collaborative robots to improve the EU's industrial competitiveness, create new jobs and retain existing ones.

4. Conclusions

Based on what has been presented in this study and the interviews and the questionnaire carried out, the following conclusions can be established:

- Industrial robotics is a clearly consolidated sector with practically constant growth. Europe is the second largest market for industrial robots, although far from Asia and with clearly lower growth. During recent years, a technology has been developed that allows direct – even with physical contact – human-robot collaboration. This technology, called collaborative robotics, is one of the pillars of Industry 4.0 and, although the market for collaborative robots is still very small compared to that of traditional robots, its growth is much higher. Most of the key players in the global cobots market are European companies. Collaborative robotic technology is considered one of the 12 potentially economically disruptive technologies that will transform life, business, and the global economy.

- The objective of collaborative robots is to combine the precision, endurance, and power of industrial robots with the individual skills and ability inherent to humans. Therefore, collaborative robots or cobots, have been designed to assist the human operator; that is, the machine does not replace the human but complements his or her capabilities and relieves the worker of arduous tasks. However, human-robot collaboration implies the need to guarantee the safety of workers. Although robots have been designed to be inherently safe, it is necessary to make an assessment. Complementing the human operator rather than replacing him or her can also have a significant influence on maintaining employment, giving this technology a friendly image in the eyes of society. However, many cobots are used for automation purposes in ways similar to traditional industrial robots, without human-robot collaboration, replacing humans rather than engaging in real collaboration with them.

- Compared to traditional industrial robots, collaborative robots have advantages such as lower cost, greater flexibility, easier installation and repositioning, and improved ergonomics at workstations. This facilitates small and medium-sized enterprises access to this technology. However, cobots also have limitations that reduce their productivity or applicability, such as reduced range, speed, or payload capacity compared to traditional industrial robots. Collaborative robots are also good drivers for the introduction of new business models such as 'robots-as-a-service' or 'pay-as-you-use'.

- Collaborative robotics reduce physical efforts for work and so can help reduce work-related musculoskeletal disorders, stress, and operator fatigue and can also mean the elimination of physical barriers (strength, height, physical condition, dexterity, mental disorders, etc.) that prevent certain people from accessing the productive sector. However, it is necessary to carry out an exhaustive ethical evaluation far beyond that necessary in traditional robotics, taking into account aspects such as the safety and wellbeing of workers, acceptability, ergonomics, and privacy.

- Currently, collaborative robots are present in most industrial sectors, such as the electronic sector or the automotive industry, and particularly in those industrial sectors that are moving to high-mix low-volume production where cobots are very useful to increase flexibility and reduce changeover times. Collaborative robots are also key to supporting agile production methodologies, i.e., the ability to respond quickly to rapidly changing customer or market needs. Regarding collaborative service robots, there are promising sectors, such as healthcare, hospitality, inspection, or construction, where cobots can help workers.

- Despite the benefits of collaborative robotics technology, many challenges remain to be resolved. The necessary security in human-robot collaboration limits the development of collaborative robots and prevents them from achieving the benefits of traditional industrial robots. It is therefore necessary to advance in key aspects such as detection of humans and increased security. Existing legislation and standards are complex and also limit development with respect to other countries outside the EU. The EU has made and is making a notable effort to promote lines of research and development with reference to collaborative robotics to improve the EU's industrial competitiveness, create new jobs and retain existing ones.

5. Policy options and their assessment

After the development of the study and following the methodology and the results of the resources used, this study analyses the scenario of possible impacts and outcomes and proposes fundamental policy options regarding the analysis exploring risks and opportunities linked to the use of robots and collaborative industrial robots in Europe.

5.1. Impacts and outcomes

5.1.1. Impacts on job creation

The main objective of collaborative robotics technology is to complement human abilities to solve complex problems in imprecise tasks with the precision, power, and endurance characteristics that robots possess. Cobots do not therefore replace humans, but provide them with assistance by improving their working conditions and relieving them of arduous and tedious tasks. Under this approach, collaborative robotics technology does not have a significant impact in the manufacturing industry but implies an advantage in the technological sector, creating new jobs and contributing to retaining existing ones. Additionally, this technology can help the survival of SMEs in the production sector by providing them with access to automation technologies that traditional industrial robotics cannot provide due to the cost and difficulty in producing small and medium-sized product batches. Unfortunately, cobots are still used in many cases with little or no interaction with workers, which largely equals their impact to that of traditional robotics. **The results obtained in personal interviews and surveys clearly show that most experts agree that this technology contributes to the creation and retention of jobs**.

5.1.2. Impacts on safety and working conditions

The main characteristic of collaborative robotics is its inherent safety. In its initial conception, the aim has always been to enable direct human-robot interaction by improving working conditions and seeking to significantly improve ergonomics. However, although cobots allow for easier risk analysis and avoid having to put them inside a protective cage, they are not yet completely safe for human-robot interaction and more advanced sensor capacities are needed. There are many possible actions to reduce risks, but these often restrict the capabilities of cobots. For several stakeholders, collaborative robotics can also expose human operators to additional stress. **In general, experts agree that collaborative robotics also implies improved safety in the manufacturing sector and a clear improvement in working conditions**. Experts also agree that collaborative robots are more easily accepted by workers than traditional industrial robots.

5.1.3. Economic, social, and environmental impacts

Supported by lower acquisition, installation and usage costs and a higher capacity for reallocation and adaptability to frequent task changes, **collaborative robotics improve the productivity of the manufacturing sector and, in the case of SMEs in particular, they increases their competitiveness and reduces production costs**. The EU's leading position therefore gives it a competitive advantage with a significant economic impact. Most experts point out that there is still a lack of knowledge on collaborative robotics in the industry, which limits their possible economic impact. The growth of the collaborative robotics market will continue to outstrip that of the industrial robot market. However, there is a risk that the EU loses its leadership in this sector and is surpassed by the Asia-Pacific region in the coming years. Experts assure that there is no major problem of social acceptability of collaborative robots.

The possibility of directly interacting with robots opens up a vast world of opportunities for service robotics in fields such as care robotics, the health sector, or the construction sector. However,

current EU legislation limits development compared to other countries such as the USA and China.

Several authors remark that collaborative robotics can contribute to improving resource efficiency and can also act as enabler of remanufacturing and circular economy. Cobots are lighter and smaller than traditional industrial robots and, therefore, consume less energy. However, **experts do not see this technology significantly reducing the manufacturing sector's carbon footprint.**

5.1.4. Ethical impacts

Ethical considerations apply to robotics in general, but especially to collaborative robotics involving the inclusion of humans working together with machines. As noted, there is no problem of worker acceptability, and cobots present a more favourable image to society than traditional robots, as they claim to avoid replacing humans with a machine. However, a lot of work remains to be done and aspects such as reducing the possible mental stress that these robots can cause to workers and ensuring the privacy of the operators must be considered in future applications of this technology.

Collaborative robotics can also mean progress in the **incorporation of people with physical or mental disabilities into the world of work**. Likewise, it can help integration in general by eliminating limitations of strength or height in certain tasks.

5.1.5. Knowledge management impacts

Collaborative robotics, as an integral part of the robotics world in general, has also contributed to the development of open-source software, making many development tools available to the robotics community. This contribution is likely to increase significantly in the future, reducing duplication of work and enabling faster technological progress. The same applies to the publication of scientific results in open-access journals. Nevertheless, **companies must maintain their leadership by adequately protecting their competitive advantage through patents**. This is a key factor for European companies that have taken the lead in this technology.

5.2. Policy options

The policy options have been grouped into legislative and standard policies, economic policies, social and environmental policies, and ethical and gender policies.

5.2.1. Legislative and standards policies

Policy option 1: Existing regulations do not clearly support the development of collaborative robotics technology. **Human-robot interaction conditions and safety assessments should be facilitated by developing clearer regulations that do not limit the development of collaborative robots and respect workers' health and wellbeing.**

A revision of the EU Machine Directive could provide a simpler definition of all aspects related to the use of collaborative robots and help to reduce and simplify the incorporation of this technology in the industry sector and society through the use of collaborative service robots. Existing regulations and standards are still difficult to implement for EU companies. It is obvious that the EU is characterised by a higher degree of protection for its citizens ensuring their safety and the quality of their working conditions. However, more permissive regulations in other countries can give their companies a competitive advantage in the development of technology. It is important to reach a compromise that allows competition on a level playing field while guaranteeing people's safety and wellbeing through agile and efficient regulation allowing for swift adaptation to technological developments. Most experts consulted agree that the current legislation and standards are still not completely developed.

5.2.2. Economic policies

Policy option 2: The EU is currently leading the world in the introduction of collaborative robotics technology. Support for this technology in Europe could contribute to economic benefit in one of the key sectors for technological developments in the coming years. **The EU should maintain or even increase the budget for research activities where human-robot interaction or collaborative robotics are relevant.**

Collaborative robotic technology is considered one of the 12 potentially economically disruptive technologies that will transform life, business, and the global economy. To maintain or increase their leadership position, matching that of US companies, financial support should be provided for research into aspects related to collaborative robotics, as well as support for the technological development of European companies in this sector. Incorporation of cobots into major robot manufacturers' product ranges has been remarkable in recent years, and the growth of the market and prospects predict a remarkable evolution in the coming years. Collaborative robotics is a key element of Industry 4.0 and can enable leadership in the production sector by increasing productivity and reducing costs, while at the same time improving working conditions. Additionally, collaborative robots can represent an important advance in service robotics in key sectors for a Europe that has an ageing population.

Collaborative robotics still has many limitations that prevent achievement of all the possible benefits of this technology. Due to the necessary safety conditions, collaborative robots cannot be as fast or exert as much force or load capacity as traditional industrial robots. Advances in technologies such as proximity detection systems or projection-based monitoring systems to slow or stop robot movement when the system detects the presence of a human, or the development of variable stiffness actuators that reduce possible physical damage, needs to be explored in more depth to allow cobot features, their productivity, and the number of possible applications to be increased.

5.2.3. Social and environmental policies

Policy option 3: Collaborative robotics and the development of applications requiring human-robot interaction could bring important societal benefits**. There is a need to encourage the development of policies to support the creation of new real-world applications using high levels of interaction by promoting training of all actors in this technology.**

Although the growth of collaborative robotics has been spectacular in recent years and the forecasts are very good, in many cases cobots are still used with a low level of human-robot interaction, without really taking advantage of their collaborative characteristics. This limits the benefits of this technology and its positive impacts. The problem often derives from the need to conceive collaborative tasks from a new perspective that includes the concept of real human-robot interaction at a high level from their design. It is therefore necessary to promote training in this technology for the main actors in the productive sector to increase knowledge of the characteristics and advantages of collaboration between humans and robots and to support research in the creation of new productive methods that contemplate this possibility from the design stage. Additionally, it would be convenient to develop policies that allow adequate training of workers in the use of collaborative robotics, increasing worker acceptance and minimising the possible risks of interaction between humans.

5.2.4. Ethical and gender policies

Policy option 4: Collaborative robotics can also mean the elimination of barriers that prevent less physically gifted people from accessing the world of work. **However, there is a need for policies that promote ethical assessments to ensure safe human-robot collaboration, worker acceptance and privacy.**

The benefits of reducing or even eliminating physical barriers that make it difficult for certain people to enter the world of work due to physical or mental effort or physical conditions are clear. However, the incorporation of humans into the control loop of robotic systems involves the need to carry out more in-depth ethical evaluations than are necessary in traditional robotics. It is not only necessary to carry out assessments regarding the physical safety of the operator in collaboration with the cobot, but other aspects such as the possible mental stress that may be caused to the user also need to be taken into account. Ergonomic aspects also play a fundamental role in the evaluation of the task. It may also be necessary to acquire information about the operator during the execution of automated tasks, which necessarily requires the need to ensure user privacy. It is also necessary to ensure worker acceptance of collaborative robotic systems. Therefore, ethics committees should carry out in-depth assessments that take all the aspects that real collaboration entails into account, even with physical contact between humans and robots. Again, training ethics committees in these new technologies could play a fundamental role in ensuring the ethical aspects of collaboration between humans and robots.

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Annex: Results of the survey

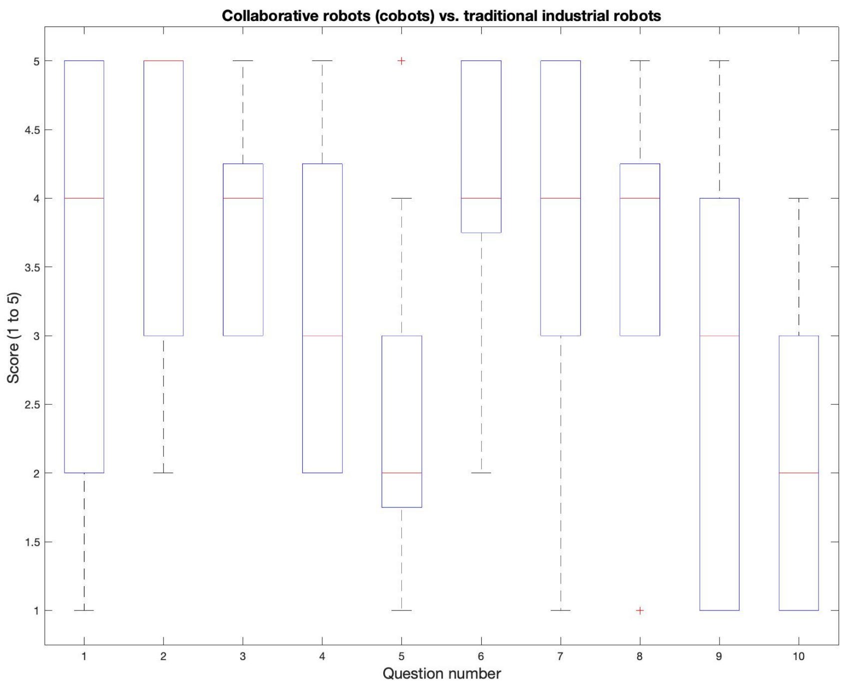
The following figures show the boxplots [27] of the questions included in the survey.

Set 1: Collaborative robots (cobots) versus traditional industrial robots

Comparing the features of cobots with traditional industrial robots, indicate your agreement or disagreement with the following statements (1 totally disagree/5 totally agree):

1. Collaborative robots allow for easier risk analysis
2. Collaborative robots are easier to program than traditional industrial robots
3. Collaborative robots are more easily accepted by workers than traditional industrial robots
4. The cost of acquisition, installation and use of collaborative robots is lower than that of traditional industrial robots
5. Collaborative robots are more efficient than traditional industrial robots
6. Collaborative robots are easier to reallocate and are more adaptable to frequent task changes than traditional industrial robots
7. Collaborative robots can help automate applications that cannot be automated with traditional industrial robots
8. When the human operator cannot be replaced by a traditional robot, collaborative robots can improve ergonomics and working conditions
9. Collaborative robots are only useful for a limited number of applications where high speed, high precision, or high force are not required and where the working range is small.
10. Collaborative robots are less reliable than traditional industrial robots

Figure 1A: Collaborative robots versus traditional industrial robots



[27] Boxplot

Risks

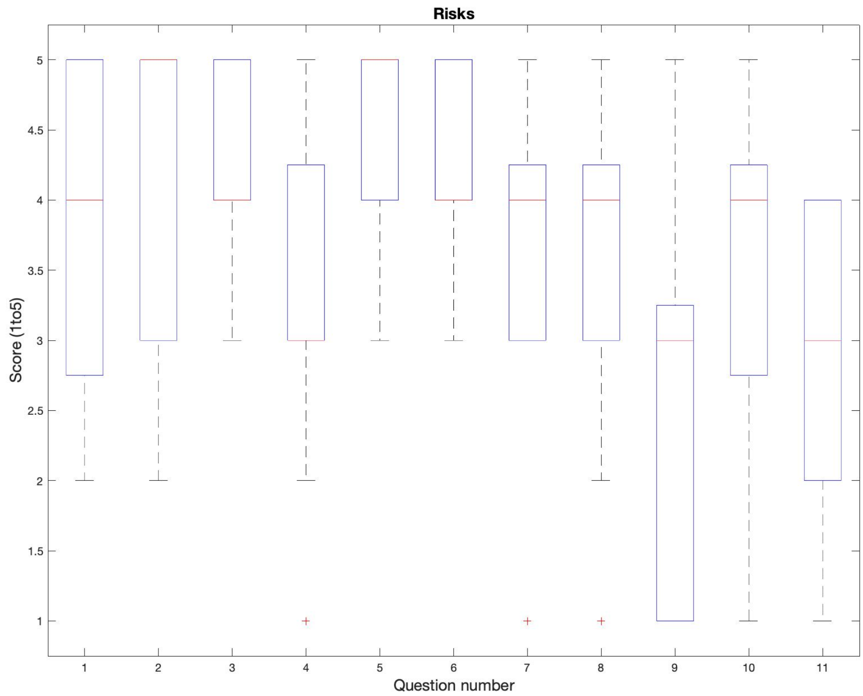
Human-robot collaboration is a source of potential risk due to possible accidents. Rate the usefulness of the following measures used in collaborative robots to prevent accidents (1 not at all useful/5 very useful):

1. Reduction of the maximum robot speed
2. Reduction of the maximum force exerted by the robot
3. Design of the robot to avoid or minimize damage in the event of contact with a human
4. Configurable stopping time & stopping distance
5. Proximity detection system (using machine vision, the system detected the presence of a person and acted, e.g., by slowing down movement or by stopping altogether).
6. Collision detection system (mechanical detection of collision, through force or torque sensing in the robot joints, and subsequent reaction to that collision)
7. Projection-based space monitoring system (safety system by means of which a safety zone around the immediate area of influence of the robot is monitored and any external intrusions in that area will cause the movement to slow down or stop)
8. Variable stiffness in actuators (through the mechanical design, the stiffness of the actuators in each join could be adjusted according to programmed rules, transitioning from a mechanically rigid robot to a low stiffness one that would give in when, e.g., colliding with a person)

Regarding human-robot collaboration using collaborative robots, indicate your agreement or disagreement with the following statements (1 totally disagree/5 totally agree):

9. Collaborative robots are completely safe for human-robot interaction even when contacts are possible
10. Collaborative robots still need more advanced sensor capabilities to allow a completely safe human-robot interaction
11. Tasks where contact between the human and the robot is possible exposed human operators to additional stress

Figure 2A: Risks



Market trends for industrial and collaborative robots

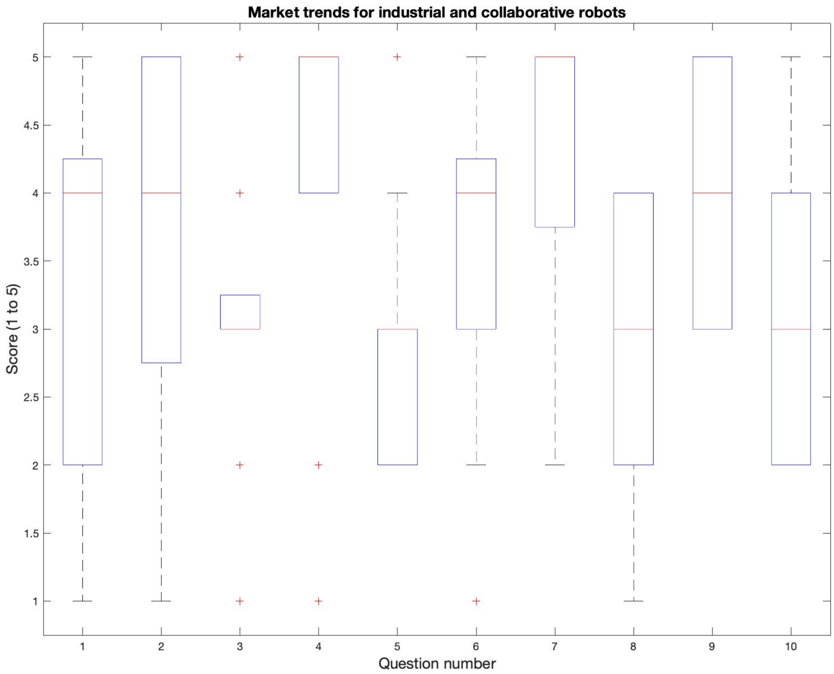
There are still important barriers that prevent the adoption of collaborative robots. Indicate the importance of the following possible barriers in order to prevent the use of cobots (1 not very important/5 very important).

1. Safety is not guaranteed
2. Legislation and standards are still not completely developed
3. Costs are still very high
4. There is a lack of knowledge about collaborative robots in the industry
5. Worker's acceptance is still very low

Regarding the market evolution for robots in the following five years, please indicate your agreement or disagreement with the following statements (1 totally disagree/5 totally agree):

6. During the last 5 years the installations of industrial robots worldwide have maintained a growth rate of around 11%. Industrial robot installations around the world will maintain a growth rate of more than 10% per year
7. In 2021, 74% of all newly deployed robots were installed in Asia (2020: 70%) and only 16% in Europe. The growth of the industrial robot market will continue to be higher in Asia than in Europe
8. Due to measures such as relocation, the differences in growth of the industrial robot market in Europe compared to Asia will become smaller and smaller
9. In 2021, collaborative robots accounted for 7.5% of the total robotics market, but their growth was 50%. The growth of the collaborative robotics market will continue to be higher than that of the industrial robot market
10. Europe and North America accounted for the largest collaborative robots market share; however, they will be surpassed by the Asia-Pacific region in the upcoming years

Figure 3A: Market trends

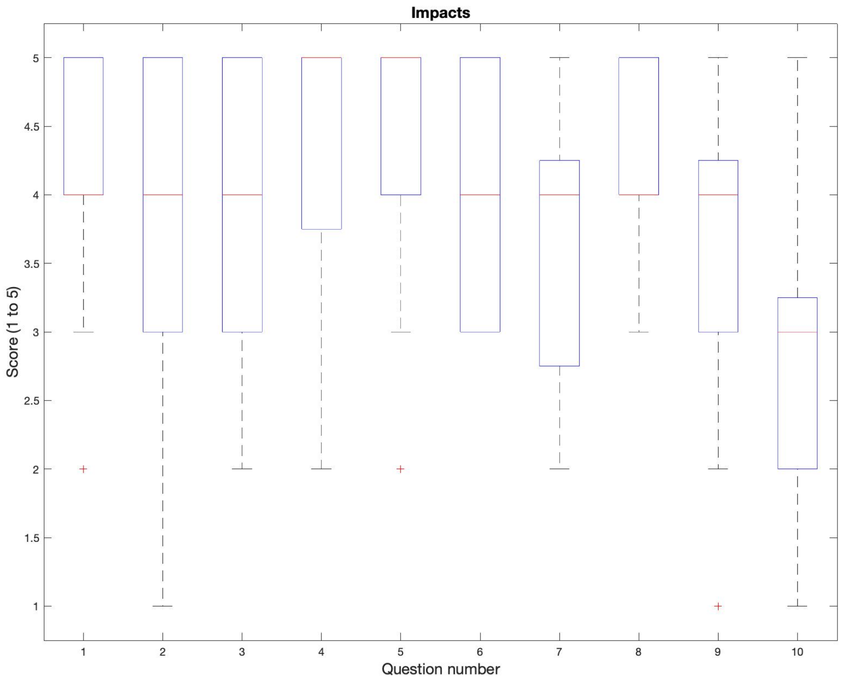


Impacts:

Rate the impact of collaborative robotic technology in the EU in the following aspects (1 very negative impact/5 very positive impact)

1. Job creation
2. Job retention
3. Productivity of the manufacturing sector
4. Productivity of Small and Medium-sized Enterprises
5. Competitiveness of the manufacturing sector
6. Reduction of the production cost of the manufacturing sector
7. Improvement of safety of the manufacturing sector
8. Improvement of working conditions in the manufacturing sector
9. Incorporation of less physically gifted people to the manufacturing sector
10. Reduction of the carbon footprint of the manufacturing sector

Figure 4A: Impacts



List of collaborators

The following list includes the collaborators who expressed their willingness to appear in this list.

- **Tapio Heikkilä** (Dr, Principal Scientist at VTT Technical Research Center of Finland, Oulu, Finland)
- **Jose Saenz** (Group Leader Assistance, Service and Industrial Robotics at the Fraunhofer Institute for Factory Operation and Automation IFF, Magdeburg, Germany)
- **Panagiota Tsarouchi** (RIS Activities Manager at EIT Manufacturing, Paris-Saclay, France)
- **Daniel Martin** (Competence Centre Robotics Manager at Pilz, Spain)
- **Enrique Lillo** (CEO of BRobot5, Madrid, Spain)
- **Kevin Haninger** (Dr, Robotic Researcher at Fraunhofer Institute for Production Systems and Design Technology IPK, Berlin, Germany)
- **Dragoljub Surdilovic** (Dr, Robotics Expert at REHA STIM MEDTEC GmbH & Co. KG, Berlin, Germany)
- **Alberto Jardón** (Robotics Prof. Dr.-Ing. at Universidad Carlos III de Madrid, Spain)
- **Jordi Pellegrí** (Country Manager. Spain & Portugal at Universal Robots, Barcelona, Spain)
- **Francisco Blanes** (Robotics Prof. at Universidad Politécnica de Valencia, Spain)
- **Arash Ajoudani** (Dr, Head of HRI2 Laboratory at Instituto Italiano di Tecnologia IIT, Genova, Italy)
- **Sarah Terreri** (Head of Collaborative Projects at PAL Robotics, Barcelona, Spain)
- **Thomas Bock** (Robotics Prof. Dr.-Ing. at Technical University of Munich and CREDO Robotics GmbH, Munich, Germany)

Profile of collaborators

In the development of this study, face-to-face interviews and a survey questionnaire were carried out to involve the most relevant stakeholders in collaborative robotics technology, including academics, researchers, cobot manufacturers, and end-users. All participants are highly experienced people in an age bracket between 40 and 65 years. The profile of the people who have collaborated has been distributed as follows:

- 22% Academics (mainly university professors)
- 28% Researchers (Mainly leaders of research teams in prestigious public and private centres)
- 18% Collaborative robot manufacturers (relevant persons in companies producing cobots)
- 32 % End-users (people using collaborative robotics in application development)

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Robot applications, including 'collaborative robots' – cobots – designed to collaborate with humans, are in high demand, with sales and installation figures constantly on the rise. However, it is necessary to analyse the risks and opportunities of this technology and its possible social, economic, and ethical impacts.

This study presents the current state of collaborative robotics, its benefits, and its disadvantages, with a special emphasis on key aspects such as safety. It presents possible policy options to enable the EU to remain at the forefront of this technology by taking advantage of the opportunities and avoiding the potential risks.

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